Estimation of potential hydrogen production from palm kernel shell in Norte de Santander, Colombia

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Abstract. This work sought to estimate the economic and environmental potential of palm kernel shell for hydrogen production as energy vector in Norte de Santander, Colombia. A field research determined that the department generates monthly 14082 t of palm biomass of which 1250 t of palm kernel shell remain available for their use. The proximate and ultimate analyses of the palm kernel shell report high heating value (19.53 MJ/kg) compared with other agro-industrial biomasses, high content of volatile material (69.82% w/w) and fixed carbon (21.68% w/w), promoters of chemical reactions in pyrolysis and gasification processes, respectively. In the Aspen Plus\textsuperscript{®} simulation process of the palm kernel shell gasification at 900 °C and steam/biomass ratio of 1.5, a yield is obtained of hydrogen production of 40.7%, equivalent to a monthly production in Norte de Santander of 51.6 t. Using H\textsubscript{2} in the generation of electric power permits producing 470.9 MWh/month that represent theoretical utilities of US$27734.5. In another scenario, 55848.8 gal/month of gasoline are substituted, equivalent to US$11708.6 through the sale of carbon credits. Regarding diesel, 45905.1 gal are replaced per month, which add US$9725.4 through the commercial transaction in the carbon market. It is concluded that using palm kernel shell as primary source to obtain H\textsubscript{2} has, in principle, a favorable economic and environmental impact for sustainable development of the department of Norte de Santander, besides contributing to the knowledge base on the penetration of this vector in Colombia’s energy matrix; however, more detailed technical and economic studies are needed to conclude regarding the economic viability of this energy conversion process.

1. Introduction

Currently, fossil fuels are consolidated as the principal secondary source of energy globally, which has led to a negative impact on the environment through the generation of greenhouse gases (GHG) product of their combustion, contributing to climate change that brings about imbalance of ecosystems, air pollution, and increased sea levels [1]. Hence, the gradual substitution of fossil fuels is necessary for more environmentally friendly, efficient, and sustainable fuels; among them, hydrogen takes the lead as the most indicated to drive human development in this century [2]. Of all the renewable primary energies that can be used as a starting point for hydrogen, biomass constitutes a promising alternative by virtue of its energy potential, availability, distributed nature, and low cost to obtain it [3]. Within this context, Colombia in 2015 had an important biomass production, nearly 72 million ton from the agricultural
sector [4]. Of this total biomass, the palm sector contributed with 1.6 million ton comprised by empty fruit bunches (EFB), fiber, and palm kernel shell (PKS), primarily [4].

In line with the aforementioned, it is necessary to use agricultural biomass to produce renewable energy, thus, this research sought to estimate the potential of the PKS as raw material for hydrogen production as energy vector in Norte de Santander, Colombia, from two perspectives: economic and environmental. Initially, the use and availability of the PKS in the department is determined, while analyzing the physicochemical properties of said biomass, by assessing the optimal operating conditions for hydrogen production through PKS gasification via a process simulated by Acevedo et al., [5] and, finally, considering to the final use of the H₂ obtained, two scenarios were studied: (i) generation of electric power; (ii) as fuel in internal combustion engines (ICE) substituting diesel and gasoline. The contribution, herein, must be seen from its effects in different dimensions: scientific, upon contributing to the country’s knowledge on the use of a type of residual biomass to generate a sustainable, environmentally friendly, and efficient energy vector in its conversion processes to useful energy; environmental, upon contributing with the disposal and use of an organic waste with negative environmental effects due to its deficient or inexistent management; economic, upon contributing to the valorization of an agro-industrial waste that could turn out attractive for producers of this type of crop; and energetic, by promoting the penetration of a last generation energy vector, substituting fossil vectors and improving the quality of the energy matrix in the department and the country.

2. Materials and Methods

2.1. Availability and use of palm biomass

The agro-industrial palm oil sector is characterized for having a high biomass production, generated during the extraction process of crude palm oil. To quantify the palm biomass available in the department of Norte de Santander, field research was conducted in the three palm oil mills in operation, by interviewing the technical and directive personnel from each company. The department generates monthly 14082 t of palm biomass composed of EFB, PKS, and palm fiber. EFB represents the highest amount of biomass generated (7800 t) of which 53% is used as raw material in composting processes; however, the 3629 t remaining are left out in the open, leading to phytosanitary problems due to the long periods necessary for their degradation [3]. Furthermore, the biomass with the highest use index is palm fiber: 3613 t (i.e., 78.9% with respect to the total palm fiber generated); its use is focused mainly as boiler fuel to generate steam required in the process. Finally, PKS, biomass of interest in this study, has a monthly production of 1705 t, with only 26.7% used as boiler fuel or roadway conditioner in palm croplands, which means 1250 t are available for their use as raw material for hydrogen production through thermochemical processes.

2.2. Physicochemical characterization of palm kernel shell

A 2 kg sample of PKS was collected in a palm oil mill located in Norte de Santander, Colombia. This sample was characterized through its proximate and ultimate analysis to determine its energy potential for use as raw material in the gasification process.

2.2.1. Proximate analysis. The PKS was subjected to a milling process to reach an approximate size of 250 µm, then, moisture content was determined along with ashes, volatile material, fixed carbon, and heating value. Table 1 shows the results obtained from the proximate analysis of PKS from the current study compared with the characterization performed by other authors. The moisture content of PKS from the present study reports the lowest value (7.43%), which is favorable because the amount of energy used in the drying process will be lower and it could be destined to the other gasification phases [6]. Another positive parameter is the low ash content (1.07%) compared with the other studies, benefitting the gasification process because ashes are considered inert material that do not react during the process and which in the end become bio-char [7]. Finally, the heating value is one of the most important characteristics, given that said parameter is a measure of the energy available from a fuel,
which depends on the proportion and quality of the sample’s organic fraction [8]. The results validate the energy potential of PKS from the current study, given that it has the highest heating value (19.53 MJ/kg) compared with the other raw materials.

### Table 1. Comparative study of proximate analysis of PKS.

| Parameter               | Current study | Marrugo [8] | Khan et al., [9] | Emery [10] | Valdés et al., [11] |
|-------------------------|---------------|-------------|------------------|------------|---------------------|
| Moisture (%w/w)         | 7.43          | 7.52        | 9.61             | 9.35       | 8.25                |
| Ash (%w/w)              | 1.07          | 2.67        | 4.31             | 3.38       | 2.99                |
| Volatile material (%w/w)| 69.82         | 60.35       | 80.92            | 66.88      | 69.57               |
| Fixed carbon (%w/w)     | 21.68         | 20.46       | 14.61            | 20.39      | 19.19               |
| Heating value (MJ/kg)   | 19.53         | 18.96       | 18.46            | 18.81      | 19.20               |

#### 2.2.2. Ultimate analysis. This analysis establishes the percentage of elements, like carbon (C), sulfur (S), nitrogen (N), oxygen (O), and hydrogen (H), which determines the degree of volatility of the study material. To analyze their CHN composition an elemental EXETER CE-440 analyzer is used in which the sample is subjected to a combustion process at 850 °C. Table 2 presents the content of the different elements present in the PKS that promote the formation of hydrogen molecules in the gasification process and said results are compared with those reported in other research.

### Table 2. Comparative study of ultimate analysis of PKS.

| Parameter | Current study | Marrugo [8] | Khan et al., [9] | Emery [10] | Valdés et al., [11] |
|-----------|---------------|-------------|------------------|------------|---------------------|
| C (%w/w)  | 49.98         | 46.05       | 49.70            | 46.83      | 47.39               |
| H (%w/w)  | 4.87          | 5.14        | 5.68             | 5.36       | 5.09                |
| N (%w/w)  | 0.41          | 0.62        | 1.07             | 0.74       | 0.64                |
| O (%w/w)  | 43.55         | 45.40       | 43.36            | 46.94      | 43.79               |
| S (%w/w)  | 0.04          | 0.14        | 0.27             | 0.13       | 0.11                |

The carbon content (49.98%) of PKS from the department presents a favorable value to promote heterogeneous reactions, methane formation, and water-gas shift reaction during the gasification stage, which maximize conversion of hydrocarbons into gases with low molecular weight, like H2, CO2, CO, and CH4 [12]. In addition, the low nitrogen content (0.41%) compared with the other PKS samples, supposes that the formation of ammonia molecules and hydrogen cyanide during the gasification stage will be low; a positive aspect, considering that said gases are highly polluting [6]. Likewise, the sulfur content (0.04%) also becomes a favorable parameter, being the lowest value compared with other studies, which means there will be a minimum production of a flammable and toxic gas, like hydrogen sulfide (H2S) during the gasification process [8].

![Figure 1. Molar composition of the synthesis gas.](image)

#### 2.3. Gasification process of palm kernel shell

In a prior research, Acevedo et al., [5] evaluated the optimal operating conditions for hydrogen production through PKS gasification through a process simulated in Aspen Plus®. The gasification process was divided into four stages: drying, pyrolysis, oxidation, and reduction by using two reactors for R-Yield and R-Equil modelling. This model was replicated in the current study by changing the biomass fed to the R-Yield reactor, inputting 1250 t/month of PKS, which corresponds to the biomass
available in Norte de Santander, Colombia. Figure 1 shows the molar composition of the synthesis gas obtained from the PKS gasification process at 900 °C and Steam/Biomass ratio of 1.5 (w/w), with a yield of 0.15 kmol of syngas/kg PKS; highlighting that the predominant gas is H₂ with 40.7%, followed by H₂O with 30.8%. Thereafter, in similar proportions there are CO and CO₂ at 15.6% and 12.3%, respectively. Finally, there is a minimum proportion of CH₄ (0.6%).

3. Results and discussion

3.1. Theoretical analysis of H₂ production

Bearing in mind the PKS available in Norte de Santander (1250 t/month) and the results obtained in the simulation in Aspen Plus® described in the previous section, the department could produce monthly 51563 kg (51.6 t) of hydrogen, which is equivalent to 26602.2 kmol. This research sought to make an approximation to the department’s potential to produce clean and renewable energy by using sub-products from the palm oil production chain, estimating some economic benefits that can be perceived by the final use of the hydrogen obtained. However, this study does not analyze the costs associated with H₂ production, like fixed costs, which include investment costs (technology, facilities, administration) and capital costs; variable costs, especially those related to operation and maintenance. Further, for a specific technology, these costs are strongly influenced by the scale economy, the density of usable energy for a specific site and the lifetime of the technology used [13]. Some studies have estimated the costs of hydrogen production, Kumar, et al., [14] determined that the cost of H₂ production for a plant with capacity of 2000 t/day, using dry algae as raw material through gasification with supercritical water and thermal gasification, is US$4.59/kg and US$5.66/kg, of H₂ respectively. Sarkar and Kumar [15] studied a gasifier to produce biohydrogen by using forest waste and wheat straw and reported US$1.17/kg and US$1.29/kg of H₂ at a plant capacity of 2000 dry tons/day. It becomes important for future research to study the cost of H₂ production from PKS through gasification processes in Norte de Santander, to determine the economic feasibility of said energy alternative.

3.2. Final use of hydrogen

Hydrogen, as energy vector, has multiple uses, like space transport, submersibles, portable, stationary, and mobile applications, internal combustion engines, and gas turbines [16]. This study analyzed two scenarios to use hydrogen from PKS available in Norte de Santander; (i) raw material to generate electric power, and (ii) substitute for fossil fuels (i.e., diesel and gasoline), to measure the economic and environmental impact of its use.

3.2.1. Generation of electric power. To transform hydrogen into electric power, it is possible to implement proton-exchange membrane (PEM) fuel cells, an electrochemical system that converts chemical energy into electric power obtaining water and heat as sub-products; likewise, these are the most promising due to their high current density and efficiency, and low operating temperature [17]. With the PEM technology in mind, one can estimate the production of electric power from the 51563 kg/month of H₂ obtained in Norte de Santander by applying the Equation (1).

\[ EP_g = P_{H_2} \times LHV_{H_2} \times E_{fc} \]  

(1)

Where \( EP_g \) is the electric power generated (kWh/month), \( P_{H_2} \) is the hydrogen production (kg/month), \( LHV_{H_2} \) is the low heating value of hydrogen (kWh/kg H₂), \( E_{fc} \) is the fuel cell efficiency. With respect to \( LHV_{H_2} \), it is equivalent to 33.33 kWh/kg H₂ [18] and the \( E_{fc} \) estimated is equal to 27.4% [19]. Additionally, the economic value is determined of the kWh/month produced from hydrogen, calculated as in Equation (2).

\[ $EP = EP_g \times C_K \]  

(2)
Where $\$ EP$ is the cost of the monthly electric power ($/month) and $C_k$ is the cost of the kilowatt ($$/kWh), which has a cost of US$0.15 in the department [20]. By applying Equations (1) and (2), the monthly production of electric power is equivalent to 470902.3 kWh (470.9 MWh) from the 1250 t of PKS available in Norte de Santander, which reaches a value of US$67632.3/month through the commercialization of the kWh generated. Although studies exist on the cost of electricity production from different electricity generation technologies, few studies exist on stationary fuel cell systems. Silveira and Gómez [21] performed a techno-economic analysis of a cogeneration system based on fuel cells for a computer center. The cost of electricity production varied between 0.0666 – 0.2249 US$/kWh, depending on the interest rate selected and the magnitude of the investment cost. Similarly, Lipman et al., [22] investigated 10 different electricity generation systems based on fuel cells, four of which were cogeneration systems with hydrogen, calculating a production cost that ranged between 0.056 – 0.294 US$/kWh. According to these data, the theoretical utilities ($\$ U_t$) of energy production from hydrogen are calculated through Equation (3).

$$\$ U_t = \$ EP - [EP_k \times (C_{P,H_2}+C_{E, PEM})]$$

(3)

Where $C_{P,H_2}$ is the cost of hydrogen production from biomass through gasification processes (US$1.17/kg H_2) [15] and $C_{E, PEM}$ is the cost of energy production from hydrogen by using PEM cells (US$0.056/kWh) [22]. It should be highlighted that the current study does not include costs of power storage and distribution. As shown in Table 3, the theoretical utilities of producing electric power from hydrogen in Norte de Santander are estimated at US$27734.5/month. These utilities demonstrate the pertinence of using PKS to produce bioenergy to add value to the sub-product, improve the competitiveness of the palm sector, and mitigate the negative impact to the environment. However, it is convenient for further research to perform an economic analysis of the total costs, from the collection and transport of the raw material to the distribution of the energy to the end user, to estimate its financial viability.

3.2.2. Substitute of fossil fuels. Certified emission reduction (CER) or carbon credits are an international mechanism to reduce polluting emissions onto the environment and among the mechanisms proposed in the Kyoto Protocol to reduce emissions causing global warming [23]. Hence, CER are traded in the market, each credit represents the right to 1 t of CO$_2$ emission. Those responsible for large GHG emissions, represented principally by highly industrialized countries and multinational enterprises, can turn to climate stock exchanges with amounts of emissions captured certified, which are sold to those who require compensating the environmental impacts generated by their production activity [13]. Thereby, the research analyzed the CER that can be generated through the substitution of fossil fuels, like gasoline and diesel, by using H$_2$ as source of energy in internal combustion engines (ICE). Equation (4) and Equation (5) calculate based on equivalencies of the low heating value, the energy provided by hydrogen that permits compensating the use of gasoline and diesel as energy sources in the ICE.

$$GS = [P_{H_2} \times (R_{H_2}/D_G)]/3.785$$

(4)

$$DS = [P_{H_2} \times (R_D/D_D)]/3.785$$

(5)

Where $GS$ is the gasoline substituted (gal/month), $R_{H_2}$ is the gasoline/hydrogen energy ratio (kg gas/kg H$_2$), $D_G$ is density of gasoline (kg/l); $DS$ is the diesel substituted (gal/month), $R_D$ is the diesel/hydrogen energy ratio (kg diesel/kg H$_2$), and $D_D$ is density of diesel (kg/l). Upon estimating the amount of gasoline and diesel that can be substituted with hydrogen, one can calculate the value of the CER to commercialize in the carbon credit market through the reduction of CO$_2$ emissions to the environment, by applying the Equation (6) and Equation (7).
CER\textsubscript{G} = GS \times E_{CO_2} \times V_{CO_2} \tag{6}

CER\textsubscript{D} = DS \times E_{CO_2} \times V_{CO_2} \tag{7}

Where CER\textsubscript{G} are the carbon credits due to the gasoline substituted (US$/month), E\textsubscript{CO_2} are the CO\textsubscript{2} emissions generated by gasoline combustion (t/m\textsuperscript{3}), V\textsubscript{CO_2} is the value of the CO\textsubscript{2} emissions (US$/t CO\textsubscript{2}), and CER\textsubscript{D} are the carbon credits due to the diesel substituted. As shown in Table 3, from 51.6 t of hydrogen obtained from the gasification of PKS, 55848.8 gal of gasoline could be substituted monthly, which is equivalent to US$11708.6 through the CER commercialization. With respect to diesel, 45905.1 gal could be replaced monthly, representing US$9725.4 through the commercial transaction in the carbon credits market. Although the current study does not include the production costs of gasoline and diesel from the processing of PKS; Patel \textit{et al.} [24] analyzed the production costs of a plant with capacity for 2000 dry tons/day of different agro-industrial biomasses to produce renewable diesel and gasoline via rapid pyrolysis and hydro-processing, estimating the production cost of gasoline per liter in US$1.06, US$1.14, and US$1.22 for wood wastes, corn stubble, and wheat straw, respectively. Regarding renewable diesel, the production costs per liter for each raw material were US$1.11 for wood wastes, US$1.19 for corn stubble, and US$1.27 for wheat straw. The aforementioned ratifies that Norte de Santander is a department with significant renewable energy potential, by virtue of the palm biomass available for its use, especially PKS as raw material for hydrogen production, generating economic and environmental benefits through the use of H\textsubscript{2} as energy vector.

| PKS available (t/month) | H\textsubscript{2} produced (t/month) | Electric power generated MWh/month | Gasoline substituted USS/month \(\times 27734.5\) | Diesel substituted USS/month CER/month | Diesel substituted gal/month | Diesel substituted USS CER/month |
|------------------------|-----------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1250                   | 51.6                              | 470.9                           | 27734.5                         | 55848.8                         | 11708.6                         | 45905.1                         | 9725.4                         |

\textsuperscript{a} Theoretical utility of the generation of energy from H\textsubscript{2}.

4. Conclusions

Norte de Santander generates 1705 t/month of PKS of which 26.7% is used as boiler fuel and roadway conditioner, with 1250 t/month remaining that can be used as raw material for hydrogen production, as source of clean and renewable energy. Additionally, contents of fixed carbon (21.68%), moisture (7.43%), and heating value (19.53 MJ/kg) demonstrate that PKS is a potential biomass for gasification, given that the fixed carbon content indicates that heterogeneous reactions will be promoted in the last stage of the gasification process, the low moisture content allows the PKS drying process to require less energy, and the high heating value denotes the amount of energy available from the biofuel.

From the PKS available in the department, 51.6 t/month of H\textsubscript{2} could be obtained through the gasification process at 900 °C and Steam/Biomass ratio of 1.5. Hydrogen, as source of electric power through PEM cells, could reach a production of 470.9 MWh/month, which represent theoretical utilities of US$27734.5/month. In another scenario, H\textsubscript{2} as substitute of fossil fuels, permits reducing CO\textsubscript{2} emissions to the environment, obtaining economic benefits through the commercial transaction in the carbon credits market. For gasoline, US$11708.6 could be perceived through the sale of CER by replacing 55848.8 gal/month. With respect to diesel, 45905.1 gal could be substituted monthly, which represent US$9725.4 through the CER commercial transaction.

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References

[1] Yusoff S 2006 *Journal of Cleaner Production* **14** 87
[2] Stern A 2018 *Int. J. Hydrogen Energy* **43** 4244
[3] García J A, et al. 2016 *Resources, Conservation and Recycling* **110** 99
[4] Marrugo G, Valdés C and Chejne F 2016 *Energy Fuels* **30** 8386
[5] Acevedo J, Posso F, Durán J and Arenas E 2018 *J. Phys. Conf. Ser.* **1126** 1
[6] Mushtaq F, Abdullah A, Mat R and Ani F 2015 *Bioresource Technology* **190** 442
[7] Chejne F, et al. 2017 *La gasificación, alternativa de generación de energía y productos con alto valor agregado para la industria* (Medellín: Universidad Nacional de Colombia)
[8] Marrugo G 2015 *Efectos de los cambios estructurales de diferentes biomasas pirolizadas sobre las características de gas de síntesis* (Medellín: Universidad Nacional de Colombia)
[9] Khan A, Yusup S, Ahmad M and Bridgi L 2014 *Energy Convers. Manage.* **87** 1224
[10] Emery E 2014 *Destilacion secundaria de alquitranes generados en la gasificacion de cuesco de palma africana* (Medellín: Universidad Nacional de Colombia)
[11] Valdés C, Marrugo G, Gómez C and Montoya J 2016 *Applied Thermal Engineering* **107** 1201
[12] Basu P 2010 *Biomass gasification and pyrolysis* (Burlington: Elsevier Inc)
[13] Posso F, Acevedo J and Hernández J 2014 *Revista en Administración e Ingeniería* **2(2)** 49
[14] Kumar M, Olajire A and Kumar A 2019 *Int. J. Hydrogen Energy* **44(21)** 10384
[15] Sarkar S and Kumar A 2010 *Energy* **35** 582
[16] Carl-Jochen W 2009 *Int. J. Hydrogen Energy* **34** S1
[17] Barreras F and Lozano A 2012 *Hidrógeno. Pilas de combustible de tipo PEM* (Zaragoza: Universidad de Zaragoza)
[18] Karim G 2003 *International Journal of Hydrogen Energy* **28** 569
[19] Barbir F and Gómez T 1997 *International Journal of Hydrogen Energy* **22(10)** 1027
[20] Colombia: Ministerio de Tecnologías de la Información y las Comunicaciones (MinTiC) 2018 *Tarifas de energía de Centrales Eléctricas del Norte de Santander (CENS)* (Colombia: Ministerio de Tecnologías de la Información y las Comunicaciones)
[21] Silveira J and Gomes L 1999 *Renewable Sustainable Energy Rev.* **3** 233
[22] Lipman T, Edwards J and Kammen D 2004 *Energy Policy* **32** 101
[23] Frondizi I 2009 *El mecanismo de desarrollo limpio* (Rio de Janeiro: Imperial Novo Milenio Ed.)
[24] Patel M, Olajire A, Kumar A and Gupta R 2019 *Fuel Processing Technology* **191** 79