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Exergy-based evaluation of crude palm oil production in North-Colombia

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ABSTRACT

Background: Palm production chain in Colombia is facing several technical demands, including the increment of efficiency in the use of energy for the process. This situation makes necessary to know its energy sinks and stages susceptible to improvement, from technical and energetic points of view. Objective: In this work, a real crude palm oil extraction process found in North Colombian region is analyzed using process simulation and exergy analysis methodologies, in order to quantify the irreversibilities of the process and define possibilities of improvement. Methodology: Simulation was performed using specialized software and the effect of operating variables on the process efficiency was evaluated. By exergy analysis, physical and chemical exergies of the species involved, total irreversibilities, exergy from utilities and wastes generated during oil extraction and overall exergy efficiency of the process were quantified, based on a robust modeled oil composition taking into account free fatty acids and heterogeneous triglycerides. Results: Through this study it was found that for a 30 t/h plant, there is a high exergetic content generated from the solid wastes of the process, like palm fruit bunches, seeds and residual cake in threshing and pressing systems. In addition, it was obtained an overall exergetic efficiency of 59 %, where drying is the most efficient step (~100 %), while centrifugation presented the lowest efficiency percentage (10 %). Conclusion: It is proposed an improved topology to optimize the process by the incorporation of a palm kernel oil unit, tighter controls respect to raw materials quality, energy integration and technical specifications of equipment in order to reduce the amount of irreversibilities along the stages of the process.

INTRODUCTION

Palm oil is a vegetable oil obtained by pressing the mesocarp of *Elaeis guineensis* palm fruit (Ani, Nna, Obi and Ubodong, 2015, Goncalves *et al*. 2016). This palm has advantages due to its low cost, resistance to high temperatures without burning, high oxidation stability, besides not produce any smoke or foam (Peña Trujillo, 2008). In terms of land area, palm cultivation occupies 7 % of the agricultural area destined to oil cultures, less than the part dedicated to soybeans (61 %), rapeseed (18 %) and sunflower (14 %). In addition, the yield of oil palm cultivation is six to ten times higher than the aforementioned cultures, producing 39 % of vegetable oil in the world, which is used in the food industry, cosmetics and as a raw material for biofuel production (FEDEPALMA, 2016). In America, the largest oil producers are Colombia and Ecuador. Colombia is the first palm oil producer of Latin America and the fourth in the world, with domestic production of 753,000 tonnes, and about 500,000 hectares of oil palm (SIC, 2011). In north Colombia, cultures have been expanded to 130,000 hectares. In addition, in Colombia there are plans to increase production to six times by 2020, which would

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require 3 million hectares for plantations (Gromko, 2015). This large production demand, mainly driven by the high global market prices which provide good profit margin compared to other types of land use (James *et al*. 2015), is leading palm growing countries to seek and implement optimal and efficient processes that can ensure a better use of raw materials and high oil yield.

Computer-aided simulation has been successfully used for evaluation and improvement of existing and emerging technologies and exergy analysis has been usually applied to thermal processes integration and optimization (Carrasquer, Martínez-Gracia and Uche, 2016). For instance, Jaimes, Acevedo and Kafarov (2012) used Aspen Hysys 6.5 and exergy analysis to make a comparison of two alternatives for palm oil biodiesel production, the traditional and a novel, with the aim to identify the magnitude of the irreversibilities and the exergetic efficiency in each one of the equipment. Authors found that global efficiency of the process was 14.2 % for traditional technology and 18 % for novel technology, which means that second option is less favorable due to largest exergy losses were presented in the separation system and heat exchangers.

In order to justify that a technology which use renewable resources is more efficient and sustainable than other, evaluations and comparisons of the processes can give a clear insight regard how energy is utilized. In this sense, exergy efficiency concept is more meaningful than energy efficiency because it gives a true measurement of how closely the actual performance of production process approaches ideality. In particular, exergy analysis clearly identifies the causes and locations of energy degradation in a process thereby facilitating process and technology improvements (Teng Tan, Teong Lee and Rahman Mohamed, 2010).

In this work, process simulation is used coupled with exergy analysis for the evaluation of crude palm oil production process in north Colombian region, in order to quantify exergy losses that can lead to improve the production chain.

MATERIALS AND METHODS

Process simulation:

Industrial professional process software was used to simulate a real crude oil extraction process from African Palm (30 t/h of palm bunch were taken as calculation basis) found in North Colombia, using a methodology previously developed and published by authors, for existing and emerging bioprocesses (Figueroa-Jimenez, Gamarra- Torres, Bonilla-Correa and Peralta-Ruiz, 2015; Cogollo-Herrera, Lombana-Carmona, Bonilla-Correa and Peralta-Ruiz, 2015). Chemical species available in software database were selected and used, and for compounds without availability in the software library, molecules were created within the software using the User Defined Compound Wizard tool. In addition, some properties available in scientific literature as normal boiling point, molecular weight, acentric factor and critical properties were introduced. Unknown properties were estimated using UNIFAC (Universal Functional Group Activity Coefficient) model and the database Thermo Data Engine (TDE). Thermodynamic properties of mixtures were calculated based on molecular structures of each compound, NRTL (Non-Random Two Liquids) and SRK (Soave-Redlich-Kwong) thermodynamic models, which were chosen because of its good representativeness of polar-non polar mixtures.

Exergy analysis:

Exergy is defined as the maximum amount of theoretical work that can be obtained from the interaction between a thermodynamic system to certain conditions and stable reference environment. If there is a difference between these two states, there is the possibility of producing work; otherwise, this possibility is reduced. In this sense, the exergy analysis becomes a powerful tool to identify potential areas for process improvement in terms of reducing unnecessary resources or replacing a unit for a one with a better thermodynamic performance, due to allows quantifying the major inefficiencies and system performance (Ruiz de la Cruz, Orozco Muñoz, Bonilla Correa and Peralta Ruiz, 2015). For an exergy balance in steady state, exergy destruction is related to net mass transfer irreversibility, work and heat by equation (1).

$$Ex_{destroyed}=Ex_{mass\text{-}net}+Ex_{heat\text{-}net}+Ex_{work\text{-}net} \quad (1)$$

Exergy related to mass transfer in the absence of electrical, magnetic, nuclear and surface tension effects is defined as the sum of physical, chemical, kinetic and potential irreversibilities (equation 2). In most of industrial processes, the kinetic and potential irreversibilities tend to be neglected by low contribution to the total exergy (Kumar *et al*. 2016), physical and chemical irreversibilities are given by the equations (3) to (5), where equation (4) can be use when stream behaves like an ideal gas mixture and equation (5) if stream is in solid or liquid state. In equation (6), allows calculating the chemical exergy of a compound, where ΔG_f^0 is the standard Gibbs free energy of formation of the substance, $Ex^0_{ch\text{-}j}$ is the chemical exergy of the j^{th} pure element of the substance and v_i is the number of atoms of the j^{th} pure element of the compound. In the case of a mixture, Chemical exergy is defined by its components and their concentration as shown in equation (7). If the stream is an energy source, can be defined exergy conversion coefficients, for the case of fuels (coal, oil, gas), exergy can be obtained by multiplying the heating value by the appropriate coefficient (β) as is shown in equation (8).

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$$Ex_{mass}=Ex_{phy}+Ex_{ch}+Ex_{pot}+Ex_{kin} \quad (2)$$

$$Ex_{phy}=(H-H_0)-T_0(S-S_0) \quad (3)$$

$$Ex_{phy-ig}=C_P(T-T_0)-T_0\left(C_P Ln\frac{T}{T_0}-RLn\frac{P}{P_0}\right) \quad (4)$$

$$Ex_{phy-liq}=C_P\left[(T-T_0)-T_0 Ln\frac{T}{T_0}\right]-v_m(P-P_0) \quad (5)$$

$$Ex_{ch-i}=\Delta G_f^0+\sum_j v_j Ex_{ch-j}^0 \quad (6)$$

$$Ex_{ch-mixture}=\sum_i y_i Ex_{ch-i}+RT_0\sum_i y_i ln(y_i) \quad (7)$$

$$Ex_{ch-fuel}=\beta(LHV) \quad (8)$$

The exergy associated to work in a system where there is no volume change is equal to the own work the system (equation 9). Regarding exergy by heat transfer, this can be calculated based on Carnot efficiency, which represents the fraction of energy transferred from a heat source at temperature T, which can become a work environment, to the reference temperature T_0, using equation (10). On the other hand, the total exergy input to a system may be associated with the process streams input and/or industrial services required by the system (equation 11), while the total exergy output can be associated with product flows and/or waste streams as shown in equation (12).

$$Ex_{work}=W \quad (9)$$

$$Ex_{heat}=\sum_i\left(1-\frac{T_0}{T}\right)Q_i \quad (10)$$

$$Ex_{total-in}=\sum_i Ex_{mass-in}+\sum_i Ex_{utilities-in} \quad (11)$$

$$Ex_{total-out}=\sum Ex_{products-out}+\sum Ex_{wastes-out} \quad (12)$$

Exergy losses or exergy destroyed refers to the irreversibilities in the process, that is, the potential of the system to produce work that there was not used, and can be calculated by subtracting total exergy input and exergy associated with the output stream of products, which was the potential used (equation 13). Finally, the exergy efficiency of a process or a stage within the process can be calculated based on the irreversibility and the total exergy input to the system by the equation (14) and the percentage of total process irreversibilities that was destroyed in a stage i can be calculated using equation (15).

$$Ex_{destroyed}=Ex_{total-in}-\sum Ex_{products-out} \quad (13)$$

$$\eta_{exergy}=1-\left(\frac{Ex_{destroyed}}{Ex_{total-in}}\right) \quad (14)$$

$$\%\ Ex_{destroyed,\ i}=\left(\frac{Ex_{destroyed,\ i}}{Ex_{total\ destroyed}}\right)x100\% \quad (15)$$

RESULTS AND DISCUSSION

Process simulation:

The process was modeled using as references two extraction plants of crude palm oil located in North Colombia, in Bolivar and Cesar states; and complemented with data reported in literature (Ng, Ng, Chong and Lim, 2015; Jaimes, Rocha, Vesga and Kafarov, 2012). Figure (1) shows the simulation of extraction process, simulation starts with a fresh water stream (WATER1) that is converted to steam (STEAM1) by a boiler to sterilize the bunch of African palm (FFBUNCH), previously transported from a hopper to a horizontal cylinders closed by trucks. This sterilization is performed in order to prevent the effect of lipase enzyme on free fatty acids and hydrolyzing the palm rachis to soften the pulp tissues. From MIXER1 equipment out the sterilized bunch (CLUSTER) and saturated steam (COND+STM). The sterilized cluster passes through a rotating drum of 35 kW to separate the fruits (FRUITS) of bunches (RACHIS). The fruits pass to the digestion step (DIGESTER equipment of 18 kW), where the fruit is heated to facilitate the oil expulsion in the pressing and to release the nuts pulp by maceration that includes the entry of steam (STEAM2) through a heat exchanger. Subsequently, the digested fruits (HOTCLUST) are pressed by a horizontal perforated basket cylindrical shape of 40 kW, where a liquor (LIQUEUR) containing large amount of oil is extracted. This liquor is generated through the mechanical action of two augers regressive step, which rotate parallel in the opposite direction, by outputting in the top the presscake (CAKE). Then, water (DESTWATR) is added to the liquor (LIQUEUR1) in a mixer to dilute it, facilitating the oil separation and purification. In static clarification stage is separated by decantation up to 90 % oil (6.04 t/h), which it is collected by overflow and is pumped (WETOIL) to a drying process.

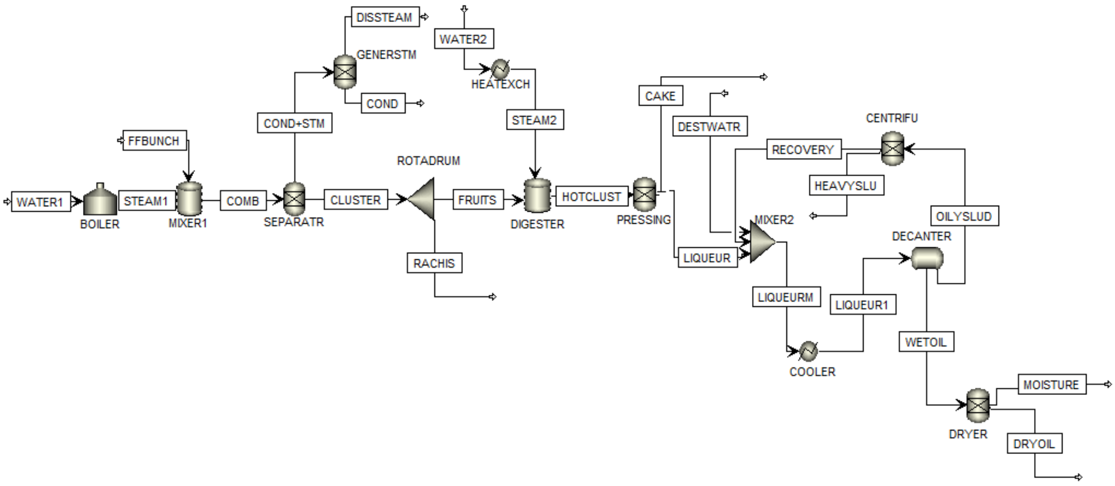

Fig. 1: Simulation of crude palm oil production process

After this stage follows, a dynamic clarification by centrifugation (30 kW), where 10% recovery of oil is achieved. At this stage enters the heavy fraction from decantation, obtaining water and heavy sludge as outputs by nozzles, oil and light sludge are concentrated in the center and discharged by a collector tube. This last outlet stream is recirculated to the static clarification with the press liquor. As last step, the oil is subjected to another drying in order to minimize the moisture and residual impurities still contains this. Due to high temperature of oil outlet, the drying is performed under vacuum, by reducing the pressure of the stream, causing evaporation of the remaining water. Dry crude palm oil (5.07 t/h) is pumped from this stage as final product to its respective storage.

Exergy analysis of production process:

Table (1) presents the results of chemical, physical and total exergy of the system for each stream. From the exergy balance is obtained that the total chemical and physical exergy were 2,121,884 and 9,931 MJ/h, respectively. In addition, the palm bunch and fruits streams have a higher exergy compared to other ones (between 300,000 and 320,000 MJ/h), which demonstrates the potential of process (Cogollo-Herrera *et al*. 2015). For instance, Teng Tan *et al*. (2010) made a comparison between exergy of empty fruit bunch (EFB) and other feedstock available to produce bioethanol, and found that the value for EFB was positive and higher respect corn, wheat, barley and sugarbeet, which suggests that the supply of exergy is readily for human needs. This same opportunity for energy utilization becomes visible by comparing the value of chemical exergy for palm oil with the one obtained for *Jatropha curcas* oil, which was 37,000 MJ/kg (Ofori-Boateng, Keat-Teong and Jit-Kang, 2012a).

Table 1: Chemical, physical and total exergies of the main process streams

Flow	Chemical exergy (MJ/h)	Physical exergy (MJ/h)	Total mass exergy (MJ/h)
Palm bunch (FFBUNCH)	318,424	0	318,424
Vapor (DISSTEAM)	735	1,017	1,752
Condensed (COND+STM)	430	247	677
Saturated vapor (STEAM1)	4,244	5,873	10,117
Esteril bunch (CLUSTER)	318,439	720	319,159
Raquis (RACHIS)	14,220	209	14,430
Fruits (FRUITS)	225,766	510	226,286
Saturated Vapor (STEAM2)	701	694	1,395
Macerated fruits (HOTCLUST)	225,700	1,219	226,918
Palm presscake (CAKE)	20,668	948	21,626
Liquor (LIQUEUR)	205,132	263	205,395
Dilution water (DESTWATR)	108	62	170
Oily sludge (OILYSLUD)	3,830	0	3,830
Heavy sludge (HEAVYSLU)	3,447	561	4,007
Centrifugal recovery (RECOVERY)	383	6	389
Wet oil (WETOIL)	202,133	89	202,222
Moisture (MOISTURE)	4	0	4
Palm oil (DRYOIL)	202,160	13	202,173

Figure (2) shows the exergy analysis for each of the stages of palm oil extraction process. It is observed that the drying step is the most efficient (100 %) regards the other ones, i.e. has minor exergy leaks in the process, either by means of waste, heat or working not used, being the least efficient, the centrifugation step (10 %). On the other hand, the pressing and threshing steps have the highest irreversibilities percentage, 66 and 15 %, respectively. This destroyed exergy may be associated with work, heat or waste, however, results for exergy residues show that the greatest leakage corresponds to these two stages (pressing 21,626 MJ/h and threshing 14,429 MJ/h), which are associated with the cake and the empty fruit bunches generated. These two steps represent opportunities for improvement, due to between both of them are missing 79 % of exergy for recoverable waste.

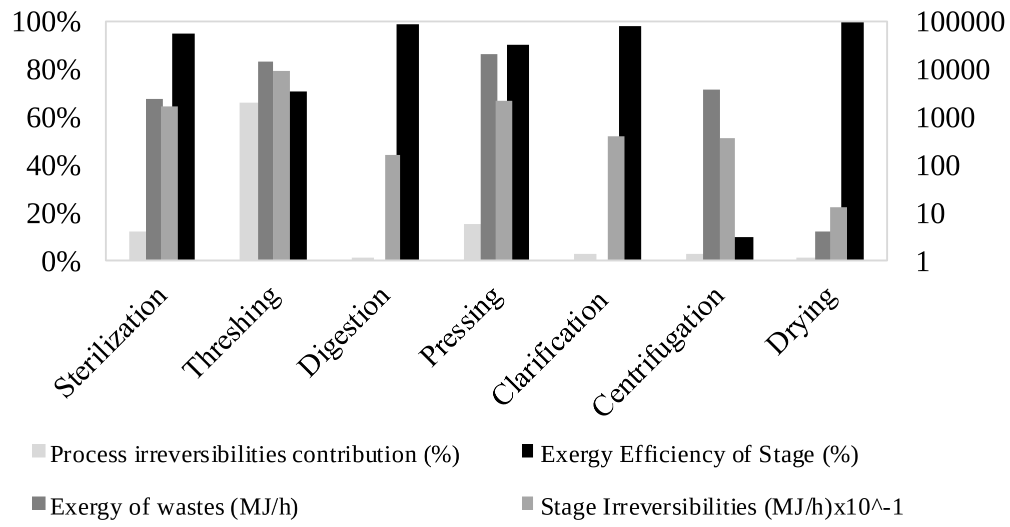

Fig. 2: Exergy analysis of stages of crude oil from African palm process

Figure (3) presents the overall results for the production process, based on the inputs and outputs thereof. It is observed that in the process were lost 140722.3 MJ/h as irreversibilities, where 30 % of these correspond to residues (42496.7 MJ/h). In addition, comparing this amount with the irreversibilities generated by industrial services (8559.7 MJ/h) can be seen that are higher, indicating that efforts should be focus on improving this indicator, either through use of waste or a change in the pressing and threshing system by one of best performance. Finally, the overall exergy efficiency (59 %) indicates that the process is efficient from the energy point of view, as well as being high compared to other oil extraction process using microalgae as feedstock where was obtained 51 %, in the most efficient route (Peralta-Ruiz, González-Delgado and Kafarov, 2013). Respect to *Jatropha* oil extraction (61.4%) can be observed that efficiencies are similar in both processes, where a large percentage of destroyed exergy belongs to wastes (Ofori-Boateng, Keat Teong and Jit-Kang, 2012b).

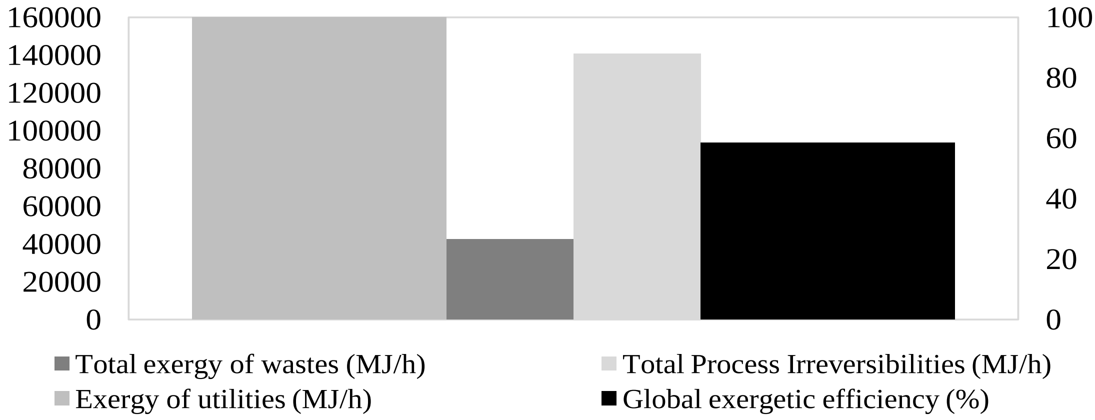

Fig. 3: Total exergy analysis of crude oil from African palm process

Conclusions:

Application of exergy analysis for the evaluation of the use of materials and biomass processing to obtain oil, constitutes a useful tool for generating, screening and designing alternatives towards sustainable development. In this study, a real crude oil extraction process with a basis calculation of 30 t/h of palm bunch was simulated, where were produced 5.07 t/h of dry crude palm oil. Then, it was analyzed from an exergy perspective in order to identify the main irreversibilities steps, and know the exergy of wastes and utilities, and exergy efficiency for each step.

Results showed an overall exergetic efficiency of 59 %. Although this process presents similar exergetic efficiency of oil extraction processes from other crops such *Jatropha curcas* and microalgae, where authors found a global exergetic efficiency of 61.4 % and 51 %, respectively. However, it would be beneficial to implement technical improvements in these processes in order to reduce the amount of irreversibilities along the stages, such as tighter controls respect to raw materials quality, process optimization and technical specifications of equipment. In addition, the stage that had the highest efficiency was drying with a value ~100 %, which suggests the proper design of this equipment, while centrifugation presented the lowest efficiency percentage (10 %). An improvement in the centrifugation step might assist to the use and waste reduction in the output of this stage, decreasing the concentration of heavy oil present in the sludge. In the other hand, the total irreversibilities were estimated on 140722.3 MJ/h, where pressing and threshing steps contributes to 25.6 % of total exergy destroyed in the process, showing losses of 21,626 MJ/h and 14,429 MJ/h, respectively, which makes them to be one of the biggest energy sinks. These two systems are the most susceptible to losses due to wastes generated in these stages such as cake and empty fruit bunches, which contribute to 79 % of the total exergy of wastes in the process. Also, the exergy calculated for industrial services was 8559.7 MJ/h. So, it is recommendable to apply optimization methodologies as process integration, in order to decrease industrial services required for oil extraction and give a positive use to wastes and byproducts streams. Finally, the analysis of chemical exergy of process streams performed allowed to demonstrate that palm bunch, fruits and oil have a high potential for energy use.

The exergy analysis performed in this study has given to scientific literature more detailed and useful information regarding attention focus that might allow, in future works, carry out process improvements in order to take advantage of the main residues generated in the system and stages, from an energetic point of view.

This analysis is a valuable method in discussing the thermodynamic performance of a system due to guide to identify the units where the most profit can be made by replacing the specific unit by a one with thermodynamically better performing. Including exergy analyses in the study of an existing chemical process might help in the suggestion of the use or reduction of utilities, which, ultimately, it is reflected in an economic and environmental impact.

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