DAZA SERNA L.V[1], CARDONA ALZATE C.A[1]*.

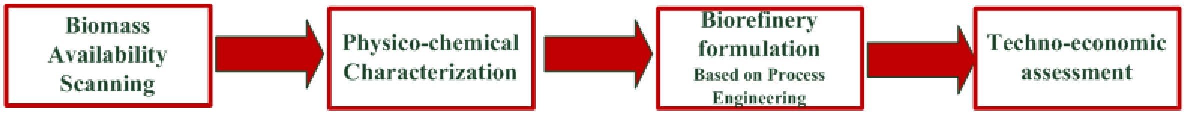
Energy Biorefineries for Agricultural Waste Management: The Colombian Case

[1]Instituto de Biotecnología y Agroindustria
Universidad Nacional de Colombia at Manizales
Address: Km 09 vía al Magdalena
Phone: (+57) (6) 8879300 ext 55354
*Corresponding Author: ccardonaal@unal.edu.co

Abstract

In this study a techno-economic analysis of energy producing biorefineries from two different agricultural wastes: Rice Husk (RH) and Plantain Pseudostem (PP) was developed. Considering the wastes availability and the experimental characterization results were evaluated two energy producing biorefineries considering ethanol, electricity and biogas production. The higher holocellulose (cellulose and hemicellulose) content 57% and 60% of RH and PP respectively makes interesting these raw materials. The economical results allow concluding about the potential of bioethanol production together with other energy products from agricultural wastes in tropical countries.

Graphical Abstract



Keywords:

Agricultural waste, bioenergy, biofuels, biorefinery approach.

1. Introduction

The total energy demand has kept an increasing behavior during the last years. According to the Global Energy Statistical Yearbook [1] the Latin American energy demand reached 854 Mtoe in 2013. That year Colombia had a participation of 4% of the mentioned demand. The energy demand is mainly supplied by non-renewable sources such as crude oil derivates, coal and natural gas.

Considering environmental factors and the depletion in resources availability, the research focused on non-conventional energy sources has been increasing based on the advantages provided by non-renewable energy sources such as high efficiency, easy transportation and huge power generation capability. In this sense the production of liquid, gas and solid biofuels as well as electricity can be an interesting alternative for biomass use.

Bioenergy producing biorefineries are referred to these schemes in which one or different types of raw materials are used to produce energy (liquid biofuels, gaseous biofuels, solid biofuels, and/or electricity). The use of liquid biofuels, as bioethanol and biodiesel, has been increased during the past few years. In this sense the Colombian Government has regulated the use of gasoline blends with 7-10% of bioethanol [2]. Bioethanol can be obtained from conventional and non-conventional sources. The production process considers the pretreatment, fermentation, distillation and dehydration processes [3]. Gaseous biofuels can be generated through anaerobic digestion (AD), where methane and carbon dioxide are produced. It consists in three main steps (Hydrolysis-acidogenesis, acetogenesis and methanogenesis) [4]. Hydrolysis stage involves the biological decomposition of organic polymers. In the acidogenesis stage some fermentative bacteria degrades glucose, xylose and xylans to produce ethanol, acetate, propionate, lactate and butyrate as mainly products. Digestate is the main residue from anaerobic digestion. This residue is widely used in land-applications due to its capability to enhance the soils nutrients retention [5]. Besides lignocellulosic residues, sugars like glucose have been tested as substrate for anaerobic digestion under different schemes [6]. Electricity is considered as a secondary energy source based on the flow of electrical power. Electricity can be produced from biomass through different termochemical technologies which includes gasification or combustion [7].

For products definition purposes it is necessary to consider the physical and chemical composition of raw materials which can be classified in first, second and third generation. First generation raw materials are referred to the edible crops used for food or agribusiness purposes [8], [9]. Second generation raw materials are mainly composed by lignocellulosic materials (cellulose, hemicellulose and lignin rich material) produced during different extraction or transformation stages such as seeding, cropping and harvesting. Other sources of second generation raw materials are the non-edible crops [10]. Finally, Microalgae are recognized as third generation raw materials [11]

1.1 Colombian Context

Colombia is a country located in a tropical region between the Pacific and Atlantic Oceans in the northern side of South America. Some geographical special features made Colombia a country assorted of a biodiversity composed by a variety of soils, hydric resources among others. Due to some geographical restrictions, different parts in the country exist under isolation conditions (for example the Amazon rainforest, high mountains regions, etc.). Infrastructure and Unsatisfied Basic Needs (UBN) represents the main gaps for isolated regions.

Non-Interconnected Zones (NIZ) are those isolated regions composed by the zones, towns and municipalities non-interconnected to the national grid of energy generation and distribution. These zones represents approximately the 52% of the national area [12]. These zones are characterized by their low population density, difficult access, poor infrastructure, as well as the Ethnic and Afrodescent native communities. According to the 'Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas no Interconectadas-IPSE', which is the govern agency dedicated to planning strategies to integrate the NIZ [13], the electricity access represents a key equity factor to promote the development and economic growth in the country based on sustainability, competitiviness and efficiency.

In this sense the purpose of this work was to evaluate the production of three different energy forms taking advantage of lignocellulosic biomass from agricultural wastes as an alternative for its management and adequate disposal.

1.2 Agricultural waste Availability

1.2.1 Rice Husk

Rice represents one of the most relevant crops for Colombian agriculture preceded by coffee and sugarcane given the production scales and the harvested areas [14]. Rice is cultivated in more than 20 Colombian regions. This crop is developed under three different culture mechanisms classified according to the water irrigation and technification scales in irrigated, non-irrigated mechanized and non-irrigated manual areas.

Rice Husk is the non edible agricultural residue generated during the whole grain de-husking process. Per each ton of rice processed can be generated approximately 0.23 tons of this residue [15] [16]. According to official statistics provided by agriculture ministry [17] from 2008 an stable area of about 500.000 Has producing 2,8 millions tons of rice is identified in the country. The production shares according the harvesting mechanism were 65%, 31% and 4% of irrigated, non-irrigated mechanized and non-irrigated manual.

This residue has restrictions in feed production due to its nutritive properties degradation restrictions[18]. Ethanol, concrete and ceramics, agglomerates and adsorbent production as well as energy generation are some of the potential uses for rice husks [19]. This residue can be used as fertilizer being applied in averages quantities of 8 kg/m^2 [20].

1.2.2 Plantain Pseudostem

Plantain culture represents a traditional sector in Colombian agriculture for internal as well as external market. In 2013 Colombia was the third world’s exporter losing the leading role against Guatemala and Ecuador [21] . This crop has been traditionally cultivated by small farmers (less than 3 has) mainly associated to other crops such as coffee, cocoa, cassava and fruit crops. Plantain is cultivated in 31 Colombian regions and it is widely consumed in the diet playing an important role in food security [22].

The plantain biomass is composed by an edible and a non-edible part. Approximately 20% of total plantain biomass is represented by the edible part called plantain bunches, while the non edible part is composed by mainly plantain pseudostem (representing the 50% of total biomass) [23]. The remaining 30% is constituted by rachis and low quality edible parts [24]. Plantain Pseudostem is commonly used as nutrient support for new plants during the agronomic stage [24]. According to official statistics provided by agriculture ministry [17] about 2,7 millions tons of plantain bunches are actually produced in the country. Considering the ratio pseudostem:bunches approximately 6,8 millions of tons of plantain pseudostem were produced. Near to 79% of the total residue is left in lands.

2. Methodology

2.1 Raw Material

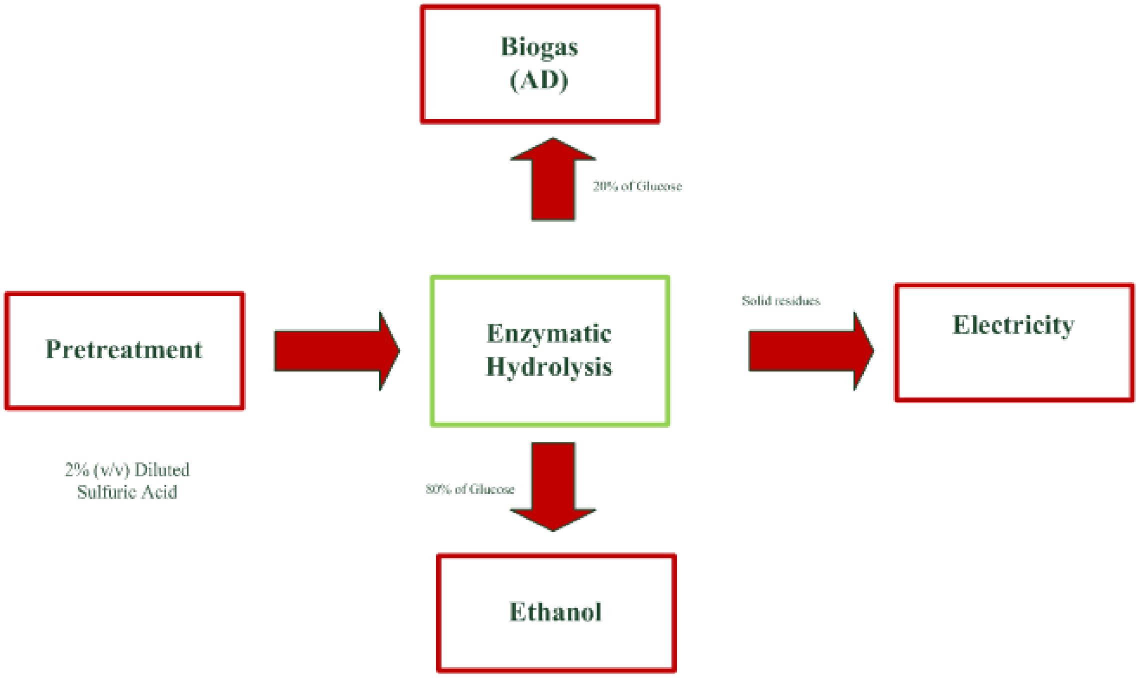
Rice Husk (RH) samples from *Oryza sativa* variety were obtained from a small farm from Saldaña town 3°55′45″N 75°00′56″W located in Tolima region. Pseudostem plantain (PP) samples from *Musa paradisiaca* variety were obtained from Bugalagrande town located in Cauca Valley region.

2.2 Experimental Characterization

These raw materials were chemically characterized to determine its extractives, cellulose, hemicellulose, lignin and ash content. The samples were dried using a convective furnace at 50°C and then milled to reduce the particle diameter below 0.85 mm. The extractives determination were developed following the ASTM Standard Test Method E 1690 “Determination of Ethanol Extractives in Biomass” [25] by using ethanol at 45°C for 24 h. Holocellulose (cellulose and hemicellulose fractions) was determined through the chlorination method described by *Rabemanolontsoa* and *Saka* [26]. The alpha-cellulose fraction was determined from the holocellulose residue through sodium hydroxide and acetic acid treatment [27]. The total lignin (soluble and non-soluble fractions) was determined by acid treatment with H_2SO_4. Finally the ash content was determined by sample ignition at 575°C according to the TAPPI standard T211 [27]. All the experimental procedures were carried out by triplicated.

2.3 Process Description

After chemical characterization, were selected the routes to obtain different energy products as bioethanol, biogas and electricity. These routes allow the design of the simulation strategy and implementation to be used. The figure 2 shows the proposed biorefinery scheme.



2.3.1 Bioethanol Production

The raw materials were submitted to pretreatment, enzymatic hydrolysis, fermentation and separation stages. During pretreatment stage the raw materials were dried and milled and then were sent to a diluted sulfuric acid (2% v/v) pretreatment at 121°C during 1.5h. The kinetic parameters were reported by *Esteghillian* et al [28]. From this stage were separated two phases: the liquid phase (mainly composed by xylose with furfural) and the solid phase (composed by non-soluble fraction rich in cellulose). This stream was detoxified for further fermentation and the xylose fraction disposed as co-product. Then, the filtrated residual biomass were destined to enzymatic hydrolysis, applying conditions reported by *Morales-Rodriguez* et al [29]. Enzymatic hydrolysis was developed by cellulases and beta-glucosidase enzymes at 50°C, transforming the cellulose fraction into glucose.

Later, the produced glucose was used as substrate to produce ethanol through submerged fermentation by *Saccharomyces cerevisiae* at 30°C [30]. After fermentation stage the fermentation products were sent to the separation zone composed by three distillation columns. The outgoing ethanol concentration reaches the azeotropic point (96%wt). Then, the azeotropic mixture was sent to the dehydratation process with molecular sieves to obtain anhydrid ethanol (99.6 %wt) [31].

2.3.2 Biogas Production

Biogas production was evaluated considering a glucose portion from enzymatic hydrolysis as substrate. The production process for anaerobic digestion (AD) is developed as complex multistage system involving acidogenesis, acetogenesis and methanogenesis. The kinetics for these reactions was proposed by *Kalyuzhnyi* and *Davlyatshina* [32] using anaerobic sludge as preinoculum. The digestion was developed at 35°C with a initial glucose concentration of 2 g/l. As AD products were obtained mainly methane and carbon dioxide followed by acetate and propionate in low amounts [32].

2.3.3 Electricity Production

A gas turbine cogeneration system as described by *Rincón* et al [33] with the aim of producing electricity and steam for process requirements. In this scheme the gases produced during biomass combustion were passed through a turbine to obtain energy.

2.4 Process Simulation

Aspen Plus V8.2 (Aspen Technology Inc., USA) was used for simulation purposes. Some physicochemical properties of non-included compounds were obtained from the National Institute of Standards of Technology. Aspen Plus database for biofuels components developed by the

National Renewable Energy Laboratory [34] was used for hexoses properties specifications. The thermodynamic models used for simulation were the Non-Random Two-Liquid (NRTL). }

The total production costs were estimated using the commercial software Aspen Process Economic Analyzer V8.2 (Aspen Technology Inc., USA) assuming the depreciation of capital for 12-year period beneath the straight-line method. The economic parameters such as income tax, interest rate, labor salaries, electricity and water costs corresponded to the Colombian context. From this stage, the capital costs as well as the operating, raw materials, utilities, equipment and other general and administrative costs were estimated. All the inputs, referred to enzymes, low pressure steam and medium pressure steam are presented in the Table 1

Table 1. Input Prices

Feature	Value	Units	Reference
Water	0.74	USD/m^3	*Moncada* et al [35]
Electricity	0.14	USD/kW	*Moncada* et al [35]
LP Steam	1.57	USD/Ton	*Moncada* et al [35]
MP Steam	8.18	USD/Ton	*Moncada* et al [35]
Nutrients	1	USD/kg	This Work *

*proposed as an average price of the needed nutrients

3. Results and discussion

3.1 Experimental Characterization

The chemical composition of RH and PP are presented in the Table 2 and Despite the similar compositions, the high initial moisture 83% represents the main disadvantage for the use of PP. This moisture content could imply higher energetic costs related to the drying process. Besides, the costs associated to the PP logistics of the harvesting can reduce the profitability potential of PP as raw material.

. The results obtained are slightly different compared to the reported by *Quintero* et al and *Cordeiro* et al. In both cases, cellulose followed by hemicellulose contents was identified as the main component. It shows a high potential of the selected raw materials to be transformed to sugars platform. However, the higher lignin content of RH represents the main drawback as raw material for sugar production. Nevertheless, its lignin content confers to RH the potential to be used in concrete and construction materials.

Table 2. Rice Husk Characterization

Feature	This Work	Literature	Reference
Moisture	11± 0.5%	11.7 %	*Srinivas* and *Reddy* [36]
Extractives$^{(db)}$	7 ± 1%	3.35 %	*Quintero* et al [37]
Cellulose$^{(db)}$	40 ± 2%	26.45 %	
Hemicellulose$^{(db)}$	16 ± 3%	27.29 %	
Lignin$^{(db)}$	26 ± 7%	28.03 %	
Ash$^{(db)}$	11 ± 1%	14.89 %	

(db): Dry Basis

Despite the similar compositions, the high initial moisture 83% represents the main disadvantage for the use of PP. This moisture content could imply higher energetic costs related to the drying process. Besides, the costs associated to the PP logistics of the harvesting can reduce the profitability potential of PP as raw material.

Table 3. Plantain Pseudostem Characterization

Feature	This Work	Literature	Reference
Moisture	83 ± 3%	85 %	*Pérez* [23]
Extractives$^{(db)}$	19 ± 1%	8.1 %	*Cordeiro* et al[38]
Cellulose$^{(db)}$	41± 7%	40.2 %	
Hemicellulose$^{(db)}$	19± 5%	25 %	
Lignin$^{(db)}$	14± 4%	14.6 %	
Ash$^{(db)}$	8± 0.1%	15.6 %	

(db): Dry Basis

3.2 Techno-economic Assessment

Ten tons per hour of each raw material were defined as basis calculation for simulation purposes. Then, based on preliminary analysis the produced glucose was distributed in 80% and 20% to ethanol and biogas plants respectively. Considering the moisture contents the available hemicellulose and cellulose varies affecting the ethanol and biogas yields. In both cases the ethanol production process gave a positive profit margin compared to the reported market prices [39] of 0.92 USD/kg. The ethanol profit margins obtained were 5% and 2%. These profit margin values are still lower and can be strongly affected by inputs and raw materials costs.

Table 4. Product costs

Products		
	RH	PP
Ethanol (USD/kg)	0.88	0.91
Biogas (USD/m^3)	5.37	6.81
Electricity (USD/kWh)	0.0097	0.0099

For understanding the prefeasibility of the proposed technology, in the case of biogas Table 5 presents the prices comparison between some conventional biogas sources. Biogas production costs from RH and PP are higher compared with the reported by *Gissén* et al[40]. This behavior might be explained by the fewer amount of glucose considered by this work using just 20% of the total availability. However, if the xylose is also used for these purposes, the total biogas yield can be considerably higher and the costs dramatically reduced. The xylose production was 135.4 kg/ ton RH and 56.4 kg/ ton PP of xylose.

Table 5. Biogas Comparison

Source of Biogas	**USD/m^3**	**Reference**
RH	5.37	This work
PP	6.81	This work
Natural Gas	0.41	*Gissén* et al[40]
Dairy	0.09	*Gissén* et al[40]

Another interesting co-product to be considered is the highly diluted anaerobic sludge, which in this work was produced at rates of 6918 kg/ton RH and 3590 kg/ton PP of anaerobic sludge as co-products. This co-product can represent additional incomes enhancing the biorefinery economical performance.

The electricity production, being one of the most important targets allowed due to the positive incomes. The low production costs could contribute to enhance the electricity access in different regions with limited access. In this sense, the use of agricultural wastes which has a huge availability in the country (isolated and non-isolated regions) would have strong applicability for NIZ.

4. Conclusions

The results showed that it is possible take advantage of agricultural wastes under biorefinery scheme considering additional products such as xylose derivatives and sludge from AD. The moisture content represents one bottleneck for waste valorization considering the increases in costs associated to drying process and low available dry matter to be transformed. Finally, this type of raw materials can be used under biorefiney scheme for those isolated zones with high rates of NBU considering the production of basic supplies and other value-added products as energy.

5. Acknowledgments

The authors express their gratitude to the Universidad Nacional de Colombia at Manizales, the Biotechnology and Angroindustry Institute as well as to COLCIENCIAS for the financial support of this research through the program ‘Jóvenes Investigadores, Convocatoria 617 de 2013’.

6. References

[1] Enerdata, “Total Energy Consumption,” *Global Energy Statistical Yearbook 2014*, 2014. [Online]. Available: https://yearbook.enerdata.net/#energy-consumption-data.html. [Accessed: 15-May-2015].

[2] Febebiocombustibles, “Estadísticas Producción de alcohol carburante,” 2014. [Online]. Available: http://www.fedebiocombustibles.com/v3/nota-web-id-487.htm.

[3] M. J. Valencia and C. a. Cardona, “The Colombian biofuel supply chains: The assessment of current and promising scenarios based on environmental goals,” *Energy Policy*, vol. 67, pp. 232–242, Apr. 2014.

[4] P. Pantamas, P. Chaiprasert, and M. Tanticharoen, “Anaerobic Digestion of Glucose by Bacillus licheniformis and Bacillus coagulans at Low and High Alkalinity,” vol. 4, pp. 1–17, 2003.

[5] L. Yang, F. Xu, X. Ge, and Y. Li, “Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass,” *Renew. Sustain. Energy Rev.*, vol. 44, pp. 824–834, 2015.

[6] a. Cohen, R. J. Zoetemeyer, a. van Deursen, and J. G. van Andel, “Anaerobic digestion of glucose with separated acid production and methane formation,” *Water Res.*, vol. 13, pp. 571–580, 1979.

[7] L. E. Rincon, J. Moncada Botero, and C. A. Cardona Alzate, *Catalytic Systems for Integral Transformations of Oil Plants through Biorefinery concept.*, First Edit. Manizales, Colombia: Universidad Nacional de Colombia sede Manizales, 2013.

[8] J. Moncada, J. a. Tamayo, and C. a. Cardona, “Integrating first, second, and third generation biorefineries: Incorporating microalgae into the sugarcane biorefinery,” *Chem. Eng. Sci.*, vol. 118, pp. 126–140, 2014.

[9] P. R. Lennartsson, P. Erlandsson, and M. J. Taherzadeh, “Integration of the first and second generation bioethanol processes and the importance of by-products,” *Bioresour. Technol.*, vol. 165, pp. 3–8, 2014.

[10] S. Pinzi and M. P. Dorado, “Feedstocks for advanced biodiesel production,” in *Advances in Biodiesel Production*, Woodhead Publishing Limited, 2012, pp. 204–231.

[11] a. L. Ahmad, N. H. M. Yasin, C. J. C. Derek, and J. K. Lim, “Microalgae as a sustainable energy source for biodiesel production: A review,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 584–593, 2011.

[12] IPSE and MinMinas, “Soluciones Energéticas para las Zonas No Interconectadas de Colombia.” IPSE, Bogotá, Colombia, 2014.

[13] IPSE, “Interconexión eléctrica como factor de equidad,” 2015. [Online]. Available: http://www.ipse.gov.co/comunicaciones-ipse/noticias-ipse/979-energia-electrica-para-colombia. [Accessed: 17-May-2015].

[14] C. F. Espinal g, H. J. Martínez Covaleda, and Xi. Acevedo Gaitán, “La Cadena del Arroz en Colombia. Una Mirada Global de su Estructura y Dinámica 1991-2005,” 2005.

[15] U. Kumar and M. Bandyopadhyay, “Sorption of cadmium from aqueous solution using pretreated rice husk.,” *Bioresour. Technol.*, vol. 97, no. 1, pp. 104–9, Jan. 2006.

[16] N. Soltani, a. Bahrami, M. I. Pech-Canul, and L. a. González, “Review on the physicochemical treatments of rice husk for production of advanced materials,” *Chem. Eng. J.*, vol. 264, pp. 899–935, Dec. 2014.

[17] DNP, “Anuario Estadistico del Sector Agropecuario-MinAgricultura,” *Departamento Nacional de Planeación*, 2008. .

[18] P. Jeetah, N. Golaup, and K. Buddynauth, “Production of cardboard from waste rice husk,” *J. Environ. Chem. Eng.*, vol. 3, no. 1, pp. 52–59, Mar. 2015.

[19] A. Prada and C. E. Cortés, “Thermal decomposition of rice husk : an alternative integral use,” *Rev. Orinoquia*, vol. 3, no. 1, pp. 155–170, 2010.

[20] D. Quiceno Villada and M. Y. Mosquera Gutierrez, “Alternativas Tecnologicas para el uso de la cascarilla de arroz como combustible,” Universidad Autónoma de Occidente, 2010.

[21] Caracol, “Colombia pasó del primer al tercer lugar en exportación de plátano en el mundo,” *Economy Section*, 2013.

[22] C. F. Espinal, H. J. Martínez Covaleda, and Y. Peña Marin, “La cadena del Plátano en Colombia. Una mirada global de su Estructura y Dinámica.,” Bogotá, Colombia, 2005.

[23] R. Pérez, “Roots, tubers, bananas and plantains,” in *Feeding pigs in the tropics*, Rome, Italy: FAO, 1997.

[24] M. Mazzeo Meneses, L. León Agatón, L. F. Mejía Gutiérrez, L. E. Guerrero Mendieta, and J. D. Botero López, “Aprovechamiento Industrial de Residuos de Cosecha y Poscosecha del Plátano en el departamento de Caldas.,” *Rev. Educ. en Ing.*, vol. 9, pp. 128–139, 2010.

[25] A. Sluiter, R. Ruiz, C. Scarlata, J. Sluiter, D. Templeton, A. Sluiter, R. Ruiz, C. Scarlata, J. Sluiter, and D. Templeton, “Determination of Extractives in Biomass,” no. January. NREL, Golden, U.S, 2008.

[26] H. Rabemanolontsoa and S. Saka, “Holocellulose Determination in Biomass,” in *Zero-Carbon Energy Kyoto 2011: Special Edition of Jointed Symposium of Kyoto*, vol. 108, 2012, pp. 135–140.

[27] J. S. Han and J. S. Rowell, “Chemical Composition of Fibers,” in *Paper and Composites from Agro-based Resources*, 1995.

[28] A. Esteghllian, A. Hashimoto, J. Fenske, and M. H. Penner, “Modeling and Optimization of the dilute-Sulfuric-Acid Pretreatment of corn stover, poplar and switchgrass.,” *Bioresour. Technol.*, vol. 59, no. 1997, pp. 129–136, 1994.

[29] R. Morales-rodriguez, K. V Gernaey, A. S. Meyer, and G. Sin, “A Mathematical Model for Simultaneous Saccharification and Co-fermentation (SSCF) of C6 and C5 Sugars,” *Chinese J. Chem. Eng.*, vol. 19, no. 2, pp. 185–191, 2010.

[30] G. Birol, P. Doruker, B. Kardar, Z. Onsan, and K. Ulgen, “Mathematical description of ethanol fermentation by immobilised Saccharomyces cerevisiae,” *Process Biochem.*, vol. 33, pp. 763–771, 1998.

[31] W. W. Pitt, G. L. Haag, and D. D. Lee, “Recovery of ethanol from fermentation broths using selective sorption-desorption.,” *Biotechnol. Bioeng.*, vol. 25, pp. 123–131, 1983.

[32] S. V Kalyuzhnyi and M. A. Davlyatshina, “Batch Anaerobic Digestion of Glucose and its Mathematical Modeling. I.Kinetic Investigations,” *Bioresour. Technol.*, vol. 59, pp. 73–80, 1997.

[33] L. E. Rincón, J. Moncada, and C. A. Cardona, “Analysis of Cogeneration as a Tool to Improve the viability of Oilseed based Biorefineries.,” in *Catalytic Systems For Integral Transformations Of Oil Plants Through Biorefinery Concept .*, 2013, pp. 77–96.

[34] V. P. R. J. Wooley, “Development of an ASPEN PLUS physical property database for biofuels components, NREL, Golden, CO, Report MP-425-20685.”

[35] J. Moncada, J. J. Jaramillo, J. C. Higuita, C. Younes, and C. A. Cardona, “Production of Bioethanol Using Chlorella vulgaris Cake : A Technoeconomic and Environmental Assessment in the Colombian Context,” 2013.

[36] T. Srinivas and B. V. Reddy, “Hybrid solar-biomass power plant without energy storage,” *Case Stud. Therm. Eng.*, vol. 2, pp. 75–81, 2014.

[37] J. Quintero, J. Moncada, and C. . Cardona, “Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: a process simulation approach.,” *Bioresour. Technol.*, vol. 139, pp. 300–7.

[38] N. Cordeiro, M. N. Belgacem, I. C. Torres, and J. C. V. P. Moura, “Chemical composition and pulping of banana pseudo-stems,” *Ind. Crops Prod.*, vol. 19, no. 2004, pp. 147–154, 2003.

[39] Fedebiocombustibles, “Precios de Etanol,” 2015. [Online]. Available: http://www.fedebiocombustibles.com/. [Accessed: 15-May-2015].

[40] C. Gissén, T. Prade, E. Kreuger, I. A. Nges, H. Rosenqvist, S. E. Svensson, M. Lantz, J. E. Mattsson, P. Börjesson, and L. Björnsson, “Comparing energy crops for biogas production - Yields, energy input and costs in cultivation using digestate and mineral fertilisation,” *Biomass and Bioenergy*, vol. 64, pp. 199–210, 2014.