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Evaluation of dual crude palm and kernel oil production in North Colombia via computer-aided exergy analysis

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Abstract
Palm production chains in Colombia have some unsatisfied demands that affect their competitiveness. Specific demands include efficiency in energy use. Therefore, in the present report, an exergy analysis for the dual crude palm and kernel oil production process was carried out to determine the main energy sinks and suggest technological improvements that allow better use of energy. For this study, the process was initially simulated in the Aspen Plus ® software, where the chemical and physical exergies of the species and streams involved were quantified. The process irreversibilities, the exergy loss, the exergy of waste, and the exergy of utilities were calculated for each stage and the whole process. An overall exergy efficiency of 18% was achieved, while the highest process irreversibilities contribution was due to the destroyed exergy with the waste in the threshing stage. To increasing the global exergy efficiency of dual crude palm and kernel oil production, it is proposed the evaluation of palm rachis use to obtain biofuels and/or high-value products.

***Keywords**: Exergy analysis; Computer-aided Process engineering; Palm oil; Kernel oil.*

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Evaluación de la producción de aceite crudo de palma y palmiste en el norte de Colombia mediante el análisis de exergía asistido por computador

Resumen
Las cadenas de producción de palma en Colombia tienen algunas demandas insatisfechas que afectan su competitividad. Entre las exigencias específicas figuran la eficiencia en el uso de la energía. Por lo tanto, en el presente estudio se realizó el análisis de exergía para el proceso de producción de aceite de palma y palmiste con el fin de determinar los principales sumideros de energía y sugerir mejoras tecnológicas que permitan un mejor aprovechamiento de la energía. Para la investigación, el proceso fue simulado inicialmente en el software Aspen Plus ®, donde se cuantificaron las exergías químicas y físicas de las sustancias y corrientes involucradas. Se calcularon las irreversibilidades del proceso, la exergía perdida, la exergía de residuos y la exergía de los servicios industriales para cada una de las etapas y para todo el proceso. Se logró una eficiencia exergética del 18%, mientras que la mayor contribución a las irreversibilidades totales se debió a la exergía destruida con los residuos en la etapa de desfrutado. Para incrementar la eficiencia exergética del proceso, se propuso evaluar el uso del raquis de palma para obtener combustibles y/o productos de alto valor.

Palabras clave: *Exergía; Ingeniería de procesos asistida por computador; Aceite de palma; Aceite de palmiste.*

Avaliação da produção de óleo de palma cru e de palmiste no norte da Colômbia pelo meio da análise da exergia assistida por computador

Resumo
As cadeias de produção de palma na Colômbia têm algums requerimentos insatisfeitos que afectam a sua competitividade. Dentro das exigências específicas incluem-se a eficiência na utilização de energia. Portanto, no presente estudo foi realizada uma análise da exergia para o processo de produção de óleo de palma e palmiste, com o intuito de determinar os principais sumidouros de energia e fornecer melhorias tecnológicas que aprimoren uma melhor utilização da energia. Na pesquisa, o processo foi inicialmente simulado no software Aspen Plus ®, onde foram quantificadas as exergências químicas e físicas das substâncias e correntes envolvidas. Foram calculadas as irreversibilidades do processo, a perda de exergia, a exergia dos resíduos e exergia dos serviços industriais para cada uma das etapas e para todo o processo. Foi atingida uma eficiência exergética de 18%, no entanto, a maior contribuição na irreversibilidade total foi dada pelo esforço destruído com os resíduos na fase de desfrutificação. Para aumentar a eficiência exergética do processo, foi proposto avaliar a utilização do rachis da palma para obter combustíveis e/ou produtos de alto valor.

Palavras-chave*: Análise de exergia; Engenharia de processos assistida por computador; Óleo de palma; Óleo de palmiste.*

Introduction

Rural development politics in Latin America have evolved to generate conditions for the continuous growth of more competitive global economies. One of the main areas of emphasis of these politics has been the development of initiatives that promote the formation of production chains in the agricultural sector around certain strategic products [1]. However, it was found that production chains in Colombia have some unsatisfied demands that affect their competitiveness. According to the United States Department of Agriculture, Colombia is the fourth-largest producer of African palm worldwide [2], therefore, satisfying the demands of the palm chain is an important issue to consider at the local level.

The specific demands of the palm chain include the reduction of dependence on fertilizers, the use of new technologies that make the industry more sustainable, innovation in cultivation technologies, efficiency in the use of energy, and the implementation of production plans to obtain value-added products from the residues of palm cultivation. Taking into account the above, this work aims to generate solutions to some of these demands by applying evaluation methodologies to improve the palm and kernel oil extraction process from the energy point of view.

On industrial processes, there is always a loss of energy (or work) associated with irreversibilities [3]. Exergy analysis allows us to identify and quantify the system thermodynamic irreversibilities [4]. This to establish those units that require the implementation of optimization strategies and increase the process efficiency. From the diagnosis thrown by the exergy analysis, it is possible to have the information that shows if there is a necessity to implement strategies of improvement as the integration of process or the intensification of the same ones [5]. Also, exergy analysis is considered by the authors as a selected criterion for novel/emerging processing routes under sustainability targets [6]. Crude palm oil production has been evaluated via exergy analysis by authors such as Jaimes *et al* [7] and Martinez *et al* [8]. These authors found in their studies that crude palm oil production shows a good performance from the energy perspective; however, a large amount of exergy is destroyed with the residues. In this work, the dual crude palm and kernel oil production process was subjected to an exergy analysis where the process exergy efficiency, the total irreversibilities, the exergy losses, the exergy of waste, and the exergy of utilities were obtained to suggest improvements in the use of process energy.

Methods

To perform the exergy analysis, the dual crude palm and kernel oil process production was initially simulated with the Aspen Plus® software. A processing capacity of 30 t h^{-1} of African palm bunch as raw material was estimated taking into account local conditions in the northern region of Colombia as the cultivated area exceeding 500,000 ha [9], the reference temperature, the freshwater availability, and utility availability. The information required for the simulation (operating conditions, mass, and energy balances) was obtained from a plant of palm and kernel oil extraction in North Colombia and information reported in the literature. The irreversibilities and exergy losses were calculated for each process step which allowed identifying critical stages.

Process description

The dual crude palm and kernel oil production process is shown in Figure 1, and the process description is as follows. For the crude palm oil extraction process, the African palm bunches are subjected to sterilization with saturated steam to hydrolyze the palm rachis. This to soften the pulp tissues and avoid the effect of the enzyme lipase on the free fatty acids [10]. From this first stage: the sterilized bunch, condensed water, and steam comes out. The fruits are separated from palm rachis by a rotating drum with 5 kW of power in the threshing stage. Subsequently, the separated fruits move towards the digestion stage, where the fruits are re-heated to facilitate the expulsion of the oil in the next step. The digested fruits are pressed, and a liquor containing a large amount of oil is extracted; water is added to this liquor to dilute it, facilitating the separation and purification of the oil. In the static clarification stage, up to 90% of the oil is separated, which is collected by overflow and pumped into a drying process. In the dynamic clarification stage (centrifugation), recovery of 10% of the oil is achieved. In this stage, the heavy fraction of the decantation enters, the water and heavy sludge leave the process, and the oil Along the light sludge are recirculated to the clarification stage. Finally, the oil is subjected to a drying process to reduce the percentage of moisture and impurities still contained in it. Due to the high temperature at which the oil leaves, this drying process is carried out under vacuum, and the pressure of the stream is reduced which causes the evaporation of the remaining water. The dry palm oil is pumped as the final product to its respective storage. For the crude kernel oil extraction stage, the palm cake obtained from the pressing stage is exposed to a separation process where the fiber is separated from the nuts. Then the fiber is sent to a boiler where it is burned, leaving the process as waste. In the next stage, the almonds are separated from shells by water steam addition, and the shells are also burned in the boiler. The treated almond is subjected to a drying process where the highest percentage possible of water is removed and the dried almonds are pressed to extract the kernel oil by mechanical action. At the end, obtaining as waste the kernel cake and a liquor as a product. The liquid stream is rich in kernel oil and is exposed to a static clarification process from which the heavy sludge is separated from crude kernel oil, and finally, the product is stored.

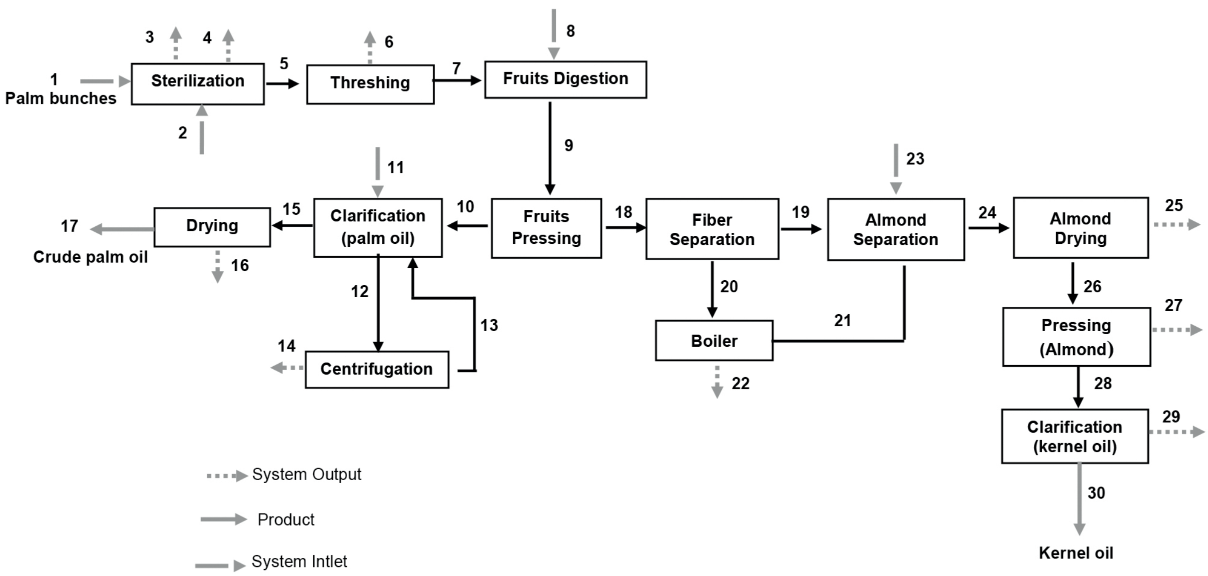

Figure 1. Block diagram of the dual crude palm and kernel oil production process.

Exergy Analysis

The exergy of a system can be defined as the maximum work that can be performed by a system when it is brought into equilibrium with its reference environment [11]. Exergy, unlike energy, can be destroyed and is conserved only when all the processes within a system are reversible [12,13]. In other words, exergy indicates the quality of energy [13], and in any real process, it is not conserved but it is destroyed or lost. The exergy analysis is a thermodynamic analysis technique based on the second law of thermodynamics [14], and is a tool to show the source of energy degradation in a process. It allows optimizing an operation, a technology, or a processing unit, and evaluating process technologies to improve the design [15].

The exergy analysis is governed by the Equations (1-13). The exergy balance at a steady state can be denoted by equation (1), where the exergy loss is defined as the difference between the in- and outflowing exergy [11].

$$\dot{E}x_{loss} = \dot{E}x_{mass,in} - \dot{E}x_{mass,out} + \dot{E}x_{heat} - \dot{E}x_{work} \quad (1)$$

Where ($\dot{E}x_{mass,in}$) and ($\dot{E}x_{mass,out}$) refer to the exergy of inlet and outlet streams across the boundary, respectively. The mass exergy flow can be defined according to Equation (2), as a sum of physical exergy ($\dot{E}x_{phy}$), chemical exergy ($\dot{E}x_{chem}$), potential exergy ($\dot{E}x_{pot}$), and kinetic exergy ($\dot{E}x_{kin}$), respectively. The last two terms are considered negligible for being significantly low compared to chemical and physical exergies.

$$\dot{E}x_{mass} = \dot{E}x_{phy} + \dot{E}x_{chem} - \dot{E}x_{pot} - \dot{E}x_{kin} \quad (2)$$

The chemical exergy of a process stream is described by Equation (3), it depends on the chemical exergy of each component i in the mixture ($Ex^0_{ch,i}$) and their molar fraction (y_i), the gas constant (R), and temperature of reference (T_0).

$$\dot{E}x_{ch,mx} = \sum_i yi\ Ex^0_{ch,i} + RT_0 \sum_i yi\ ln(yi) \quad (3)$$

The Chemical exergy of a component is calculated by Equation (4), this value is generally available in the literature.

$$Ex^0_{ch,i} = \Delta G^0_{f,i} + \sum_j n_j\ Ex^0_{ch,j} \quad (4)$$

Where (n_j) is the number of atoms of elements j in component i, ($Ex^0_{ch,j}$) is the chemical exergy of elements j and $\Delta G^0_{f,i}$ is the Gibbs free energy of formation of component i. The physical exergy of a process stream is defined by Equation (5), it is related to system enthalpy ($\dot{H}$) and entropy ($\dot{S}$) at operating temperature and pressure, and ($\dot{H}_0$)and ($\dot{S}_0$) at conditions of reference.

$$\dot{E}x_{phy} = (\dot{H} - \dot{H}_0) + T_0\ (\dot{S} - \dot{S}_0) \quad (5)$$

In cases of an ideal gas and solid-liquid mixture physical exergy flow can be estimated by Equations (6) and (7) respectively.

$$\dot{E}x_{phy} = C_p\ (T - T_0) - T_0 \left(C_p\ \mathrm{In} \frac{T}{T_0} - R\ \mathrm{In} \frac{P}{P_0} \right) \quad (6)$$

$$\dot{E}x_{phy,liq-sol} = C_p \left[(T - T_0) - T_0\ \mathrm{In} \frac{T}{T_0} \right] - v_m\ (P - P_0) \quad (7)$$

Where (C_P) is the heat capacity, (v_m) the molar volume, (P) and (T) the operating pressure and temperature, (P_0) and (T_0) the reference pressure and temperature.
The exergy by heat flow ($\dot{E}x_{heat}$) is estimated by Carnot expressions as shown in Equation (8), considering heat flow ($\dot{Q}$) temperature (T), and temperature of reference (T_0), ($\dot{E}x_{work}$) is the exergy by work, is defined as the workflow for the system ($\dot{W}$) by Equation (9).

$$\dot{E}x_{heat} = \left(1 - \frac{T_0}{T} \right) \dot{Q} \quad (8)$$

$$\dot{E}x_{work} = \dot{W} \quad (9)$$

The exergy efficiency of the process can be calculated taking into account the destroyed exergy ($\dot{E}x_{destroyed}$) and the total exergy entering ($\dot{E}x_{total,in}$) as follows:

$$\eta_{exergy} = 1 - \left(\frac{\dot{E}x_{destroyed}}{\dot{E}x_{total,in}} \right) \quad (10)$$

A balance around the system provides the total exergy entering by mass and utilities as indicated in Equation (11).

$$\dot{E}x_{total,in} = \dot{E}x_{mass,in} + \dot{E}x_{utilities,in} \quad (11)$$

The destroyed exergy indicates the total process irreversibilities, that is, the unused potential work, and can be calculated by Equation (12).

$$\dot{E}x_{destroyed} = \dot{E}x_{total,in} - \dot{E}x_{product,out} \quad (12)$$

Non-evitable irreversibilities indicate the unused potential work without considering the exergy of residues, can be calculated as follows:

$$\dot{E}x_{loss} = \dot{E}x_{total,in} - \dot{E}x_{out} \quad (13)$$

It is worth mentioning that the extended mass and energy balance, the operating conditions (temperature and pressure), and the physical exergy of process streams were obtained as a result of the simulation. The chemical exergy of the components was consulted in the literature and allowed to determine the chemical exergy of process streams. The heat flow and workflow were obtained for each stage from the process simulation.

Results and Discussion

The dual crude palm and kernel oil production was simulated using Aspen Plus ® software for a production rate of 2.28 t h^{-1} crude palm oil and 0.57 t h^{-1} kernel oil. The palm bunch composition assumed is presented in Table 1. The chemical species involved in the process were all available in the software database, except hemicellulose which was considered as xylose. The mixture thermodynamic properties were calculated from the molecular structures of each species, and the Non-Random Two Liquids (NRTL) thermodynamic model was selected according to the presence of polar-nonpolar mixtures.

Table 1. Palm bunch composition

Component	Mass fraction
Water	0.3010
Ashes	0.0353
Silica	0.0019
Cellulose	0.1784
hemicellulose	0.0999
Lignin	0.1212
Palmitic acid	0.0055
Stearic acid	0.0005
Oleic acid	0.0052
Linoleic acid	0.0009
Myristic acid	0.0002
Lauric acid	0.0002
Tripalmitin	0.0142
1,3-Dipalmitoyl-2-oleoylglycerol	0.0722
1,2-dioleoyl-3-palmitoylglycerol	0.0622
1-Palmitoyl-2-oleoyl-3-linoleoyl-rac-glycerol	0.0261
1,2-Dipalmitoyl-3-lauroylglycerol	0.0240
Trioleina	0.0160
1-Palmitoyl-2-oleoyl-3-stearoyl-rac-glycerol	0.0157
1,2-Lauroyl-3-miristoylglycerol	0.0049
Trilaurina	0.0059
1,3-Lauroyl-2-oleoylglycerol	0.0027
1,2-Miristoyl-3-Lauroylglycerol	0.0033
CCLA: 1,2-Dicaprylyl-3-Lauroylglycerol	0.0028

Table 2, presents the operating conditions, mass flow, and the physical and chemical exergies of the main process streams. The results indicate that stream 1 (containing the palm bunch) shows total mass exergy of 568,401.98, which suggests the high potential of the process. On the other hand, the exergy of the residual streams is over 250, 000 MJ h^{-1}, showing there is high work potential that is not taken advantage of. The palm rachis, which is a process waste, has higher total mass exergy than the streams containing crude palm oil and kernel oil.

Figures 2 - 4, show the exergy analysis results for the dual crude palm and kernel extraction process per stage. The irreversibilities (destroyed exergy), the exergy of wastes, exergy losses, the exergy of utilities, percentage irreversibilities contribution, and the exergy efficiency were calculated for each stage to identify the main energy sinks. The results show the threshing stage features the highest value for irreversibilities and exergy of waste 258,300.84 MJ h^{-1} and 202709.26 MJ h^{-1}, respectively. The exergy losses in this stage 55,591.58 MJ h^{-1} allows determining that the irreversibilities are mainly due to the wastes, 13 t h^{-1} of palm rachis which are not used for this process. The boiler is the second most critical stage, it describes irreversibilities of 195,856.21 MJ h^{-1}. The irreversibilities in this stage are represented by 78% of the exergy of waste (streams of fiber and nutshell) and 22% of the unavoidable exergy losses. These results reveal that the wastes removed from the process have high exergy that can be utilized.

Table 2. Operating conditions, mass flow, physical exergy, and chemical exergy of the main process stream

Stream	T (°C)	P (bar)	Mass flow (t h^{-1})	Chemical exergy (MJ h^{-1})	Physical exergy (MJ h^{-1})
Palm bunches (1)	30	1.013	30.00	568,401.98	0.00
Vapor (2)	148	4.053	8.18	4,244.19	5,872.60
Condensed (3)	85	1.013	10.06	430.43	246.50
Saturated vapor (4)	148	4.053	8.18	735.14	5,872.60
Sterilized bunch (5)	101	1.013	27.93	568,341.16	719.54
Rachis (6)	133	1.013	12.77	200,923.26	1,786.00
Saturated vapor (8)	148	4.053	1.35	700.88	694.47
Digested fruits (9)	95	1.013	16.51	309,035.67	111.52
Liquor (10)	105	1.013	5.41	91,637.29	64.68
Palm cake (18)	105	1.013	11.10	216,634.97	46.84
Water (11)	85	1.013	2.54	108.44	61.80
Heavy sludge (14)	90	1.013	5.66	2,100.52	372.55
Palm oil (17)	59	1.013	2.28	90,856.81	5.67
Nuts (19)	95	1.013	9.27	179,993.02	41.87
Vapor (23)	148	1.013	10.00	5,191.67	7,183.57
Almond (25)	95	1.013	5.47	24,032.32	150.85
Dried almond (26)	101	1.013	1.64	23,893.31	30.32
Liquor (28)	101	1.013	1.56	22,972.44	28.81
Kernel cake (29)	101	1.013	0.08	1,194.67	1.52
Kernel oil (30)	101	1.013	0.57	22,733.55	12.70

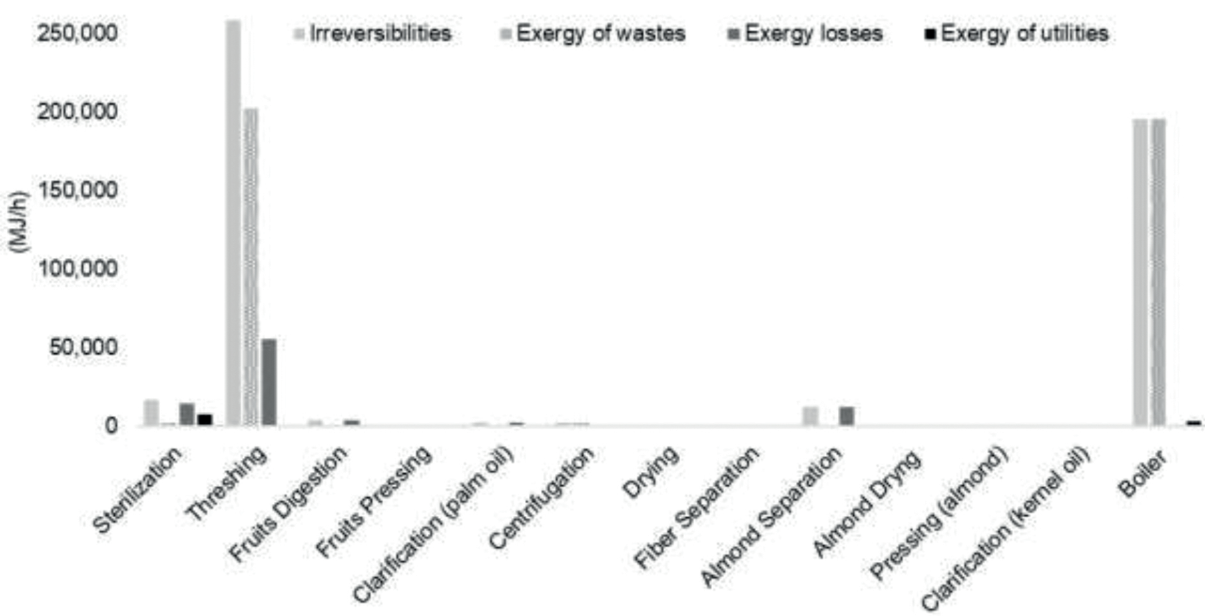

Figure 2. Exergy results for dual crude palm and kernel oil extraction process per stage.

The percentage of destroyed exergy contribution indicates this stage affected the global process irreversibilities the most. In Figures 3 and 4, can be observed the threshing and boiler generate the highest process irreversibilities contributions 52.11%, and 39.51%, respectively. The exergy efficiency of the boiler was estimated at 1%, being the stage with the lowest efficiency, as a consequence of the destroyed exergy with the wastes. The exergy efficiency for the threshing stage was calculated at 52%, approximately. Although in this stage there is a destruction of exergy with the wastes, there is also a large amount of exergy contained in the product streams that are processed. Centrifugation is the second stage with the lowest exergy efficiency (10%) due to the differences between the exergy of products and the input exergy. Therefore, the main energy sinks of the process are found in the threshing, boiler, and centrifugation stages.

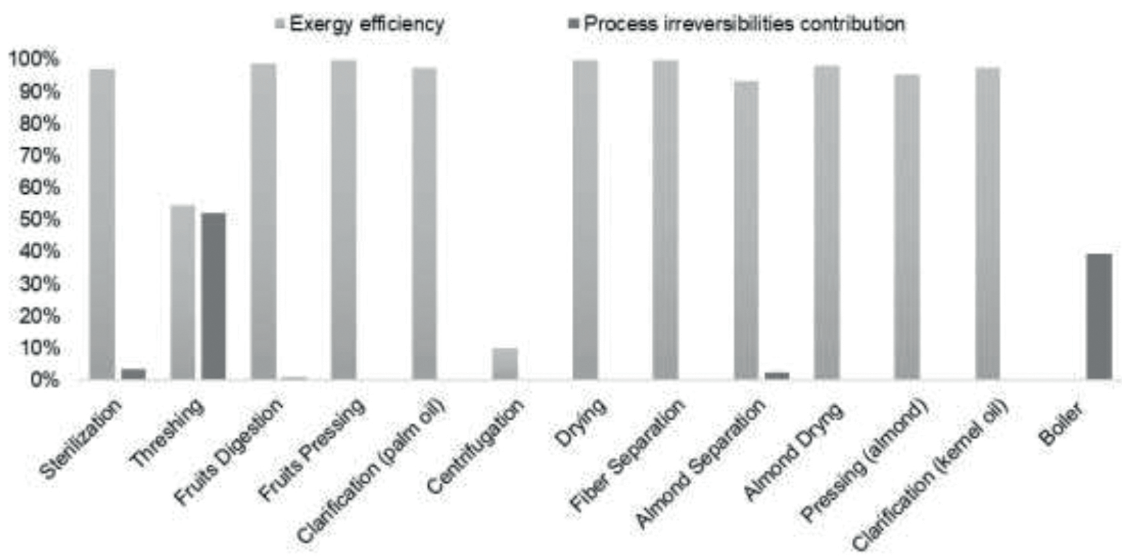

Figure 3. Exergy efficiency and contribution to exergy loss per stage

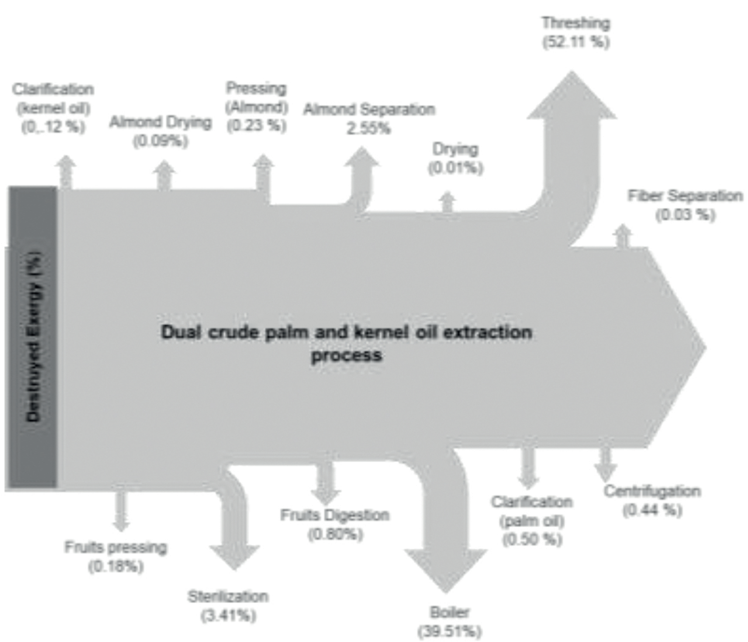

Figure 4. Sankey diagram for dual crude palm and kernel oil extraction process

The global exergy analysis for the dual crude palm and kernel extraction process is illustrated in Figure 5. The value for total irreversibilities is 495,676.41 MJ h^{-1} where 82% are due to exergy of wastes. The other percentage is represented by the exergy losses, known as unavoidable destroyed exergy, 90,110.44 MJ h^{-1} for this process. Nevertheless, these irreversibilities compared to the palm oil production process (993,000 MJ h^{-1}) [5] are lower because the palm cake is processed. The above reveals the positive impact of the recovery of waste such as palm cake on the exergy efficiency of the process.

On the other hand, the exergy for industrial services 14,461.49 MJ h^{-1} does not contribute significantly to the generation of irreversibilities because the energy requirement in the stages is low. The global exergy efficiency was estimated by 18% which confirms the potential in energy terms of the typical crude palm and kernel oil extraction process modeled for this research. However, the result compared to the overall exergy efficiency of an oil extraction process from microalgae (51%) [16], and a palm biorefinery (38%) [17], is lower which suggests that improvements should be implemented to optimize the process, especially, alternatives to make use of palm rachis and palm fibers. Studies suggest that palm fibers can be used to improve the mechanical properties of panels [18], while rachis can be used for obtaining synthesis gas [19], hydrogen production [17, 20], biodiesel production [21], and in the biosorbent preparation for uptaking Cd(II) and Ni (II) [22].

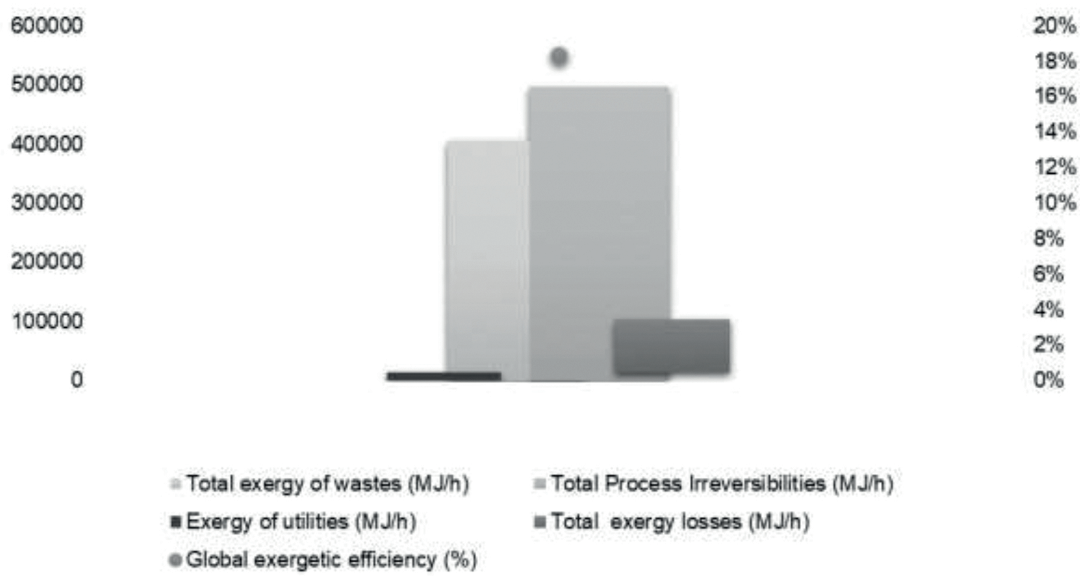

Figure 5. Global exergy results for dual crude palm and kernel oil extraction process.

Conclusions

The exergy analysis carried out on dual crude palm and kernel oil production process allowed identifying the stages of highest exergy destruction and to propose possible improvements that optimize the process. A real crude oil extraction process was simulated, where was included 30 t h^{-1} of African palm bunches as raw material, for which 2,28 t h^{-1} and 0,57 t h^{-1} of palm oil and kernel oil, were produce, respectively. Then, it was analyzed from an exergy viewpoint and the process irreversibilities, the unavoidable exergy losses, the exergy of wastes, the exergy of utilities, and exergy efficiency were calculated. According to the results obtained, the total process irreversibilities were 495,676.41 MJ h^{-1}, caused mainly by the exergy of the waste. The highest exergy destruction for this process was found in the threshing stage, 52% approximately, while the exergy of utilities does not mainly affect global irreversibilities. The exergy efficiency for the process was estimated at 18% which compared to other oil extraction processes is lower. It is recommendable for the process evaluated to apply optimization methodologies such as process integration to decreases irreversibilities, and give a positive use to waste streams that can increase the overall exergy efficiency.

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