

# Índice de seguridad inherente de una biorrefinería de aguacate (*Laurus Persea L.*) en el departamento de Bolívar

## Inherent safety index of an avocado (*Laurus Persea L.*) biorefinery in the department of Bolivar

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### Resumen

**Introducción:** El aguacate se cultiva en diferentes regiones de Colombia. En el norte del país se producen aguacates nativos, pero parte de la producción de la región se ha visto afectada por diversos factores que ocasionan la acumulación de frutos en mal estado, generando lixiviados, malos olores y presencia de roedores.

**Objetivo:** La producción de aceite, biocarbón y clorofila a partir de pulpa, semilla y cáscara de aguacate, respectivamente, se propone como una alternativa para el aprovechamiento de los residuos del aguacate.

**Metodología:** En este estudio se realizó un análisis de seguridad inherente y sostenibilidad de una biorrefinería de aguacate para la producción de aceite, biocarbón, clorofila, pulpa libre de grasa y compost en los Montes de María en el norte de Colombia, con una capacidad de procesamiento de 10.500 t/año. La seguridad del proceso se evaluó utilizando el Índice de Seguridad Inherente (ISI), que mide de manera general qué tan seguro es un proceso en las etapas de diseño conceptual.

**Resultados:** De acuerdo con los resultados, se observa que en el proceso existe una reacción endotérmica en la etapa de pirólisis necesaria para producir biocarbón, asimismo, las puntuaciones asociadas a subíndices como inflamabilidad, explosividad, toxicidad y corrosividad corresponden a la presencia de sustancias como el hexano en el proceso, en este caso para producir aceite de aguacate. Otro aspecto que contribuye al índice de seguridad inherente al proceso es la temperatura de este, siendo la más alta la de la etapa de pirólisis a 400 °C.

**Conclusiones:** En general, el proceso es seguro, ya que se obtiene un Índice de seguridad inherente total (ISI) inferior a 24 puntos.

**Palabras clave:** Índice de Seguridad inherente; biorrefinería de aguacate; pirólisis; aceite; clorofila; biochar.

### Abstract

**Introduction:** Avocados are grown in different regions of Colombia. In the north of the country, native avocados are produced, but part of the production in the region has been affected by various factors that cause the accumulation of fruits in poor condition, generating leachates, bad odors and the presence of rodents.

**Objective:** The production of oil, biochar and chlorophyll from avocado pulp, seed and peel, respectively, is proposed as an alternative for the utilization of avocado waste.

**Method:** In this study, an inherent safety and sustainability analysis was conducted for an avocado biorefinery to produce oil, biochar, chlorophyll, fat-free pulp and compost in the Montes de María in northern Colombia, with a processing capacity of 10,500 t/y. The safety of the process was evaluated using the Inherent Safety Index (ISI), which measures in a general way how safe a process is in the conceptual design stages.

**Results:** According to the results, it is observed that in the process there is an endothermic reaction in the pyrolysis stage necessary to produce biochar, likewise, the scores associated with sub-indices such as flammability, explosiveness, toxicity and corrosiveness correspond to the presence of substances such as hexane in the process, in this case to produce avocado oil. Another aspect that contributes to the safety index inherent to the process is the temperature of the process, the highest being the pyrolysis stage at 400 °C.

**Conclusions:** Overall, the process is safe, with a total Inherent Safety Index (ISI) of less than 24 points.

**Keywords:** Inherent safety index; avocado biorefinery; pyrolysis; oil; chlorophyll; biochar.



## INTRODUCTION

The growing demand for sustainable development has encouraged the implementation of biorefineries as promising alternatives for the valorization of agro-industrial biomass. Large amounts of this biomass are generated, representing a contamination risk but can be utilized through processes such as pyrolysis, solid-liquid extraction, hydrolysis, or fermentation [1], to mitigate the environmental impact caused by the indiscriminate disposal of waste [2]. In this context, avocado (*Laurus Persea L.*), a fruit widely cultivated in the department of Bolívar, emerges as a raw material to produce various products by valorizing its pulp, seed, and peel. However, production in biorefineries must integrate not only economic and environmental aspects but also ensure the intrinsic safety of the chemical processes involved [3].

Process safety is a preventive approach aimed at minimizing risks during the conceptual design stages. The Inherent Safety Index (ISI) has been widely used to analyze and improve the safety of chemical processes, allowing decisions to be made about the safest conditions for operation [4]. In the literature, some assessments have been carried out applying the ISI methodology. Another author analyzed shrimp biorefining using inherent safety methodologies, obtaining safety indices for different stages of the process and providing strategies for their improvement [5].

In this study, the contribution of the stages, chemical substances, and operating conditions to process safety was determined. This corresponds to an avocado biorefinery located in the department of Bolívar, in northern Colombia. The objective of this topology is the valorization of avocado cultivation residues by obtaining various products from the pulp, seed, and peel of the fruit. The study aims to identify and prioritize the risks associated with the plant's main operations, considering parameters such as toxicity, flammability, chemical reactivity, and critical operating conditions.

## RELATED WORK

In the literature, several safety assessments of different processes have been reported. An extractive-based biorefinery was developed in the Montes de María region for the production of oil, chlorophyll, and biopesticides, primarily. This process was evaluated using the Inherent Safety Index (ISI), obtaining a score of 18, which is below the reference value of 24 points. This indicates that the implementation of this process is inherently safe [6]. However, risks associated with the use of methanol, as well as with the drying and distillation stages, were identified. The authors propose replacing methanol with green solvents such as bioethanol to enhance the safety of the process. In another study, the safety of oil extraction from avocado pulp was analyzed, yielding an ISI score of 17 points. This score is attributed to the use of hexane for extraction and sodium hypochlorite for fruit cleaning [7]. Moreover, research has been reported in which the ISI is used to evaluate the safety of other biorefineries. One such study involves a topology that utilizes shrimp for the production of value-added products. According to the methodology, the shrimp biorefinery is inherently safe, achieving an ISI score of 21 points. This score is due to the presence of highly exothermic reactions and the use of acetone [8].

Other types of methodologies to predict the safety performance of processes have also been identified. Studies have been conducted on the safety of biorefineries for bioethanol production, focusing on the hazards of the substances involved and the types of equipment used, which may pose risks to human health or to the operation itself [9]. In other investigations, methodologies such as NuDIST have been employed to evaluate a shrimp biorefinery. It was found that the index with the highest score was flammability, due to the use of acetone and ethanol in the recovery of astaxanthin [10].

## METHODOLOGY

To determine the safety of chemical processes, there are a series of methodologies that allow them to be evaluated from this perspective. The avocado biorefinery located in the Montes de María region aims to utilize the seed, pulp, and peel of the avocado, requiring an understanding of the risks associated with setting up a plant for obtaining products from the biomass sources.

## Process description

The proposed biorefinery utilizes avocado cultivation residues to produce oil, defatted pulp, biochar, chlorophyll-rich extract, and fertilizer. The process begins with a fruit washing stage where a sodium hypochlorite solution is used to remove bacteria, and other contaminants present on the avocado. Next, the fruit is peeled, yielding three streams corresponding to the peel (stream 6), pulp (stream 7), and seed (stream 8). The peel and seed are washed to remove any remaining pulp. The resulting wash streams (13 and 10, respectively) are sent to a centrifuge to separate the water from the pulp (stream 17). This pulp is sent to a homogenization stage where streams 7 and 17 are mixed to form a paste, which is then dried at a temperature of 70 °C to eliminate moisture. This temperature is suitable for preventing the oxidation of the raw material [11]. The dehydrated pulp is contacted with hexane in the extraction stage, yielding a mixture (stream 23) composed of pulp, oil, and solvent. This mixture is sent to a centrifuge to separate the defatted pulp from the hexane and oil. In the distillation stage, avocado oil is obtained, while hexane is recovered through stream 28, a portion of which is recirculated to the extraction stage.

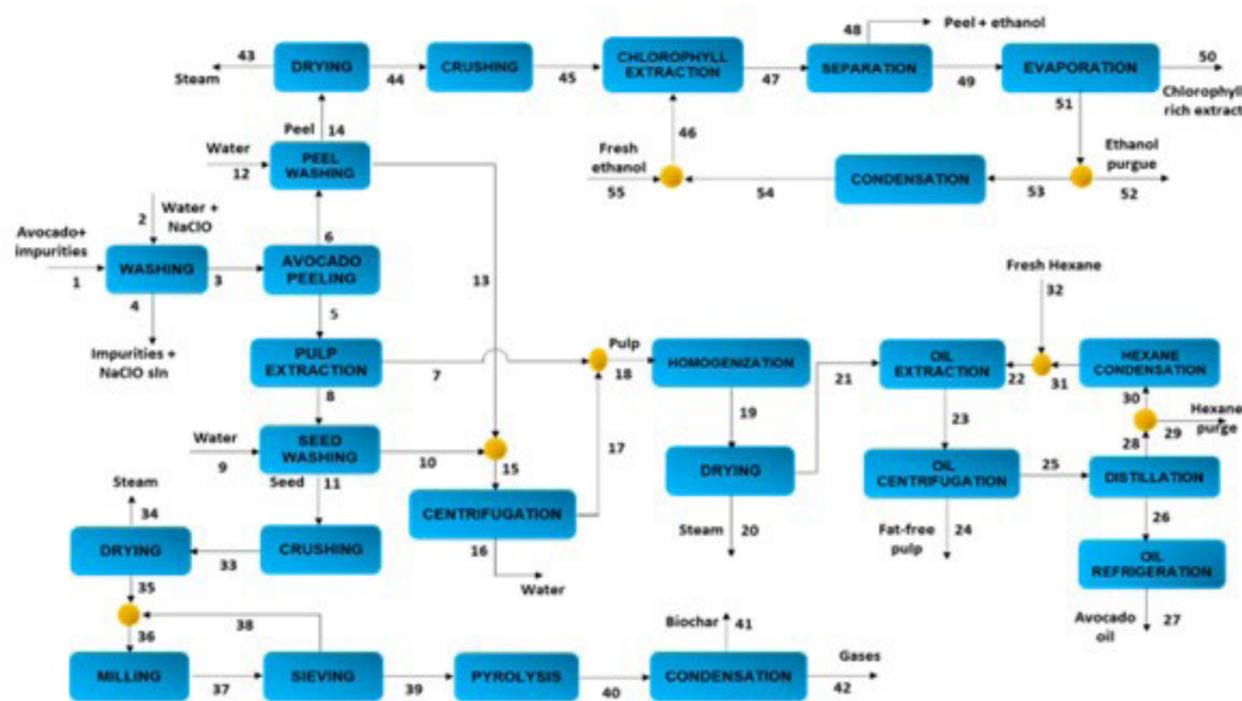


Fig 1. Process flow diagram of the avocado biorefinery in the department of Bolívar, Colombia. Source: self-made

To produce biochar, the clean seed (stream 11) is cut into small pieces and dried at 110 °C [12]. The dried seed is then ground and sieved, resulting in stream 39. Biomass that does not meet the desired size is recirculated to the grinding stage. The sieved seed is sent to a pyrolysis reactor operating at 400 °C under an inert atmosphere provided by nitrogen. This promotes biochar production, which is collected in stream 42 along with a gas mixture primarily composed of CO<sub>2</sub>, CH<sub>4</sub>, and CO [13], emitted through stream 41. Meanwhile, the washed peel (stream 14) is dehydrated at 60 °C to prevent biomass degradation [14]. The peel is ground to reduce particle size, facilitating the extraction of the green pigment or chlorophyll extract. Ethanol is used for this purpose, contacting the ground peel to produce a mixture consisting of the solvent, peel, and extract. This mixture is centrifuged to separate the liquid phase (ethanol and extract) from the solid phase (peel with solvent traces), which can be used as fertilizer. Finally, the ethanol and extract are sent to a distillation stage to remove the solvent, yielding chlorophyll via stream 50 and ethanol via stream 51, the latter being recirculated to the pigment extraction process. It is important to note that all biorefinery stages operate at a pressure of 1 bar.

## Inherent safety index

Several methods are available to assess the risks of safer process alternatives and their suitability for use during the early design stage of a process where data is limited. Scoring for process alternatives is based on a parameter value that is divided into several subintervals [15]. The Inherent Safety Index (ISI), implemented by Heikkilä [3], considers toxicological aspects, flammability, corrosion, chemical interactions, reaction heats, pressures, temperatures, and structural considerations, among others. ISI calculations help identify the risks and hazards

associated with a chemical process at the conceptual design stage. Eq. (1) is used to calculate the total inherent safety index, where ICI refers to the chemical substance index and IPI corresponds to the process safety index [16].

$$I_{SI} = I_{Ch} + I_{Ps} \quad (1)$$

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

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

To determine the contribution of chemical substances to process safety, Eq. (2) is used, which considers the indices of toxicity, flammability, explosiveness, and corrosiveness, as well as the primary and secondary reaction heat [6]. Toxicity is determined based on the TLV (Threshold Limit Value in ppm), scaled to the Permissible Exposure Limits issued by the Occupational Safety and Health Administration [17]. Flammability is measured according to the boiling and ignition points, which refer to the minimum temperature at which a substance ignites [18]. Explosiveness indicates a gas's ability to form an explosive mixture with air, as described by the Lower Explosion Limit (LEL). Finally, corrosiveness depends on the material used in the construction of the equipment. On the other hand, the process safety index can be calculated using Eq. (3), which considers operating temperatures ( $I_{T,max}$ ) and pressures ( $I_{P,max}$ ), the equipment construction material ( $I_{EQ,max}$ ), equipment inventory (Ii), and the safe process structure ( $I_{ST,max}$ ).

The scores assigned according to Heikkilä's [3] methodology for the chemical substance index range from 0 to 4 for sub-indices such as primary and secondary reaction heat, chemical interaction, flammability, and explosiveness, with a score of 4 indicating high hazard levels based on the evaluated parameter. Sub-indices like toxicity have a broader range, from 0 to 6 points, based on the TLV. Lastly, the corrosiveness sub-index has a scoring range of 0 to 2, where a score of 2 applies to processes requiring specialized materials for equipment construction. Regarding the process safety index, the methodology assigns scores from 0 to 4 for the sub-indices of maximum temperature and pressure. Similarly, scores are given for equipment located outside battery limits (OSBL), while for those inside battery limits (ISBL), the score ranges from 0 to 3. The assigned scores depend on the type of equipment used in the processes, such as pumps, heat exchangers, reactors, furnaces, and others. The sub-indices for inventory and safe structure have a scoring range of 0 to 5. Inventory scoring is based on the maximum volume processed during a residence time of 1 hour, whereas the safe structure sub-index considers reported accidents in similar processes [3].

## RESULTS AND DISCUSSION

### Chemical inherent safety index (Ich)

In the biorefinery, the production of biochar from avocado seeds involves an endothermic chemical reaction, where the biomass decomposes into a solid phase and volatiles [19]. Since it is an endothermic reaction, a score of zero is assigned to the parameter for the main and secondary heat of reaction. Additionally, the hazards of the substances were considered, evaluating aspects such as flammability, explosiveness, toxicity, and corrosivity. For this purpose, information was gathered on the properties of the solvents used (hexane and ethanol) in the topology, as shown in Table 1.

Properties	Hexane	Ethanol
Flash point (°C)	-23	14
Boiling point (°C)	68.5	78.5
LEL-UEL (%)	7.7	3-19
TLV (ppm)	50	1,000
Storage (material)	Iron, steel, aluminium	Metal, aluminium

TABLE 1. PROPERTIES OF THE SOLVENTS USED IN THE AVOCADO BIOREFINERY IN THE DEPARTMENT OF BOLÍVAR. SOURCE: SELF-MADE

For the flammability sub-index, the substance with the highest score was hexane, with a flash point  $<21$  °C, for which a score of 3 is assigned. It is worth noting that this substance is used in oil extraction and is evaluated to assess process safety. Regarding explosiveness, both substances fall within the range of “not very explosives” (0-20 %), with a score of 1. On the other hand, the toxicity indicator is applied in an industrial context to protect employees in the workplace. For this purpose, the TLV parameter (Threshold Limit Values) is evaluated, which is issued by the Occupational Safety and Health Administration (OSHA) in the United States [17]. A score of 3 is therefore assigned to TLV values  $\leq 100$  ppm. Finally, for the construction material of equipment used for storage and the overall process, a score of 0 is assigned, indicating that no special materials are needed, and that corrosion will not be an issue.

### Process inherent safety index (Ips)

To determine the process safety index, it is necessary to calculate the inventory. The total inventory is calculated from the sum of the equipment flow of the process obtained from the simulation, considering a residence time of 1 hour. The inventory values for the stages of avocado oil extraction, fat-free pulp, biochar, chlorophyll-rich extract, and fertilizer are shown in Table 2, with an inventory of 16.85 tons, where the ISBL (Inside Battery Limit) equipment was considered, and a score of 2 was assigned, corresponding to the 10–50 t range.

Biorefinery processes	Inventory (t)
Avocado oil extraction and fat-free pulp	12.29
Biochar production	3.06
Chlorophyll extraction and fertilizer	1.49
<b>Total</b>	<b>16.85</b>

TABLE 2. INVENTORY CALCULATION FOR THE AVOCADO BIOREFINERY IN THE BOLÍVAR DEPARTMENT. SOURCE: SELF-MADE

The sub-indices for temperature and pressure were determined based on the required process operating conditions. For the transformation of the seed into biochar through pyrolysis, a temperature of 400°C is needed, which is the maximum anticipated temperature, therefore, a score of 3 is assigned corresponding to the temperature range of 300 – 600°C. Meanwhile, the operating pressure of the plant is 1 bar for most stages and does not exceed 5 bars; therefore, the pressure conditions do not pose a risk and a score of 0 is assigned. The equipment safety index considered the ISBL area due to the distillation, drying, and pyrolysis stages; therefore, the assigned score is the maximum equivalent to 4. For the sub-index of process safety structure, the range is from 0 to 5, with zero being the score for recommended and standardized processes, and 5 for processes where major damage has been documented. In this case, a score of 3 was assigned, corresponding to configurations that are likely to be questionable in terms of safety, even if accidents have not yet occurred, given that pyrolysis and hexane extraction processes are involved.

### Total Safety Index of the Biorefinery

The modeled biorefinery was evaluated considering process safety. For this purpose, the Inherent Safety Index (ISI) methodology was used, which is employed to globally measure how safe a chemical process is during the conceptual design stages. The results of each sub-index are presented in Table 3.

Biorefinery processes	Inventory (t)
Avocado oil extraction and fat-free pulp	12.29
Biochar production	3.06
Chlorophyll extraction and fertilizer	1.49
<b>Total</b>	<b>16.85</b>

TABLE 3. SCORES FOR THE INHERENT SAFETY INDEX OF THE AVOCADO BIOREFINERY IN THE DEPARTMENT OF BOLÍVAR. SOURCE: SELF-MADE

The avocado utilization process is inherently safe according to the methodology [5], as an ISI of 21 points was obtained, which is less than 24. It was found that for the biomass

gasification process to obtain hydrogen, the ISI was 35 points. This is due to the use of flammable substances such as hydrogen, methane, and carbon monoxide, as well as operating conditions of 750 °C for gasification and a pressure of 32.42 atm for the WGS reactor [16].

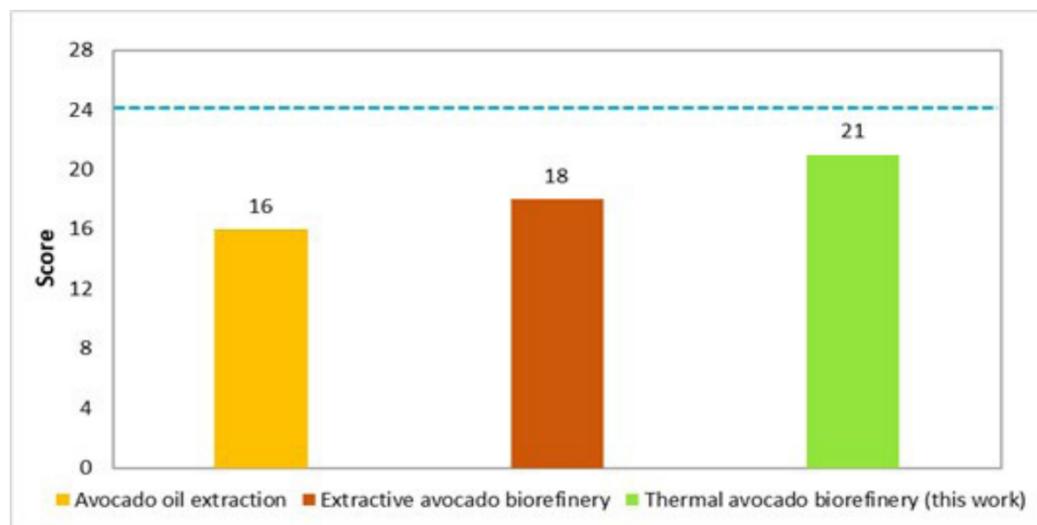


Fig 2. Comparison of the ISI of other processes using avocado for product production. Source: self-made

In Fig 2, a comparison of the ISI values obtained for other processes using avocado for the synthesis of value-added products is shown. The avocado oil extraction process had an ISI of 16, using only the fruit pulp and hexane as a solvent [7]. Meanwhile, the extractive-based avocado biorefinery had an ISI of 18 points, two points higher than the previously mentioned process, due to the inclusion of two additional processes: biopesticide production from avocado seed and chlorophyll extraction from the peel [6]. The difference with the process evaluated in the present study lies in the fact that, in avocado oil extraction, no hazardous chemical interactions occur, resulting in a score of 0 for this sub-index. However, in the biorefinery, interactions may occur that generate non-flammable gases or soluble toxic substances due to the presence of hexane and ethanol during product extraction stages. Another reason for the higher ISI in this study is that the previously mentioned processes do not include a pyrolysis stage, which avoids the need for high-temperature conditions (300–600 °C).

## CONCLUSIONES

This research demonstrates that utilizing avocado waste to produce oil (1,000.01 t/y), biochar (504.78 t/y), chlorophyll (31.32 t/y), fat-free pulp (798.15 t/y), and compost (1,237.59 t/y) is a viable alternative for managing this biomass in northern Colombia. The inherent safety analysis shows that the process, although involving potential risks such as flammability and toxicity due to substances like hexane and high temperatures during pyrolysis, remains safe overall, with a total Inherent Safety Index (ISI) of 21 points, which is below the threshold established by the process evaluation methodology in the conceptual design stages employed in this study. This suggests that the proposed avocado biorefinery can operate safely and sustainably, contributing to waste reduction and resource recovery. The use of solvents with lower hazard indices or green solvents is recommended, as well as ensuring that the process includes safety layers to control the high temperatures required for biochar production through pyrolysis.

## CRedit AUTHORSHIP CONTRIBUTION STATEMENT

T. Herrera-Rodríguez: Formal analysis, Writing: original draft, Validation, Methodology, Software, Research, Data curation. V. Parejo-Palacio: Methodology, Software, Research, Data curation. A. González-Delgado: Conceptualization, Resources, Writing: review and editing, Visualization, Supervision, Fund acquisition, Project management, Validation.

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