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Case Study: Simulation of Synthetic Natural Gas Production Plant from Empty Fruit Bunches

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Colombia has a privileged geography and location that allow it to have a great potential in terms of variety and availability of useful raw materials to produce synthetic natural gas (SNG) through the combined gasification-methanation process. In this study, the steady state simulation model of a proposed plant to produce SNG from empty fruit bunches (EFB) is done in Aspen Plus. The combined gasification-methanation process has been modeled in four stages. In the first stage, the moisture content of the biomass is reduced. In the second stage, gasification of the dry EFB is performed. In the third stage, cleaning and conditioning of the produced gas (syngas) is carried out, removing ash, tars, COS, H_2S and CO_2. In the fourth stage, methanation of the syngas is carried out using Tremp technology to produce SNG. The SNG produced contains a methane molar concentration of 95% and an approximate yield of 0.064 m^3 SNG/kg of biomass. The plant simulation has been improved by means of an energy integration, implemented through Pinch technology. The energy integration enabled savings of 100 % of the required heating utilities and 37.7 % of the cooling utilities.

1. Introduction

Industrialization and the world population are continuously growing, which causes an increase in energy demand both commercially and domestically. The main source of energy to supply this demand is fossil fuels, which make up about 81.1% of the world energy mix (Shahbaz et al., 2017). Fossil fuels have the disadvantage of being non-renewable natural resources, and the problems of climate change and global warming have been attributed to their use. Therefore, worldwide, the energy sector is seeking to expand to include cleaner energy sources. Biomass, considered a CO_2-neutral renewable fuel, can contribute toward the development of a larger and cleaner energy sector (AlNouss et al., 2020). Colombia has a privileged geography and location that allows it to have a large quantity and variety of biomasses, including wastes associated with the production of oil palm fruit bunches such as empty fruit bunches (EFB). In 2022, approximately 1846956 tons of EFB were produced in Colombia (Federación Nacional de Cultivadores de de Palma de Aceite, 2023; Pérez-Rodríguez et al., 2022). EFB is used as a nutritional supplement in plantations due to its organic matter characteristics, with high nitrogen, phosphorus, and potassium contents; however, its abundance has created enormous environmental issue, ranging from fouling, attraction of pests, greenhouse gas emissions to soil acidification (Akpan Sunday, 2022).

There are currently two main ways by which biomass can be turned into useful products: biological or thermochemical processes. The thermochemical route of energy conversion can convert feedstock to energy through three different processes: combustion, pyrolysis, hydrothermal liquefaction, and gasification. Among these three processes, gasification is considered to be the most influential, with higher efficiency for electricity generation and lower greenhouse gas emissions than other technologies (Akolgo et al., 2019). In addition, syngas methanation technology is the core of biomass production for natural gas. Its main process is to convert H_2 and CO in the biomass gasification of syngas into CH_4 (Xing et al., 2020). Considering that the operation of gasifiers, methanators, and other plant equipment is associated with great complexity and high costs, simulation becomes an important tool for process optimization. Among the software available for the simulation of thermochemical processes, Aspen Plus supplies tools that allow the system to be modeled for describing it with

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a great level of detail, as well as maintaining extensive databases for the calculation of properties, reaction kinetics, design of molecules and user-defined compounds, management of solids, liquids, and gases, and equipment models, among others (Sierra et al., 2021).
In this work, a combined gasification-methanation energy integrated process for SNG (CH_4-rich) to valorize one of the most produced residual biomasses in Colombia (EFB) was proposed using the Advanced System for Process Engineering (Aspen) Plus software. This process not only offers a solution to the problem of open-air disposal of EFB, but the SNG produced can also be used to cover the energy needs of a large part of the Colombian population that does not have access to the national natural gas grid.

2. Case study analysis

The analysis of the case study was performed in two stages: 1) process design using the Aspen Plus simulator and taking into account the characteristics of the biomass, and 2) energy integration in order to increase the net energy gain of the process.

2.1 Biomass characteristics

EFB was chosen as a fuel and the ultimate and proximate analyses of the sample are shown in Table 1. The lower heating value (LHV) of EFB was determined using a 6400 automatic Isoperibol Calorimeter. The elemental composition of biomass was obtained from an elemental analyzer LECO (ASTM D-5373-08), while the proximate analysis was performed on a Linseis STA PT 1600 thermal analyzer (ASTM D3172, ASTM D5142).

Table 1: Ultimate-proximate analysis, and LHV of EFB

Ultimate analysis (wt. %, dry-ash free basis)	
C	46.51
H	5.46
O[a]	46.46
N	1.53
S	0.04
Proximate analysis (wt. %)	
Moisture	6.18
Volatile matter	70.52
Ash	6.20
Fixed carbon	17.10
LHV (MJ/kg)	18.11

[a] Calculated by difference

Table 2: Gas composition at the gasifier outlet

Compound	Mass percentage (%wt)
H_2	4.1383
CO	15.4993
CH_4	3.4599
C_2H_4	2.3517
C_2H_6	0.1183
CO_2	45.1542
H_2S	0.0202
COS	0.0039
H_2O	25.7381
C_6H_6	0.2504
$C_{10}H_8$	0.5843
Ash	2.6814
LHV (MJ/kg)	10.06
cold gas efficiency	0.43

2.2 Aspen plus simulation

The following assumptions were taken into account for the simulated process design: 1) the gas composition at the gasifier outlet is based on the results obtained experimentally and the addition, with respect to the mass balance, of common compounds in syngas such as H_2S, COS, C_6H_6, $C_{10}H_8$. (see Table 2); 2) the steam/biomass (S/B) ratio used is 0.5; 3) the energy required in the gasifier is supplied by the bed material (olivine); 4) the methanation stage is based on the TREMP technology (Tonpakdee et al., 2021); 5) the solvent used for the removal of the heavier tar is known as RME (rapeseed oil methyl esters) and consists of palmitic, oleic and linoleic acids (Tonpakdee et al., 2021). For the amount of fresh RME entering the process, a feed ratio of 0.03-0.035 MWRME/MWbiomass was used as reference (Gambardella and Yasin Yahya, 2017); 6) for H_2S removal, methylenedioxyethylamphetamine (MEDA) at 35 %wt, 40 °C and a feed of 2 kg MDEA/kg gas is used (Park et al., 2021); 7) for CO_2 removal, monoethanolamine (MEA) at 30 %wt, 90 % efficiency, and a feed ratio of 0.23 mol de CO_2/ mole MEA is used (Dinca et al., 2018).

2.3.1 Physical property method

The Redlich-Kwong– Soave cubic equation of state method (RK-SOAVE) was chosen as the physical property method to estimate all the physical properties of conventional components. RK-SOAVE is characterized by its ability to calculate the physical properties of non-polar and weakly polar substances such as hydrocarbons and light gasses (CO_2, H_2). With RK-SOAVE, more accurate predicted results can be obtained under various temperature and pressure conditions (Gao et al., 2021). For the calculation of the enthalpy and density of the non-conventional components (biomass and ash), the HCOALGEN and DCOALIGT models were selected, respectively.

2.3.2 Process description

A schematic of the proposed plant is shown in Figure 1. The overall process can be divided into four main stages: drying of the EFB, gasification in a dual fluidized bed (DFB) reactor, cleaning and conditioning of the produced gas, and syngas methanation for syngas (SNG) production. First, the biomass created on the basis of its final and proximate analysis (stream 1) is introduced into the drying stage to reduce moisture using hot air (stream 3). The dried biomass is then fed into a dual-type gasifier (stream 5), where the gasifier is simulated based on experimental data as a RYield reactor and the combustor as a RStoic reactor, to generate a raw gas called syngas (stream 15) with the composition shown in Table 2. The syngas mainly contains H_2, CO, CO_2, CH_4, H_2O and in smaller quantities, tars, sulfur compounds such as H_2S and COS and particulate matter. The latter poisons the methanation catalyst and must therefore be removed beforehand. The unconverted char is transported along with the bed material (olivine) to the combustor (stream 8), which is fluidized with preheated air. In the combustor, the char, along with other waste streams from the process, is burned to heat the olivine, which returns to the gasifier and provides the heat for the endothermic gasification reactions. Fresh olivine (stream 9) is continuously fed to the combustor to maintain its catalytic activity and replenish the material leaving the system along with ash and flue gas. The syngas is cooled (stream 16) and passes through a filter that removes the ash and entrained bed material. After filtering, the syngas (stream 18) is fed to a scrubber that uses rapeseed methyl ester (RME) as a scrubbing liquid, which removes 99.9% of the heavy tars and polycyclic aromatic hydrocarbons. The spent RME containing the extracted tar (stream 20) is sent to the combustor for destruction and heat recovery. After scrubbing, the unwanted components present in the gas are predominantly light cyclic hydrocarbons, such as benzene, toluene, and xylene (referred to as BTX), a small fraction of naphthalene, and traces of heavier tar components. These compounds were removed in a series of three fixed beds containing activated carbon. The stream containing the BTX (stream 24) is sent to a separator tank to remove water, and the resulting stream (stream 25) is sent to the combustor for combustion and heat production. The product gas leaving the activated carbon beds (stream 27) is compressed in a centrifugal compressor and sent to the R-2 reactor (RStoic) where the alkenes are converted to alkanes. Next, the COS component is catalytically converted to H_2S in the COS hydrolysis unit, reactor R-3 (RStoic), the resulting stream (stream 31) is cooled to enter a scrubber employing MDEA as a scrubbing solvent, where 99.0 % of H_2S present is removed. The gas (stream 35) then enters a scrubber using MEA as the scrubbing solvent to remove 95 % of the CO_2. Finally, the syngas (stream 38) enters the methanation stage, which consists of three adiabatic fixed-bed reactors. In the first methanation reactor R-4, recycling of part of the outgas stream is used to control the temperature increase. The outlet gas from the first methanation reactor (stream 41) is divided into two streams: one of these streams is pressurized, recirculated (stream 42), and mixed with the gas coming from the CO_2 scrubber, while the second stream (stream 44) enters the second methanation reactor. For the other two reactors, heat exchangers are placed between them to reduce the temperature of the streams. At the end of the methanation stage, CH_4-rich synthetic natural gas (SNG) is obtained (stream 53).

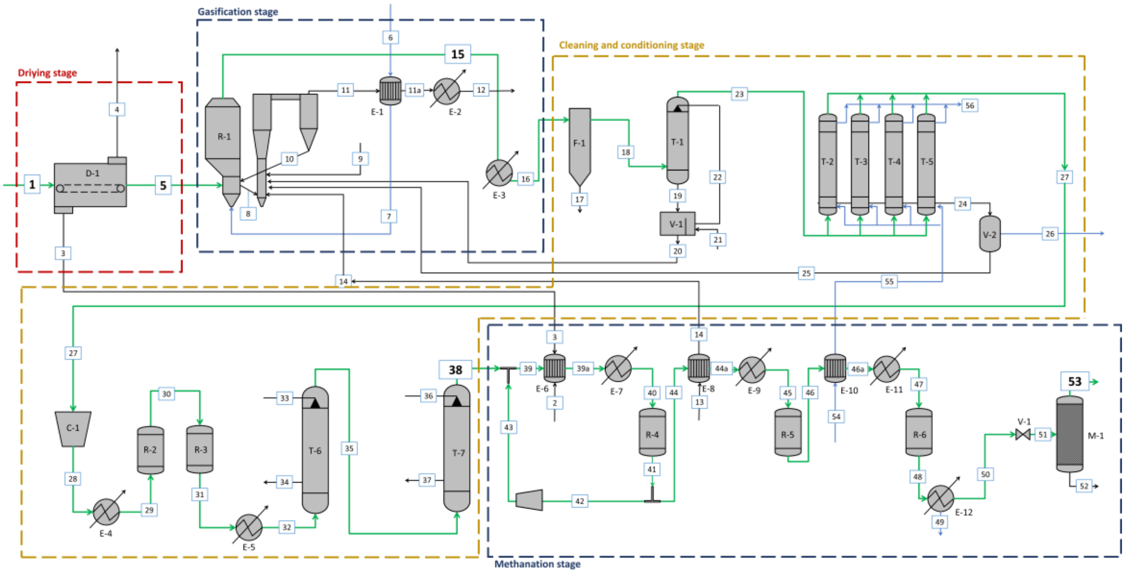

Figure 1: Diagram of the production plant of SNG from EFB

2.3 Energy integration

Energy integration is a key solution in the chemical process and crude refining industries to minimize external fuel consumption and face the impact of growing energy crises. Typical energy integration projects can reduce heating fuels and cold utilities by up to 40 % compared with original designs or existing installations. Pinch analysis is a leading tool and an efficient method for increasing energy efficiency and minimizing fuel flow consumption (Gadalla, 2015). The increase in energy efficiency refers to the savings in heating and cooling utilities obtained by implementing Pinch technology. The calculation was made by comparing the energy requirements before and after applying the energy integration. In this study, the Pinch technology (Kemp, 2006) was implemented to design an energy-efficient plant for the production of GNS from EFB.

3. Results and discussion

For the conceptual design and simulation in Aspen Plus of the GNS production plant, a feed of 26.6 t/h of EFB was selected, which corresponds to approximately 65% of the production of this residue in the eastern region of Colombia, according to a report by Fedepalma (Federación Nacional de Cultivadores de Palma de Aceite, 2023). Characterization of the main process streams, the input and output streams to each of the four stages of the process, is shown in Table 3.

Table 3: Characterization of the main streams

Stream	1	5	15	38	53
Temperature (°C)	25	111	820	27	40
Pressure [bar]	1,01	1,01	1,01	33,01	6,00
Mass flow [kg/h]	26660	19891	28765	7926	4584
			Mass fraction		
H_2	--	--	0,0414	0,1440	0,0065
CO	--	--	0,1550	0,5625	--
CH_4	--	--	0,0346	0,1255	0,9935
C_2H_4	--	--	0,0235	--	--
C_2H_6	--	--	0,0012	0,0957	--
CO_2	--	--	0,4515	0,0680	--
H_2S	--	--	0,0002	--	--
C_6H_6	--	--	0,0025	--	--
H_2O	--	--	0,2574	0,0042	--
$C_{10}H_8$	--	--	0,0058	--	--
EFB	1,0000	1,0000	--	--	--
Ashes	--	--	0,0268	--	--

Stream 1 corresponds to the EFB feed to the drying stage. Stream 5 is the dry EFB stream that is fed to the gasifier, which is why the mass flow is lower than that of stream 1. Stream 15 is the output of the gasifier (gasification stage) and therefore shows the composition of the raw syngas. Stream 38 is the one obtained after the cleaning and conditioning stage of the syngas, which is why in the composition compounds such as H_2S, COS, ashes, CO_2, and tars are not obtained in a representative way. Finally, stream 53 is reported, which corresponds to the output of the process. The molar composition of the SNG produced (95 %) is within the range of compositions reported in the literature for simulated SNG production processes produced from biomass. Duret et al. (2005) used the commercial software BELSIM-VALI to simulate SNG production from wood, obtaining a CH_4 molar composition of 96.1 %; similarly, Gassner and Maréchal (2009) simulated SNG production from wood and obtained a gas with a CH_4 molar composition of 96 %. Van der Meijden et al. (2010) analyzed the Bio-SNG production process from biomass using the following three gasification technologies: 1) Entrained Flow, 2) Circulating Fluidized Bed and 3) Allothermal or Indirect gasification; the molar compositions of CH_4 present in the SNG obtained with the three technologies were 90.5, 89.9 and 90.7 %, respectively.

With the implementation of Pinch technology, for process optimization through energy integration, the following results were obtained: 1) the total process was identified as having eight hot streams that needed to be cooled and four cold streams that needed to be heated, representing an approximate energy consumption of 41023 kW of cooling utility and 15472 kW of heating utility; 2) with the construction of the cascade diagram it became evident that the process was below the Pinch point and, therefore, only utility cooling was needed. According to the calculations performed, approximately 25.55 MW were needed; 3) the construction of the Composite Curves confirm that using a minimum temperature delta ($\Delta T_{minimum}$) of 10 °C, approximately 25.55 MW of cooling utility is needed after energy integration; 4) finally, with the construction of the exchanger network, it is observed that energy integration can be implemented using the same number of heat exchangers (12 exchangers), but four of them allow energy exchange between different streams of the process. The utilities required for this process, before and after energy integration, are shown in Figure 2.

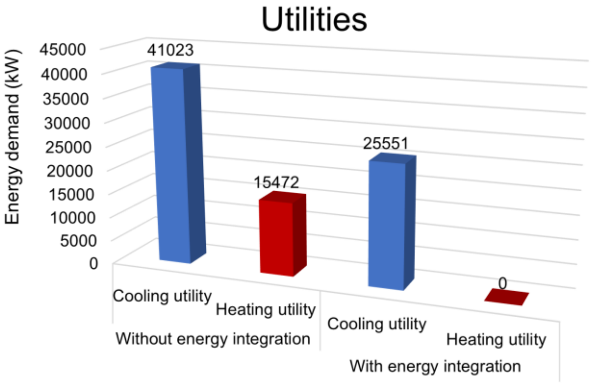

Figure 2: Required utilities in the production plant of SNG from EFB

The results obtained show that the implementation of the systematic methodology of the pinch technology helps to minimize energy losses by adapting the heat exchanger network, since a 100% saving was achieved in heating utility and 37.7% in cooling utility. Such process optimizations using waste energy streams are important for reducing industrial energy and resource consumption. Finally, there is still approximately 25.5 MW of waste heat available in the process that could be used for electricity production.

4. Conclusions

This study proposes a conceptual design for a plant to produce SNG from EFB. This combined gasification–methanation process conforms to the worldwide interest in finding cleaner energy sources and could provide a solution to the problem of open-air disposal of EFB. It was found that using EFB with a moisture content of 30% as feed, it is possible to obtain an SNG with a CH_4 molar percentage of 95 % (mass percentage of 99.35 %) and an approximate yield of 0.064 m3 SNG/kg of EFB. In addition, the energy-optimized plant through the implementation of the Pinch technology allows a saving of 100% of the heating utility requirement and 37.7 % of the cooling utility requirement (approximately 15,472 kW). This study is important because it proposes an alternative use for one of the most produced biomasses in the country, EFB, to reduce environmental problems such as fouling, pest attraction, and greenhouse gas emissions up to soil acidification. In addition, the SNG produced can be used to meet the energy needs of a large part of the Colombian population that does not have access to the national natural gas grid.

References

Akolgo, G. A., Kemausuor, F., Essandoh, E. O., Atta-Darkwa, T., Bart-Plange, A., Kyei-Baffour, N., Maria, C., & De Freitas Maia, B. (2019). Review of Biomass Gasification Technologies: Guidelines for the Ghanaian Situation. *INTERNATIONAL JOURNAL of ENGINEERING SCIENCE AND APPLICATION Akolgo et Al*, *3*(4).

Akpan Sunday, N. (2022). Oil Palm Empty Fruit Bunches (OPEFB) – Alternative Fibre Source for Papermaking. *IntechOpen*, *11*(Papermaking), 13. https://doi.org/10.5772/intechopen.98256

AlNouss, A., McKay, G., & Al-Ansari, T. (2020). A comparison of steam and oxygen fed biomass gasification through a techno-economic-environmental study. *Energy Conversion and Management*, *208*(February), 112612. https://doi.org/10.1016/j.enconman.2020.112612

Dinca, C., Slavu, N., Cormoş, C. C., & Badea, A. (2018). CO2 capture from syngas generated by a biomass gasification power plant with chemical absorption process. *Energy*, *149*, 925–936. https://doi.org/10.1016/j.energy.2018.02.109

Duret, A., Friedli, C., & Maréchal, F. (2005). Process design of Synthetic Natural Gas (SNG) production using wood gasification. *Journal of Cleaner Production*, *13*(15), 1434–1446. https://doi.org/10.1016/j.jclepro.2005.04.009

Federación Nacional de Cultivadores de de Palma de Aceite, F. (2023). Minianuario estadístico 2023: Principales cifras de la agroindustria de palma de aceite en Colombia. *Federación Nacional de Cultivadores de de Palma de Aceite. Fedepalma.* https://repositorio.fedepalma.org/handle/123456789/142826

Federación Nacional de Cultivadores de Palma de Aceite, F. (2023). Anuario Estadístico 2023: Principales cifras de la agroindustria de la palma de aceite en Colombia y en el mundo 2018-2022. In *Fedepalma*.

Gadalla, M. A. (2015). A new graphical method for Pinch Analysis applications: Heat exchanger network retrofit and energy integration. *Energy*, *81*, 159–174. https://doi.org/10.1016/j.energy.2014.12.011

Gambardella, A., & Yasin Yahya, Y. (2017). *Power-to-Gas concepts integrated with syngas production through gasification of forest residues Process modelling Master's thesis in Sustainable Energy System Programme*.

Gao, N., Chen, C., Magdziarz, A., Zhang, L., & Quan, C. (2021). Modeling and simulation of pine sawdust gasification considering gas mixture reflux. *Journal of Analytical and Applied Pyrolysis*, *155*(February), 105094. https://doi.org/10.1016/j.jaap.2021.105094

Gassner, M., & Maréchal, F. (2009). Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. *Biomass and Bioenergy*, *33*(11), 1587–1604. https://doi.org/10.1016/j.biombioe.2009.08.004

Kemp, I. (2006). Pinch Analysis and Process Integration. *Pinch Analysis and Process Integration*, *1*, 125–162. https://doi.org/10.1016/B978-0-7506-8260-2.X5001-9

Park, J., Lee, S. Y., Kim, J., Um, W., Lee, I. B., & Yoo, C. (2021). Energy, safety, and absorption efficiency evaluation of a pilot-scale H2S abatement process using MDEA solution in a coke-oven gas. *Journal of Environmental Chemical Engineering*, *9*(1), 105037. https://doi.org/10.1016/j.jece.2021.105037

Pérez-Rodríguez, C. P., Ríos, L. A., Duarte González, C. S., Montaña, A., & García-Marroquín, C. (2022). Harnessing Residual Biomass as a Renewable Energy Source in Colombia: A Potential Gasification Scenario. *Sustainability (Switzerland)*, *14*(19), 1–14. https://doi.org/10.3390/su141912537

Shahbaz, M., Yusup, S., Inayat, A., Ammar, M., Patrick, D. O., Pratama, A., & Naqvi, S. R. (2017). Syngas Production from Steam Gasification of Palm Kernel Shell with Subsequent CO2 Capture Using CaO Sorbent: An Aspen Plus Modeling. *Energy and Fuels*, *31*(11), 12350–12357. https://doi.org/10.1021/acs.energyfuels.7b02670

Sierra, V. J., Ceballos, C. M. M., & Chejne, F. J. (2021). Simulation of Thermochemical Processes in Aspen Plus As a Tool for Biorefinery Analysis. *CTyF - Ciencia, Tecnologia y Futuro*, *11*(2), 27–38. https://doi.org/10.29047/01225383.372

Tonpakdee, P., Hongrapipat, J., Siriwongrungson, V., Pang, S., Rauch, R., Messner, M., Henrich, C., Pessl, P., & Dichand, M. (2021). Replacement of Palm Methyl Ester to Rapeseed Methyl Ester for Tar Removal in the Nong Bua Dual Fluidized Bed Gasification Power Plant. *IOP Conference Series: Earth and Environmental Science*, *801*(1). https://doi.org/10.1088/1755-1315/801/1/012021

Van der Meijden, C. M., Veringa, H. J., & Rabou, L. P. L. M. (2010). The production of synthetic natural gas (SNG): A comparison of three wood gasification systems for energy balance and overall efficiency. *Biomass and Bioenergy*, *34*(3), 302–311. https://doi.org/10.1016/j.biombioe.2009.11.001

Xing, W., Liu, Y., Zhang, W., Sun, Y., Kai, X., & Yang, T. (2020). Study on Methanation Performance of Biomass Gasification Syngas Based on a Ni/Al2O3Monolithic Catalyst. *ACS Omega*, *5*(44), 28597–28605. https://doi.org/10.1021/acsomega.0c03536