Electronic Journal of Biotechnology 33 (2018) 52–62

Contents lists available at ScienceDirect

Electronic Journal of Biotechnology

Review

Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material

Juan Camilo Solarte-Toro, Yessica Chacón-Pérez, Carlos Ariel Cardona-Alzate *

Instituto de Biotecnología y Agroindustria, Universidad Nacional de Colombia, Manizales Campus, Km 09 vía al Magdalena, Colombia

ARTICLE INFO

Article history:
Received 28 September 2017
Accepted 20 March 2018
Available online 03 April 2018

Keywords:
Anaerobic digestion
Biogas power generation
Biomass gasification
Biomethane
Energy sources
Energy vectors
Heat generation
Lignocellulosic energy production
Power generation
Renewable energy
Syngas production

ABSTRACT

The use of nonrenewable energy sources to provide the worldwide energy needs has caused different problems such as global warming, water pollution, and smog production. In this sense, lignocellulosic biomass has been postulated as a renewable energy source able to produce energy carriers that can cover this energy demand. Biogas and syngas are two energy vectors that have been suggested to generate heat and power through their use in cogeneration systems. Therefore, the aim of this review is to develop a comparison between these energy vectors considering their main features based on literature reports. In addition, a techno-economic and energy assessment of the heat and power generation using these vectors as energy sources is performed. If lignocellulosic biomass is used as raw material, biogas is more commonly used for cogeneration purposes than syngas. However, syngas from biomass gasification has a great potential to be employed as a chemical platform in the production of value-added products. Moreover, the investment costs to generate heat and power from lignocellulosic materials using the anaerobic digestion technology are higher than those using the gasification technology. As a conclusion, it was evidenced that upgraded biogas has a higher potential to produce heat and power than syngas. Nevertheless, the implementation of both energy vectors into the energy market is important to cover the increasing worldwide energy demand.

How to cite: Solarte-Toro JC, Chacón-Pérez Y, Cardona-Alzate CA. Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material. Electron J Biotechnol 2018:33:52-62. https://doi.org/10.1016/j.ejbt.2018.03.005

Contents

---

* Corresponding author.
E-mail address: ccardonaal@unal.edu.co. (C.A. Cardona-Alzate).
Peer review under responsibility of Pontificia Universidad Católica de Valparaíso.

https://doi.org/10.1016/j.ejbt.2018.03.005

1. Introduction

The energy derived from nonrenewable resources such as crude oil, coal, and natural gas has encouraged technological progress and supported advances in a wide variety of productive sectors [1]. Fossil fuel consumption has provided 78.4% of the worldwide energy needs since 2014. In addition, the demand for crude oil and natural gas has increased progressively more than 0.5% in the past years [2,3], which has caused different problems such as global warming, water pollution, and smog production [4]. Therefore, a high dependency on fossil fuels is observed. This overview can have risk from an energy security point of view owing to the constant fluctuation in crude oil prices [5,6]. In this sense, the research on alternative energy sources has been considered as a fundamental step in the development of a sustainable economy in the near future [7].

The research, production, and use of renewable energy have gained importance in transportation, industrial, and building sectors in response to reach a sustainable development [1]. According to the International Energy Agency (IEA), renewable energy is defined as the energy derived from natural processes that are replenished at a higher rate than they are consumed [8]. Thus, renewable energy can be classified according to the source used to produce it [9]. Some of the renewable energies are solar energy, wind energy, hydropower, geothermal energy, and bioenergy. In 2015, 8.9% of the worldwide energy demand was supplied by the use of bioenergy, whereas about 10.35% was supplied by the other forms of renewable energy [3]. The high share of bioenergy in the worldwide supply was achieved because of the growing interest in the use of biomass as raw material to produce liquid and gaseous energy vectors with different applications through chemical, biochemical, thermochemical, and catalytic pathways [10,11,12].

At industrial level, the most important liquid energy carriers are bioethanol and biodiesel [10,13]. These liquid carriers have a well-established market in the transportation sector and their implementation by blending with gasoline and diesel to reduce the greenhouse gas (GHG) emission has been successful [14]. Moreover, gaseous energy vectors such as biogas and syngas can be used for heating and cooling as well as to produce electricity [15,16]. These energy requirements are obtained through two competitive processes: anaerobic digestion (AD) and gasification. Both processes have been implemented in several European countries, the United States, and some countries in Latin America [17,18]. Biogas facilities have developed since 2012. These plants use some lignocellulosic biomass from energy crops and the organic fraction of municipal solid waste. However, not all lignocellulosic feedstocks can be upgraded through this process [19]. On the other hand, few gasification facilities use lignocellulosic residues as the main raw material to produce syngas. Cogasification systems are gaining strength with an aim to reduce the use of coal [20]. Consequently, an in-depth study on the suitable biomass must be carried out before applying some of the above options to convert second-generation biomass into gaseous energy vectors.

Biogas and syngas have similar applications from an energy production point of view. They have different fuel components, requirements for gas cleaning, and heating values. Additionally, their applicability and production conditions can vary depending on the type of biomass [21,22]. Therefore, the aim of this review is to develop a comparison between these energy vectors considering features based on literature reports. Moreover, a techno-economic and energy assessment of the heat and power generation using biogas and syngas as fuels is performed. Finally, the cogeneration process also considers the production of these fuels using the oil palm rachis (OPR) as feedstock, which is a lignocellulosic residue produced in large quantities in Colombia.

2. Biogas production and anaerobic digestion: an overview

Biogas production has emerged in Europe and North America as an alternative fuel for transport overcoming its delay due to the lack of policies and regulations. The five largest producers of biogas worldwide are Germany, Sweden, Switzerland, the United Kingdom, and the United States [3,23]. Nevertheless, most of the produced biogas in the United States comes from landfill gas [3]. Meanwhile, agricultural wastes are used for this purpose in Europe [3,24]. Other efforts performed by countries such as Colombia, Costa Rica, China, and India have been focused to establish a natural gas infrastructure in which biogas could be incorporated [25]. On the other hand, biogas is also used for industrial and urban applications to generate heat and power in cogeneration systems [26]. Additionally, biogas is the cheapest fuel used for cooking, with a per capital cost of 0.17 USD/person/day. This price is even three times lower than the wood price [3].

Biogas is the main product obtained from the AD of organic matter or biomass. This process can be defined as a complex sequence of chemical reactions where organic matter is degraded and stabilized through different metabolic routes carried out by a microorganism consortium in an oxygen-free environment [19,27]. Four stages have been identified in the AD process: hydrolysis, acidification, production of acetate, and production of methane. These steps are interrelated. Therefore, any of these stages can be considered as the limiting step in the AD process [28].

The main product of the digestion process is a gas mixture composed mainly of methane (CH_4) and carbon dioxide (CO_2). Nevertheless, hydrogen sulfide (H_2S), ammonia (NH_3), hydrogen (H_2), and carbon monoxide (CO) are other trace gases that are present [29]. Furthermore, the so-called raw biogas is saturated with water, and it has other impurities such as dust particles and siloxanes [19]. In addition, a wet solid or liquid (i.e., digestate) that has the potential to be used as fertilizer is produced. However, a conditioning process must be carried out to avoid any risk in its use [26].

The AD process must meet some basic conditions to ensure efficient substrate degradation. The conditions are related to typical operating parameters considered in biotechnological processes, such as temperature, pH, nutrient supply (C/N/P ratio), and redox potential [19]. Moreover, important features related to the employed substrate as feedstock also must be known. These features include the content of total solids (TS) and volatile solids (VS), carbon-to-nitrogen ratio (C/N), theoretical methane yield, biochemical methane potential (BMP), and surface area [30,31]. Commonly, this process is carried out under mesophilic conditions (32°C-42°C), pH values between 5.2. and 6.3, C/N ratio between 10 and 45, and redox potential between +400 mV and -300 mV. These variables and values enable to design a well-supported digestion process without drawbacks in the biogas production. However, the AD process can be performed at low and high temperatures, which are called psychrophile and thermophile digestions, respectively.

This process at the industrial level can be carried out using one-step or two-step reactors in one phase or two phases as a batch or continuous mode, with or without liquid phase recirculation [32]. However, during the selection of reactor type and design, the above-mentioned feedstock characteristics must be considered. Once biogas has been produced, it can be cleaned or upgraded to increase its heating value and its application range. Current biogas upgrading technologies include absorption, adsorption, membrane separation, and cryogenic separation. Each one has different advantages and disadvantages related to its energy requirements, solvents, as well as capital and operational expenditures (CAPEX and OPEX) [23,29]. In addition, these technologies are considered relatively mature, which is described in the next sections.

2.1. Lignocellulosic biomass as raw material for biogas production

Lignocellulosic biomass is an abundant renewable resource that can be used for biogas production, and it is available in the developed and developing countries [25,33]. This raw material is considered as a potential source of fermentable sugars such as glucose, xylose, mannose, and arabinose as well as other organic compounds such as proteins and lipids that can be anaerobically degraded. The gas produced by the AD of lignocellulosic materials is rich in CH_4 and has an energy content higher than 22.6 MJ/m^3 [19]. Nevertheless, the direct use of lignocellulosic biomass has a drawback of longer residence time that is needed to complete the AD process because of the hemicellulose and lignin cross-linked matrix [34,35].

Different lignocellulosic raw materials have been characterized and tested with the aim to know their technical and economic feasibility for biogas production through different standard methods at the laboratory scale (e.g., ASTM E2170-01, VDI 4630) [17,30]. However, the reported yields for the same substrate vary greatly owing to the harvest time and storage conditions, which make the objective analysis difficult [36]. Examples of lignocellulosic feedstocks employed for biogas production as well as their characterization, biogas yield, digestion time, and high heating value (HHV) are reported in

As can be seen in Table 1, the AD of lignocellulosic materials has a long residence time that can affect the productivity of the entire process and decrease its economic feasibility. Therefore, a pretreatment stage has been considered as a fundamental step to reduce the residence time of the substrate inside the bioreactor and to increase the CH_4 yields [31,44]. For this reason, many authors have reviewed the effect of the pretreatment stage in the fermentable sugar production for biogas production [45,46,47]. However, it is not possible to ensure that the same pretreatment for different lignocellulosic materials has the same results owing to the variability and complexity of biomass internal structure. Parameters such as accessible surface area, decrystallization of cellulose, as well as lignin and hemicellulose solubilization have been evaluated to define the success of the applied pretreatment with regard to the lignocellulose matrix rupture and production of low-molecular-weight compounds (e.g., monomeric sugars and low lipid chains) [34]. The most applied pretreatment technologies to enhance the digestibility of lignocellulosic biomass are dilute acid hydrolysis, steam explosion, alkaline hydrolysis, size reduction, and liquid hot water (LHW) due to their high potential for easy scale-up at the industrial level. Table 2 shows the CH_4 yields for different lignocellulosic materials and the residence time after a pretreatment stage:

Table 1
Lignocellulosic feedstock utilized for biogas production.

Feedstock	TS (%)	VS (%)	C/N ratio	Y. CH_4 (mL/g VS)	Time (d)	HHV (MJ/kg)	Ref.
Wheat straw	92.2	84.8	92	226	40	17.5	[37,38]
Corn stover	84.9	76.9	54	215	28	17.8	[38,39]
SCB[a]	55.4	53.2	116	281	35	17.7	[38,40]
Rice husk	89.2	77.8	99	44	36	15.7	[38,41]
Rice straw	87.8	79.6	43	436	36	15.1	[38,41]
EFB[b]	6.7	5.7	17	202	45	18.0	[42,43]

Y. CH_4: Methane Yield

[a] Sugarcane bagasse.

[b] Empty Fruit Bunches.

Finally, an increase in the CH_4 yield of the raw materials reported in Table 1 is observed. Therefore, the pretreatment stage must be considered as a fundamental step in the overall biogas production process when lignocellulosic biomass is used as substrate. Nevertheless, the design and implementation of the process require a comprehensive understanding of economic and environmental aspects to avoid a negative impact on the sustainability of the entire process.

2.2. Energy content and quality

Methane is a fuel gas that has been identified as the main component of the raw biogas produced from the anaerobic degradation of biomass [56]. The CH_4 concentration depends on the amount of fats, proteins, and carbohydrates added in the anaerobic digester. In general terms, raw biogas has a CH_4 concentration range between 50% and 70%. Additionally, CO_2 is found in high concentrations in raw biogas. Its content varies from 30% to 45% [57]. The HHV of CH_4 as pure gas is 37.78 MJ/m$_n^3$. Therefore, raw biogas has an energy content between 19 MJ/m$_n^3$ and 26 MJ/m$_n^3$ or 6.0 kWh/m$_n^3$ and 6.5 kWh/m$_n^3$, which can replace 0.65 liters of crude oil [19]. These energy contents reported for raw biogas vary significantly based

Table 2
Methane yields from pretreated lignocellulosic raw materials.

Feedstock	Pretreatment	Pretreatment agent	Y. CH_4 (mL/gVS)	Time (d)	Ref.
Wheat straw	Steam explosion	Steam	273.0	40	[37]
	Liquid hot water	Water	386.0	60	[48]
	Ammonia-based	Aqueous ammonia	199.7	25	[49]
Corn stover	Alkaline	NaOH	372.4	40	[50]
SCB[a]	Liquid hot water	Water	100.6	23	[51]
Rice husk	Ammonia-based	Aqueous ammonia	55.7	45	[52]
Rice straw	Alkaline	Na_2CO_3	292.0	47	[53]
	Oxidation	H_2O_2	327.5	30	[54]
EFB[b]	Ionic liquids	N-methylmorpholine-N-oxide	408.0	50	[46]
	Acid	H_3PO_4	285.0	30	[55]
	Alkaline	NaOH	404.0	30	[55]

[a] Sugarcane bagasse.

[b] Empty Fruit Bunches.

on the type of lignocellulosic material because of the different energy properties as well as C/H and C/O ratios, which can favor the CH_4 or CO_2 production. However, the previously reported HHV for raw biogas covers a wide variety of feedstocks [58].

Raw biogas has a limited application range because of the presence of trace compounds that can have a negative effect on equipment used for biogas utilization. Therefore, compounds such as H_2S, NH_3, H_2O, N_2, and siloxanes must be avoided with an aim to guarantee an appropriate biogas use [29,59]. Effects caused by the above-mentioned impurities are pipeline corrosion, decrease of biogas heating value, and formation of undesired products such as NO_x and SO_2 after a combustion process. A more detailed explanation of each of the above impurities is given below.

2.2.1. Carbon dioxide (CO_2) and water vapor (H_2O)

Carbon dioxide is one of the main gases produced in the AD process. Its production and concentration depend only on the employed substrate. CO_2 is produced at different stages during the AD process (mainly in the hydrolysis step). Substances or molecules with a high degree of oxidation should be added to decrease its content in raw biogas. Therefore, long-chain hydrocarbons such as fats and molecules with a high number of carbon atoms are preferential substrates [19]. Raw biogas rich in CO_2 has a low heating value (LHV), and its applicability for energy production in industrial equipment is reduced. Thus, the heat and power generation in a cogeneration plant requires a CO_2-removing stage.

On the other hand, H_2O is an inherent component present in raw biogas because of the water evaporation process that occurs during the AD process. Its average concentration at 35°C is around 40 g/m^3 [19]. Frequently, raw biogas conditioning involves a compression stage to improve the separation of impurities, which promotes the condensation process, thus favoring the production of corrosive components such as carbonic acid (H_2CO_3) and sulfuric acid (H_2SO_4). To avoid the above-mentioned problem, a reduction in water concentration in raw biogas is necessary. This process can be performed through a drying or dehumidification stage before the removal of impurities in raw biogas [57].

2.2.2. Hydrogen sulfide (H_2S) and ammonia (NH_3)

Hydrogen sulfide and ammonia are two common impurities produced during the AD process of lignocellulosic biomass and occur in raw biogas with a maximum concentration of 0.5% and 0.05% v/v, respectively [60]. These gases are present in high concentration in raw biogas that uses substrates such as stillage, microalgae, and slaughterhouse wastes [19]. The high concentration of these gases can be related to the high elemental sulfur and nitrogen contents in the entire process volume (i.e., inoculum and substrate). However, the H_2S content in raw biogas produced from lignocellulosic materials is low because of the minimum amount of elemental sulfur in second-generation feedstocks [61]. The impurities can produce SO_2 and NO_x emissions after burning them in a cogeneration system. Moreover, H_2S and NH_3 can produce problems associated with the equipment corrosion. Therefore, these gases must be removed from raw biogas by wet scrubbing or other technologies available for this purpose [21].

2.2.3. Siloxanes

Siloxanes are a type of volatile organic compounds that have a silicon atom in their structure. These compounds are produced when sewage sludge, food leftovers, and some industrial wastes are used as codigestion substrates. The high content of siloxanes can produce problems such as corrosion and deposition if raw biogas is burned without any conditioning stage because of the silicon dioxide production. Therefore, a concentration of 0.2 mg/m^3 has been recommended as the highest limit of these compounds in biogas to be used for energy applications with the goal to avoid abrasion in high-pressure equipment [62].

2.3. Purification technologies

Biogas has low energy content in its original state. After the removal of the above-mentioned impurities, the energy content of the raw biogas can increase by around 15%. This increase converts the raw biogas into an alternative energy source with the properties same as those of the natural gas [63,64]. Therefore, the biogas upgrading process is necessary to use this renewable fuel in the transportation and industrial sectors. In this way, various technologies have been implemented, such as cryogenic separation, physical or chemical absorption, membrane separation, amine scrubbing, water scrubbing, and pressure swing adsorption [65]. In each of these technologies, the physicochemical properties of the impurities are considered as an advantage. However, most of these technologies are based on physical phenomena as in the case of the cryogenic separation, which uses the difference in the condensation temperatures of CH_4 and CO_2 to separate them, thus producing a liquid rich in biomethane.

In other technologies, impurities are removed considering the equilibrium involved between liquid and gas phases at different pressures. That is the case for physical absorption and water scrubbing, where the CO_2 solubility in organic solvents (e.g., methanol and dimethyl ethers of polyethylene glycol) or water is used as a separation mechanism [63]. Nevertheless, Sun et al. [57] showed that the use of these kinds of solvents in plants with a capacity of 100–200 m^3/h increases the operating and maintenance costs between 1.05 and 1.42 euro cent/kWh. These costs are double of the reported costs (i.e., 0.47 and 0.45 euro cent/kWh) for water scrubbing and regeneration technology [57]. The above OPEX difference can affect the sale price of the biomethane as well as the feasibility and sustainability of the process. Therefore, water scrubbing is the most commonly used technology at the industrial level because of the competitive biomethane prices and high purity reached (i.e., 80–99%). Nevertheless, the energy consumption of this technology is higher than those of the above-mentioned technologies [56].

2.4. Upgraded biogas and natural gas

Biomethane, as a renewable fuel, has more significant environmental benefits than the natural gas. According to Koornneef et al. [66], the use of biomethane could avoid around 8 Gt CO_2-eq of GHG emissions in 2050. Nevertheless, there is no significant difference in the use of biomethane and natural gas from the technical point of view because of the similar properties. In fact, most of the technologies used for heat, steam, as well as electricity and power production can be used with both energy sources. Additionally, the current technologies for heating have high flexibility to the use of biomethane, biogas, and, even, synthetic natural gas. However, depending on the application of these gaseous energy vectors, some impurities must be removed to achieve a gas with acceptable calorific value and combustion properties. Natural gas has a low content of H_2S (i.e., 1.1-5.9 ppm) and there is no presence of water, but it has a high content of heavy carbons by its nature. Thus, biogas must have a CO_2 and H_2O content near to 25–30% v/v and 6% v/v, respectively, as well as the H_2S content lower than 10 ppm to be used in kitchen stoves and industrial boilers. Nevertheless, biogas use into the natural gas grid has more demanding requirements with regard to the CO_2, H_2O, and H_2S contents, which do not exceed 3% v/v, 8% v/v, and 15 mg/m^3, respectively [32]. The above-mentioned requirements for biogas use into the natural gas grid can vary from one country to another owing to the policies of each country. For instance, France is more flexible in the CH_4 content but not with the total sulphur content as Sweden or Austria [23,57].

2.5. Biogas applications

Biomethane has different uses. One of the uses is as fuel in the residential or industrial sector to obtain heat or/and electricity. The most common equipment used to produce these services are boilers, internal combustion engines, Stirling engines, and gas turbines. In these systems, biogas is commonly used without any upgrading process compared to biomethane because some equipment do not require high-quality gas as in the case of the Stirling engines, which can use gas with a CH_4 molar concentration of 35% [57]. On the other hand, biomethane is employed in fuel cells or it is introduced into the natural gas grid, preferably. Moreover, biomethane can be transported easily where needed, and it can be stored avoiding corrosion problems. In accordance with the above-mentioned uses of biogas and biomethane, Sweden used 50% of the produced biogas for heating, 8% for electricity generation, and 18% as vehicle fuel in 2006. In 2011, this country focused on the biogas upgrading to be used as vehicle fuel [57]. Nevertheless, it may be more suitable to consider the advantage of the high calorific value of this upgraded biogas in the industrial sector to produce heat and power because of the high thermal efficiencies that its use offers [23].

In addition, biomethane (upgraded biogas) not only is important as a renewable energy carrier but also can be used as chemical platform because of the well-defined routes to use CH_4 as the raw material. Therefore, it can be converted into syngas, which is considered as the basis for obtaining fuels such as methanol, dimethyl ether, and hydrogen [58]. For this conversion, any available way to reform the natural gas can be useful, although the most common is the steam reforming. Afterwards, the syngas can be involved in different catalytic systems to obtain methanol or hydrocarbon compounds (i.e., olefins and paraffins) through the Fischer–Tropsch process, which is considered as a complex process that requires well-defined operating conditions to synthesize the desired products. In that way and considering the CH_4 selectivity, different authors have focused their works on enhancing catalytic systems, also involving it in biological systems [67,68]. In the last case, the use of a group of bacteria known as *Methanotrophs* has been researched. Thus far, some success has been reported in the field of lactate, biodiesel, and biopolymers production [68].

3. Syngas production and biomass gasification: An overview

The gasification technology has already been studied and implemented in the past years to produce energy [69]. However, a renovated interest for this technology has been aroused because of the use of lignocellulosic biomass (e.g., forestry and wood residues) as raw material, which combined with pretreatment technologies (e.g., densification) can be able to produce energy at a low scale as well as value-added products [70]. This can be reflected in the statistics provided by the Gasification and Syngas Technologies Council (GSTC), who reports that there are more than 250 gasification facilities operating and more than 680 gasifiers worldwide. From this, 10% of these plants operate using lignocellulosic biomass as the main feedstock. Currently, gasification facilities are distributed in North America, Europe, and Asia. Nevertheless, Asia, specifically China, will gain a worldwide potency with regard to gasification plants because of a planned increase of 190,000 MW in its installed capacity from 2013 to 2020, which exceeds the rest of regions in the world [71]. This behavior is supported by the market growth of chemical, fertilizer, and coal-to-liquid industries located in Asia [71].

In the gasification process, by-products such as tars and char as well as ashes are produced. These are produced in low quantities when the gasification technology is used. However, there are other thermochemical processes such as pyrolysis and torrefaction that produce syngas, bio-oil, and char. The differences between these processes, as thermochemical ways for biomass processing, lie in the operating conditions and the amounts of syngas, bi-oil, and char that are obtained. Thus, gasification is employed to produce syngas in large amounts, whereas the torrefaction process produces low quantities of gases because this process is mostly used to increase the energy content of lignocellulosic feedstocks by removing its oxygen content. Finally, the pyrolysis process is carried out in the absence of any oxidizing agent at atmospheric pressure and temperatures from 300°C to 600°C. This process involves high heating rates (1000°C/min) to produce a mixture of gases that can be condensed. Bio-oil, as the main product of the pyrolysis process, has a heating value lower than that of the fossil fuels by approximately 50% [58,72,73].

Syngas is the main product obtained through the gasification of nonrenewable and renewable energy sources such as coal and lignocellulosic biomass, respectively. The gasification process is defined as the thermochemical conversion of carbonaceous materials in a partially oxidized environment to produce char, tars, and a mixture of gases composed by H_2, CO, CO_2, and CH_4 as well as other low-molecular-weight hydrocarbons [74]. This mixture of gases is combustible, and it can be used in different applications such as power generation and chemical production [75]. Syngas production is possible by using an oxidizing agent provided in substoichiometric quantities with the goal to avoid a complete combustion of the raw material [76]. The most common oxidizing agents used in gasification facilities are steam, oxygen, and air [77,78]. Commonly, the term "syngas" is used to describe the gaseous product from the gasification of any raw material without considering the oxidizing agent, and this term is highly used in the literature [79,80]. However, some authors make a difference between the terms "syngas" and "producer gas." The first one is obtained only when steam or oxygen is used to carry out the gasification process, and the second one is used when air is used. The main difference between these terms is the energy content of the gas obtained in each case [74].

The gasification process involves a series of complex gas–solid and gas phase reactions carried out in a temperature range between 800°C and 1000°C. These reactions have been studied by different authors using software tools such as MATLAB, Aspen Plus, and CFD programs [81,82,83]. However, a complete modeling with kinetics and reaction mechanisms is still under-researched. On the other hand, this process has well-established steps in which raw materials are converted into syngas. The four steps are drying, pyrolysis, combustion/oxidation, and reduction [74,79]. These steps involve water removal, devolatilization of raw materials, thermal energy production, and gaseous species formation, respectively. Finally, this process can be classified considering different criteria such as heating method and feedstock disposition into the gasifier [74,84].

3.1. Raw materials used for syngas production

Coal, petcoke, biomass, and waste are feedstocks employed to produce syngas through the gasification process. Coal is the most commonly used raw material because its conversion and treatment are considered as a mature process. In addition, coal is the cheapest nonrenewable energy source, which makes it an ideal feedstock. On the other hand, the gasification of biomass and waste has emerged as a response to the search for new alternatives to dispose them. However, there are few gasification plants globally that operate with biomass as their main feedstock. For this reason, the implementation of biomass gasification into the renewable energy sector has been at a low scale to provide energy in noninterconnected zones.

Similar to the AD process, the feedstock employed in the gasification process must meet some requirements related to moisture content and particle size. These characteristics can affect the performance of the gasification process with regard to efficiency and gas product conversion. Moisture content below 30% as well as a particle size below 38.10 mm and above 25.40 mm are common feedstock characteristics, even if the raw material has been pelletized [85]. On the other hand, the syngas composition is affected by the elemental composition of the raw material employed in this process. Therefore, different analyses such as proximate and ultimate analyses should be performed [58]. From these analyses, it is possible to calculate the

HHV of the raw material and to determine whether this is suitable for syngas production. The HHV of coal is around 32 MJ/kg, whereas the HHV of lignocellulosic biomass is between 17 and 20 MJ/kg [86,87]. In addition, an advantage of coal over lignocellulosic biomass is the low tar production as well as its high content of silicon dioxide in its ash fraction [88].

Finally, new alternatives have been developed to increase the energy density of lignocellulosic biomass to be used in thermochemical processes, and not only in gasification. For example, torrefaction is a pretreatment that is carried out in a temperature range between 200°C and 300°C in the absence of oxygen to remove the most volatile fraction of the raw material (i.e., hemicellulose), which increases the energy content between 20% and 60% [89].

3.2. Quality and energy content

The syngas composition obtained from coal, petcoke, lignocellulosic biomass, and municipal solid waste gasification, as well as its quality and energy content, is a function of a wide variety of variables such as the gasifier design, gasifying medium employed, raw material elemental composition, and operating pressure. These variables have been studied by different authors with an aim to find better operation conditions to carry out an optimal gasification process [90,91,92,93]. However, different experiences on gasification have demonstrated that the heating value of the syngas can vary between 3 MJ/m_n^3 and 15 MJ/m_n^3 [80,94,97]. The compositional range of the syngas obtained from coal, petcoke, lignocellulosic biomass, and municipal solid waste as well as their heating value is reported in the literature, and the details are shown in Table 3.

As can be seen in Table 3, the syngas obtained from coal and petcoke has a higher HHV than the HHV from lignocellulosic biomass and municipal solid waste gasification. For this reason, the use of these raw materials, at the industrial level, has been preferred. However, the compositions shown in the previous table can vary significantly if the operating conditions are optimized. Therefore, lignocellulosic biomass has a great potential to be used as the main raw material for the gasification process to decrease the coal exploitation in different regions across the world. On the other hand, it was mentioned that air, oxygen, and steam are the main gasifying media employed to perform the gasification process. The use of each of these media provides heating values different from those of the syngas due to the variation in the H_2 and CO concentration. A brief description of the syngas properties obtained with these agents is as follows.

Air is one of the most employed gasifying media because this does not have costs associated with its acquisition and use. However, syngas produced by air-blown gasification has the lowest heating value that can be obtained through this technology. This is because of the presence of N_2 and other impurities in the syngas composition. Thus, the syngas obtained using these oxidizing agents and lignocellulosic biomass as raw material has an HHV between 4 MJ/mn^3 and 7 MJ/mn^3 with an H_2 content between 12 and 16%, CO content of 18–24%, and CH_4 content of 1–6% [92,98]. However, some benefits with the use of air are the low tar formation and high syngas yield [80]. On the other hand, the amount of air needed to perform the gasification process is evaluated using the equivalence ratio (ER) concept. This concept is defined as the ratio between the air–fuel ratio of the gasification process and the air–fuel ratio for complete combustion. A higher ER means that the amount of O_2 in the gasifier increases, thus reducing the calorific value of the syngas. Moreover, a lower ER results in higher calorific syngas [99]. In the case of biomass, the ER employed to carry out the gasification process is approximately 0.25 [100,101].

Table 3
Syngas composition obtained by the gasification of different raw materials.

Feedstock	H_2 (% mol)	CO (% mol)	CH_4 (% mol)	CO_2 (% mol)	HHV (MJ/m_n^3)	Ref.
Coal	25–30	30–60	0–5	5–15	7–15	[94]
Petcoke	22–30	39–48	0–1	18–34	8–11	[95,96]
Biomass	5–16	10–22	1–6	8–20	4–7	[80]
MSW	8–23	22–24	0–3	6–15	3–7	[97]

Oxygen and steam are the preferred oxidizing agents to perform the gasification of different raw materials because the energy content of the syngas is increased [58]. However, there are some economic issues related to their production that have restricted their use. When biomass is used as raw material to be gasified, the heating value of the syngas produced is 10–18 MJ/m_n^3 and 12–28 MJ/m_n^3 for steam and oxygen, respectively [58]. The HHV of the syngas is due to the absence of inert gases such as N_2 and the high content of H_2 and CO in the mixture.

3.3. Syngas applications

Syngas can be used for heat and power generation as well as to obtain value-added products such as biofuels (i.e., methanol and ethanol), ammonia, hydrogen, synthetic natural gas, and dimethyl ether [11]. However, the production of the above-mentioned compounds is related to the syngas composition. Some applications are mentioned below:

3.3.1. Heat and power generation

The generation of heat and power from syngas in combined heat and power systems commonly known as cogeneration systems is not considered as a transformation technology. By contrast, this is considered as a process that enables to obtain useful energy from the syngas through thermodynamic cycles. These cogeneration processes normally employ equipment such as turbines, compressors, generators, boilers, and heat exchangers, which are strategically arranged to obtain high energy efficiencies [33,34].

3.3.2. Fischer–Tropsch process

This process involves the chemical transformation of syngas to produce hydrocarbons in the liquid phase through highly exothermic reactions. The Fischer–Tropsch process can be described as the catalytic conversion of H_2 and CO to hydrocarbon compounds such as diesel. This process has been implemented in different plants at the industrial level for the production of different types of olefins and paraffins [26,35].

3.3.3. Syngas fermentation

Syngas fermentation involves the employment of CO and CO_2 present in the syngas to produce ethanol using the following microorganisms: *Clostridium ljungdahlii* and *Clostridium autoethanogenum* [36,37]. An advantage of this process is its low energy requirements to carry out the fermentation and the application of the well-established techniques of ethanol separation and dehydration [38]. However, major challenges from an engineering point of view have been required to improve production yields and to improve aspects related to the mass and energy transfer.

4. Case of study

4.1. Lignocellulosic feedstock

Biogas and syngas production was simulated using a lignocellulosic residue susceptible to be used in both the AD and gasification processes. Afterwards, these gases were used to produce heat and power in a cogeneration system with the goal to analyze from a techno-economic point of view their potential to be used for this application. The lignocellulosic material employed to perform the simulations was the OPR, which is obtained from the Colombian oil

Table 4
Chemical characterization and proximate analysis of the oil palm rachis.

Chemical Composition [% w/w][a]		Proximate analysis [% w/w][a]	
Moisture	9.68 ± 0.39	Moisture	11.71 ± 0.52
Extractives*	14.08 ± 0.91	Fixed Carbon*	14.72 ± 0.91
Cellulose*	37.92 ± 4.39	Volatile Matter*	80.45 ± 0.21
Hemicellulose*	20.88 ± 3.37	Ash*	4.81 ± 1.12
Lignin*	15.64 ± 0.67	HHV (MJ/kg)	18.56
Ash*	1.80 ± 0.11		

* Values given in dry basis.
[a] The chemical composition and proximate analysis were determined in triplicate.

palm crop. It was characterized in terms of its chemical composition (i.e., cellulose, hemicellulose, and lignin) as well as its volatile matter, fixed carbon, and ash content by following the procedures described by Moncada et al. [102] and Daza et al. [103] as well as the ASTM standard D1173–01. The characterization of this raw material is shown in Table 4.

4.2. Simulation procedure and processes description

The simulation of the biogas and syngas production, as well as the heat and power generation from these energy vectors, was performed using an OPR mass flow rate of 20 ton/h (dry basis) as feedstock. The simulation was accomplished using Aspen Plus software v8.6 (Aspen Technology Inc. USA) [104]. The nonrandom two-liquid (NRTL) activity model and Peng–Robinson equation of state were used to describe the behavior of the liquid and vapor phases [105,106]. In addition, the thermodynamic properties reported by the National Research Energy Laboratory (NREL) were used to introduce components such as cellulose, hemicellulose, and lignin which are not available in the software database [107]. A brief description of the gasification, AD, and cogeneration processes is given below.

4.2.1. Gasification process

The OPR gasification was simulated using two stages. The first one is the particle size reduction from 150 mm to 20 mm using the crusher model available in the solids section of the software. The second one is the OPR gasification using an air-blown downdraft gasifier operating at an ER of 0.25. Nevertheless, the software does not have a gasifier model. For this reason, its simulation was divided into three steps: pyrolysis, combustion, and reduction.

The pyrolysis step involves raw material devolatilization under anoxic conditions. This was simulated using the stoichiometric approach reported by Sharma [108] applied to the lignocellulosic components (i.e., cellulose, hemicellulose, and lignin). Moreover, it was considered that this process occurs at 600°C. The main products obtained were char (C), CO, CO_2, H2, H_2O, light hydrocarbons modeled as CH_4, and heavy hydrocarbons (i.e., tar) modeled with the empirical formula ($C_6H_6O_{0.2}$) [108,109]. The combustion was modeled using the kinetic expressions reported by Tinaut et al. [110] using the RYIELD block. The char gasification to produce CO_2, CO, H_2, and CH_4 was simulated using a RGIBBS reactor [100]. Finally, the remaining char and ashes from the gasification process were separated from the syngas using a cyclone. The overall syngas production process described above is presented in Fig. 1.

4.2.2. Anaerobic digestion process

The biogas production was simulated considering the LHW pretreatment of the lignocellulosic raw material and the water scrubbing cleaning method. The LHW pretreatment was simulated according to the conditions reported by Goh et al. [111] (i.e., 175°C, 10 bar, and a liquid-to-solid ratio of 8.0). The AD process was simulated considering the yields and conditions reported by Kaparaju et al. [48] (i.e., 50°C and the VS of substrate-to-inoculum ratio of 46.92%w). The above stages were simulated using the RSTOIC blocks available in the software. Finally, biogas upgrading was performed using the water scrubbing technology [29]. The equipment involved in the biogas purification stage were specified according to Cozma et al. [59]. The process flow diagram of the biogas production is presented in Fig. 2.

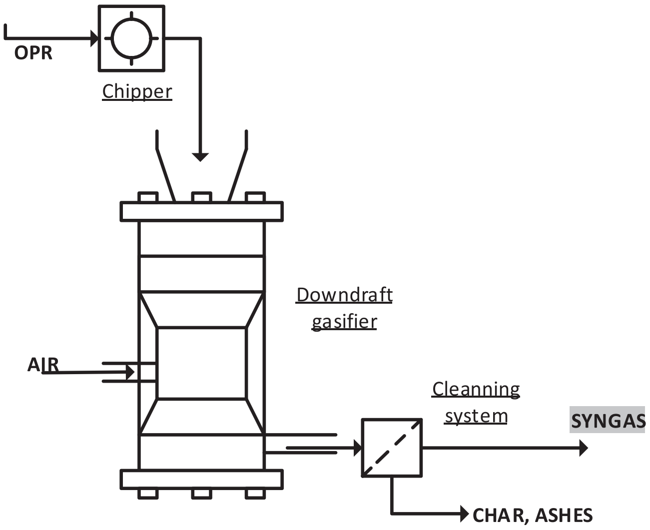

Fig. 1. Process flow diagram of OPR gasification using a downdraft gasifier.

4.2.3. Cogeneration system

The simulated cogeneration plant is composed of a gas turbine, a heat recovery steam generator (HRSG), and a steam turbine. The flow diagram of the system is shown in Fig. 3, and each of these elements is described as follows. The gas turbine uses the fuel gases generated by the gasification and AD processes to produce power and fuel. It is composed of a series of two compressors, one burner, and two turbines in an intercooling, reheating, and regenerative cycle (ICRHR). This type of turbine was selected to be used in the simulation because of the high thermal efficiencies compared with those of the simple cycle gas turbines. The ICRHR gas turbine uses atmospheric air (288 K, 1 bar) in excess to ensure complete combustion of syngas or upgraded biogas. The compressors used in the cycle, as well as the turbines, have the same pressure ratio with the goal to improve the power requirements [112]. The combustor was simulated using an RSTOIC block. The main characteristics of the simulated gas turbine are presented in Table 5.

The outlet gases from the gas turbine were mixed and combusted with more fuel (i.e., syngas or upgraded biogas), thus resulting in the increase in its temperature. This secondary combustion was performed in a firing system that was modeled as an RSTOIC block. The hot gases from this system were carried out to the HRSG system and used to produce steam at different pressures. The HRSG system was simulated according to Zheng et al. [113]. From this process, HP-Steam at 60 bar, IP-Steam at 30 bar, and LP-Steam at 3 bar were obtained.

4.3. Economic assessment

The economic assessment was performed using the commercial software Aspen Process Economic Analyzer (Aspen Technology Inc., USA) to calculate the capital expenditures (CAPEX) (i.e., equipment costs) and operational expenditures (OPEX) (i.e., utilities, maintenance, and operating labor cost) for both simulations [75,103]. As input data, the results of the material and energy balances were supplied. In addition, the following data were considered to complete the analysis in the Colombian context. The water market price was 0.74 USD/m^3,

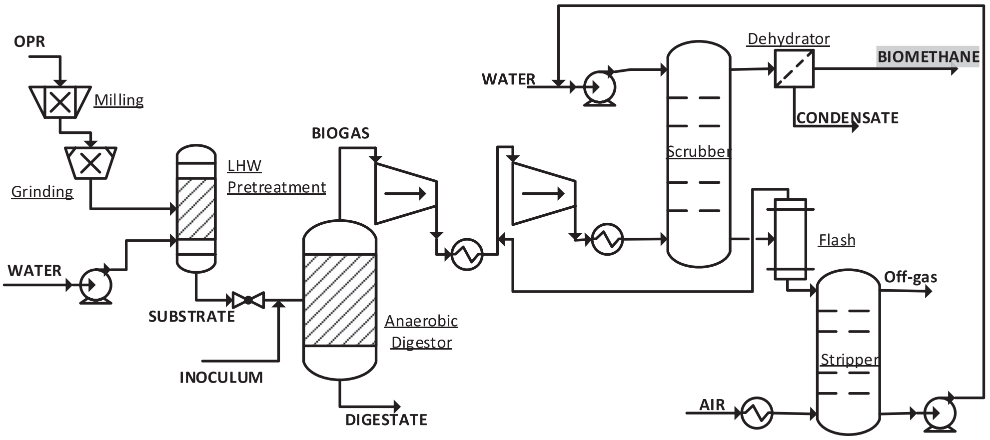

Fig. 2. Process flow diagram of biomethane production with liquid hot water pretreatment [59].

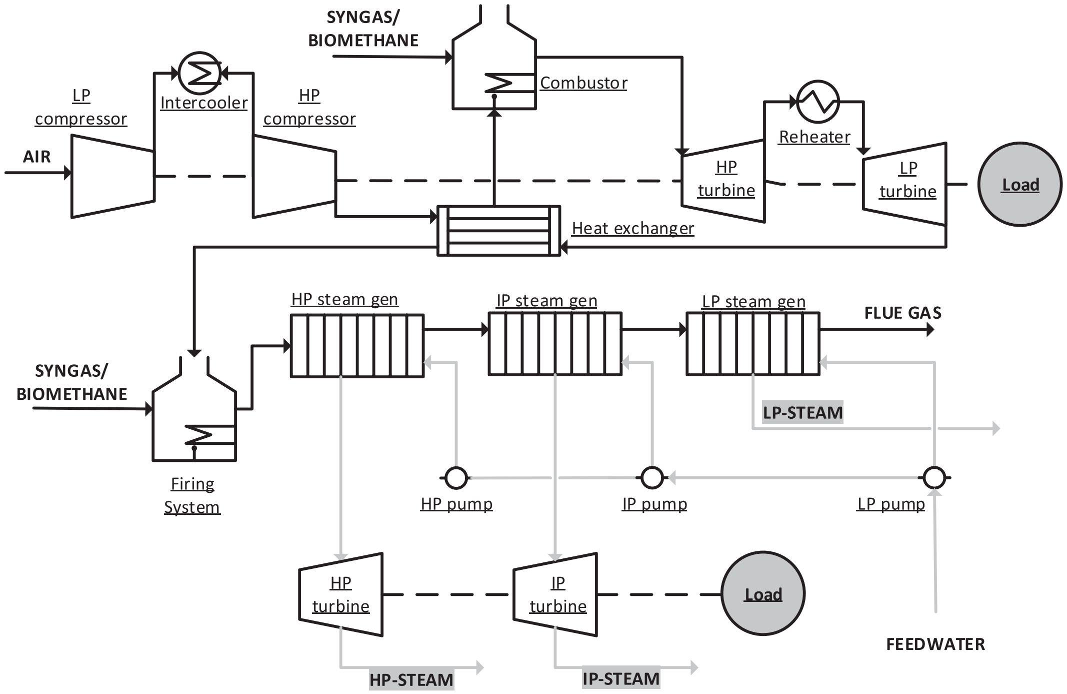

Fig. 3. Process flow diagram of the cogeneration system plant.

HP-steam market price was 9.86 USD/ton, IP-steam market price was 8.18 USD/ton, LP-steam market price was 1.57 USD/ton, electricity value market price was 0.1 USD/kWh [114,115], and the price of the raw material considered was 19.40 USD/ton. The labor wages for operators and supervisors were 2.56 USD/h and 5.12 USD/h, respectively [115]. In addition, this analysis was performed considering the straight-line method for the capital depreciation calculation involving an annual interest rate of 17.0% and a 25.0% of tax rate in a 10-year period. The environmental assessment was achieved through the calculation of the global warming potential of all scenarios defined as the mass ratio between the CO_2 emissions and raw material [111].

Table 5
Main characteristics of the simulated gas turbine [112].

Item	Value	Item	Value
Compressors pressure ratio	10.0	Turbine pressure ratio	5.0
Compressor isentropic efficiency (%)	85.0	Turbines isentropic efficiency (%)	90
Intercooler pressure drop (%)	1.0	Reheater pressure drop (%)	2.0
Boiler pressure drop (%)	5.0	Turbine entrance temperature (K)	1600
Air-to-fuel ratio	6.4	Equivalence ratio	4.0

4.4. Results and discussion

4.4.1. Process simulation

The syngas composition obtained from the simulation was 13.5%, 15.5%, 9.0%, and 60.0% of CO, CO_2, H_2, and N_2, respectively. These results are in agreement with the syngas composition from oil palm fronds reported by Atnaw et al. [91]. Additionally, the syngas production exhibited the highest mass yield with regard to fuel and steam production. However, this situation is given by the high air flow that was needed to carry out a complete combustion of the syngas in the combustion chamber inside of the gas turbine to maintain an ER of 4.0. On the other hand, the upgraded biogas composition was 94.4%.

Table 6
Mass yields of the simulated processes.

Scenario	Fuel yield [kg fuel/kg OPR]	Total steam yield [kg steam/kg OPR]
Syngas	3.6	3.5
Upgraded Biogas	0.3	2.4

These results are similar to the syngas composition reported by Cozma et al. [59]. The mass yields of the simulated processes are given in Table 6.

The above results do not imply that the syngas production process is the best option to produce heat and power in the proposed cogeneration plant. The above is performed to provide a series of characteristics from different points of view to identify the advantages and disadvantages that each technology can offer. In this sense, the energy analysis can provide more information related to the considered scenarios. The energy analysis was carried out calculating the LHV of the syngas and biomethane generated as well as the thermal efficiency (n_{th}) of the gas turbine, the net energy value, and the global efficiency of the process. These results are shown in Table 7.

The above results show that the upgraded biogas has a higher LHV than that of the raw syngas. For this reason, the generated electrical power is higher when the cogeneration system is complemented with the AD technology. However, the net energy value of the gasification process is higher than that of the AD process. The above can be attributed to the low energy demand of the thermochemical process compared with the high energy demand of the biotechnological route. Finally, according to the simulation results, it is possible to observe that the syngas can be used to produce steam, whereas the upgraded biogas can be used to produce electricity. Therefore, both technologies have the potential to be used as energy carriers to produce heat and power. However, their use will depend on the final purpose of these utilities (e.g., industrial services or urban development).

4.4.2. Economic assessment

The CAPEX and OPEX obtained from the economic evaluation indicate that the syngas production and its subsequent use for steam and electricity generation have a lower CAPEX an OPEX. On the other hand, the simulation that considers the upgraded biogas to produce steam and electricity has the highest CAPEX and OPEX. Moreover, it is possible to note that the gasification technology requires less equipment than the AD process. However, the upgraded biogas heating value is higher than that of the produced syngas. This fact can be observed in total investment costs associated with each project. The overall process that involves the syngas production and its utilization for energy purposes has a total capital investment cost of USD 32 million, whereas the overall upgraded biogas production and its use has a total capital investment cost of USD 85 million. Finally, according to the generated power, it was possible to propose the use of the SGT-400 gas turbine to reach the generated power in the syngas simulation and the use of a SGT A-45 TR gas turbine to cover the power generated by the upgraded biogas simulation.

Table 7
Energy indicators calculated for each simulation.

Scenario	LHV [kJ/kg]	n_{th} [%]	Generated Power [MWe[a]]	NEV [kJ/kg OPR]
Syngas	7.0	41.8	23.7	28574
Upgraded Biogas	47.4	52.2	43.5	23432

[a] MWe: Electrical megawatt.

5. Conclusions

Biogas and syngas are two energy carries that can be used to produce heat and power to supply different energy needs. However, the use of biogas obtained from lignocellulosic biomass has received more attention than the syngas production using these types of raw materials. This can be explained because syngas has been traditionally used to produce value-added products in the chemical industry using coal as the main raw material. In addition, differences related to their heating values suggest that biogas is better to achieve a high energy production. Nevertheless, the total investment costs and the total operating costs are higher to produce biogas than syngas. Therefore, a careful selection of these energy vectors must be performed considering energy needs and economic issues. Finally, it is possible to mention that both, syngas and biogas, will be a fundamental part of the energy market in the near future.

Conflict of interests

The authors declare that they do not have potential conflict of interests.

Financial support

This work was supported by the Departamento Administrativo de Ciencia, Tecnología e Innovación (Colciencias, grant number 761 Jóvenes Investigadores), the research project entitled “Small-Scale Integrated biorefineries to produce an optimal range of bio-products from a variety of rural agricultural and agro-industrial residues with a minimum consumption of fossil fuels energy” (grant number 202010011331), and the research project entitled “Evaluación tecno-económica y ambiental de una biorrefinería utilizando los residuos del café” (grant number 202010014230).

References

[1] Singh R, Krishna BB, Mishra G, Kumar J, Bhaskar T. Strategies for selection of thermo-chemical processes for the valorisation of biomass. Renew Energy 2016: 1–12. https://doi.org/10.1016/j.renene.2016.03.023.
[2] BP. BP statistical review of world energy [London, UK] ; 2016.
[3] Renewable energy policy network for the 21st century (REN21). Renewables 2016 global status report. Paris: Renewable energy policy network for the 21st Century; 2016.
[4] Sawatdeenarunat C, Surendra KC, Takara D, Oechsner H, Khanal SK. Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. Bioresour Technol 2015;178:178–86. https://doi.org/10.1016/j.biortech.2014.09.103.
[5] Blazev Anco S. Energy security for the 21st century. CRC Press; 2015.
[6] Mehdi BJ, Slim BY. The role of renewable energy and agriculture in reducing CO_2 emissions: Evidence for North Africa countries. Ecol Indic 2017;74:295–301. https://doi.org/10.1016/j.ecolind.2016.11.032.
[7] Gupta VK, Potumarthi R, O'Donovan A, Kubicek CP, Sharma GD, Tuohy MG. Bioenergy research: An overview on technological developments and bioresources. In: Gupta VG, Tuohy M, Kubicek CP, Saddler J, Xu F, editors. Bioenergy Res. Adv. Appl. 1st ed. Elsevier B.V.; 2014. p. 23–47.
[8] International Energy Agency (IEA). Renewable energy. https://www.iea.org/about/faqs/renewableenergy/, Accessed date: 22 August 2017.
[9] Solarte Toro JC, Cardona Alzate CA. The environmental aspects of bioenergy production in Peru. Peru Polit. Soc. Environ. Issues. Nova Science Publishers; 2017.
[10] Demirbas A. Biofuels securing the planet's future energy needs. Energy Convers Manag 2009;50:2239–49. https://doi.org/10.1016/j.enconman.2009.05.010.
[11] Williams CL, Dahiya A, Porter P. In: Dahiya Anju, editor. Chapter 1 — Introduction to bioenergyBioenergy; 2015. p. 5–36. https://doi.org/10.1016/b978-0-12-407909-0.00001-8.
[12] Fatih Demirbas M. Biorefineries for biofuel upgrading: A critical review. Appl Energy 2009;86:S151–61. https://doi.org/10.1016/j.apenergy.2009.04.043.
[13] Claassen PAM, van Lier JB, Lopez Contreras AM, et al. Utilisation of biomass for the supply of energy carriers. Appl Microbiol Biotechnol 1999;52:741–55. https://doi.org/10.1007/s002530051586.
[14] Mohsin R, Majid ZA, Shihnan AH, Nasri NS, Sharer Z. Effect of biodiesel blends on engine performance and exhaust emission for diesel dual fuel engine. Energy Convers Manag 2014;88:821–8. https://doi.org/10.1016/j.enconman.2014.09.027.
[15] Demirbas A. Biorefineries: Current activities and future developments. Energy Convers Manag 2009;50:2782–801. https://doi.org/10.1016/j.enconman.2009.06.035.
[16] U. S. Environmental Protection Agency. Biomass combined heat and power catalog of technologies [USA] ; 2007.

[17] Raposo F, De La Rubia MA, Fernández-Cegrí V, Borja R. Anaerobic digestion of solid organic substrates in batch mode: an overview relating to methane yields and experimental procedures. Renew Sustain Energy Rev 2012;16:861–77. https://doi.org/10.1016/j.rser.2011.09.008.

[18] Goyal HB, Seal D, Saxena RC. Bio-fuels from thermochemical conversion of renewable resources: A review. Renew Sustain Energy Rev 2008;12:504–17. https://doi.org/10.1016/j.rser.2006.07.014.

[19] Deublein D, Steinhauser A. Biogas from waste and renewable resources: An introduction. Wiley; 2010.

[20] Alzate CA, Chejne F, Valdés CF, Berrio A, La Cruz JD, Londoño CA. Co-gasification of pelletized wood residues. Fuel 2009;88:437–45. https://doi.org/10.1016/j.fuel.2008.10.017.

[21] Qian Y, Sun S, Ju D, Shan X, Lu X. Review of the state-of-the-art of biogas combustion mechanisms and applications in internal combustion engines. Renew Sustain Energy Rev 2017;69:50–8. https://doi.org/10.1016/j.rser.2016.11.059.

[22] Mondal P, Dang GS, Garg MO. Syngas production through gasification and cleanup for downstream applications — Recent developments. Fuel Process Technol 2011; 92:1395–410. https://doi.org/10.1016/j.fuproc.2011.03.021.

[23] Ullah I, Ha M, Othman D, Hashim H, Matsuura T, Ismail AF, et al. Biogas as a renewable energy fuel — A review of biogas upgrading, utilisation and storage. 2017;150: 277–94. https://doi.org/10.1016/j.enconman.2017.08.035.

[24] Seadi TA, Rutz D, Prassl H, Köttner M, Finsterwalder T, Volk S, et al. Biogas handbook; 2008 https://doi.org/10.1533/9780857097415.1.85.

[25] Surendra KC, Takara D, Hashimoto AG, Khanal SK. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renew Sustain Energy Rev 2014;31:846–59. https://doi.org/10.1016/j.rser.2013.12.015.

[26] Da costa gomez C. Biogas as an energy option: An overview. In: Wellinger A, Patrick Murphy J, Baxter D, editors. Biogas Handb. Sci. Prod. Appl. Woodhead; 2013. p. 1–16.

[27] Solarte-Toro J, Mariscal J, Aristizábal B. Evaluación de la digestión y co-digestión anaerobia de residuos de comida y de poda en bioreactores a escala laboratorio. Rev Ión 2017;30:105–16.

[28] Lemos Chernicharo CA. Anaerobic reactors. IWA publications; 2007.

[29] Beil M, Beyrich W. Biogas upgrading to biomethane. Biogas Handbook; 2013. p. 342–77. https://doi.org/10.1533/9780857097415.3.342.

[30] Angelidaki I, Alves M, Bolzonella D, Borzacconi L, Campos JL, Guwy AJ, et al. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays. Water Sci Technol 2009;595. https://doi.org/10.2166/wst.2009.040.

[31] Cotana F, Cavalaglio G, Petrozzi A, Coccia V. Lignocellulosic biomass feeding in biogas pathway: State of the art and plant layouts. Energy Procedia 2015;81: 1231–7. https://doi.org/10.1016/j.egypro.2015.12.334.

[32] Dussadee N, Ramaraj R, Cheunbarn T. Biotechnological application of sustainable biogas production through dry anaerobic digestion of napier grass. 3 Biotech 2017;7. https://doi.org/10.1007/s13205-017-0646-4.

[33] Gerssen-Gondelach SJ, Saygin D, Wicke B, Patel MK, Faaij APC. Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renew Sustain Energy Rev 2014;40:964–98. https://doi.org/10.1016/j.rser.2014.07.197.

[34] Zheng Y, Zhao J, Xu F, Li Y. Pretreatment of lignocellulosic biomass for enhanced biogas production. Prog Energy Combust Sci 2014;42:35–53. https://doi.org/10.1016/j.pecs.2014.01.001.

[35] Haghighi Mood S, Hossein Golfeshan A, Tabatabaei M, Salehi Jouzani G, Najafi GH, Gholami M, et al. Lignocellulosic biomass to bioethanol, a comprehensive review with a focus on pretreatment. Renew Sustain Energy Rev 2013;27:77–93. https://doi.org/10.1016/j.rser.2013.06.033.

[36] Al Seadi T, Rutz D, Janssen R, Drosg B. Biomass resources for biogas production. Biogas Handbook. Sci. Prod. Appl. IWA Publications; 2013. p. 19–51.

[37] Ferreira LC, Donoso-Bravo A, Nilsen PJ, Fdz-Polanco F, Pérez-Elvira SI. Influence of thermal pretreatment on the biochemical methane potential of wheat straw. Bioresour Technol 2013;143:251–7. https://doi.org/10.1016/j.biortech.2013.05.065.

[38] Nhuchhen DR, Abdul Salam P. Estimation of higher heating value of biomass from proximate analysis: A new approach. Fuel 2012;99:55–63. https://doi.org/10.1016/j.fuel.2012.04.015.

[39] Li Y, Zhang R, Liu X, Chen C, Xiao X, Feng L, et al. Evaluating methane production from anaerobic mono- and co-digestion of kitchen waste, corn stover, and chicken manure. Energy Fuels 2013;27:2085–91. https://doi.org/10.1021/ef400117f.

[40] Janke L, Leite A, Nikolausz M, Schmidt T, Liebetrau J, Nelles M, et al. Biogas production from sugarcane waste: Assessment on kinetic challenges for process designing. Int J Mol Sci 2015;16:20685–703. https://doi.org/10.3390/ijms160920685.

[41] Contreras LM, Schelle H, Sebrango CR, Pereda I. Methane potential and biodegradability of rice straw, rice husk and rice residues from the drying process. Water Sci Technol 2012;65:1142. https://doi.org/10.2166/wst.2012.951.

[42] Nyakuma BB, Johari A, Ahmad A, Abdullah TAT. Comparative analysis of the calorific fuel properties of empty fruit bunch fiber and briquette. Energy Procedia 2014;52:466–73. https://doi.org/10.1016/j.egypro.2014.07.099.

[43] Thermophilic anaerobic co-digestion of oil palm empty fruit bunches with palm oil mill effluent for efficient biogas production, Appl Energy 2012;93:648–54. https://doi.org/10.1016/j.apenergy.2011.12.092.

[44] Teghammar A, Forgács G, Sárvári Horváth I, Taherzadeh MJ. Techno-economic study of NMMO pretreatment and biogas production from forest residues. Appl Energy 2014;116:125–33. https://doi.org/10.1016/j.apenergy.2013.11.053.

[45] Qiao W, Yan X, Ye J, Sun Y, Wang W, Zhang Z. Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. Renew Energy 2011;36:3313–8. https://doi.org/10.1016/j.renene.2011.05.002.

[46] Pretreatment of oil palm empty fruit bunch (OPEFB) by N-methylmorpholine-N-oxide (NMMO) for biogas production: Structural changes and digestion improvement, Bioresour Technol 2013;128:461–6. https://doi.org/10.1016/j.biortech.2012.10.088.

[47] Dehghani M, Karimi K, Sadeghi M. Pretreatment of rice straw for the improvement of biogas production. Energy Fuels 2015;29:3770–5. https://doi.org/10.1021/acs.energyfuels.5b00718.

[48] Kaparaju P, Serrano M, Thomsen AB, Kongjan P, Angelidaki I. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. Bioresour Technol 2009;100:2562–8. https://doi.org/10.1016/j.biortech.2008.11.011.

[49] Dongyan Y, Yunzhi P, Hairong Y, Shulin C, Jingwei M, Liang Y, et al. Enhancing biogas production from anaerobically digested wheat straw through ammonia pretreatment. Chin J Chem Eng 2014;22:576–82. https://doi.org/10.1016/s1004-9541(14)60075-6.

[50] Zhu J, Wan C, Li Y. Enhanced solid-state anaerobic digestion of corn stover by alkaline pretreatment. Bioresour Technol 2010;101:7523–8. https://doi.org/10.1016/j.biortech.2010.04.060.

[51] Simo W, Jong E, Kapseu C. Improving biogas production of sugarcane bagasse by hydrothermal pretreatment. Chem Biomol Eng 2016;3:1–21. https://doi.org/10.11648/J.CBE.20160103.11.

[52] Das A, Mondal C, Roy S. Kinetic study of biogas recovery from thermo-chemically pre-treated rice husk. Indian Chem Eng 2017:1–17. https://doi.org/10.1080/00194506.2017.1374218.

[53] Dehghani M, Karimi K, Sadeghi M. Pretreatment of rice straw for the improvement of biogas production. Energy Fuel 2015;29:3770–5. https://doi.org/10.1021/acs.energyfuels.5b00718.

[54] Song Z, Yang G, Guo Y, Zhang T. Comparison of two chemical pretreatments of rice straw for biogas production by anaerobic digestion. BioResources 2012;7:3223–36. https://doi.org/10.15376/biores.7.3.3223-3236.

[55] Carrillo Nieves D, Karimi K, Sárvári Horváth I. Improvement of biogas production from oil palm empty fruit bunches (OPEFB). Ind Crop Prod 2011;34:1097–101. https://doi.org/10.1016/j.indcrop.2011.03.022.

[56] Gis W, Samson-bręk I. Review of technology for cleaning biogas to natural gas quality. Automot Ind Inst PIMOT 2012;2012:33–9.

[57] QieSun Hailong Li, Yan Jinying, Liu Longcheng, Yu Zhixin, Yu Xinhai. Selection of appropriate biogas upgrading technology — A review of biogas cleaning, upgrading and utilisation. Renew Sustain Energy Rev 2015;51:521–32. https://doi.org/10.1016/j.rser.2015.06.029.

[58] Basu P. Biomass gasification and pyrolysis: Practical design. 1st ed. Kidlington, Oxford: Elsevier; 2010.

[59] Cozma P, Wukovits W, Mămăligă I, Friedl A, Gavrilescu M. Modeling and simulation of high pressure water scrubbing technology applied for biogas upgrading. Clean Technol Environ Policy 2015;17:373–91. https://doi.org/10.1007/s10098-014-0787-7.

[60] Masebinu SO, Aboyade A, Muzenda E. Enrichment of biogas for use as vehicular fuel: A review of the upgrading techniques. Int J Res Chem Metall Civ Eng 2014; 1:89–98.

[61] Le DM, Sørensen HR, Meyer AS. Elemental analysis of various biomass solid fractions in biorefineries by X-ray fluorescence spectrometry. Biomass Bioenergy 2017;97:70–6. https://doi.org/10.1016/j.biombioe.2016.12.018.

[62] Petersson A. Biogas cleaning. In: Wellinger A, Murphy P, Baxter D, editors. Biogas Handb. Sci. Prod. Appl. IWA Publications; 2013. p. 329–41.

[63] Wellinger A, Murphy J, Baxter D. The biogas handbook; 2013. https://doi.org/10.1533/9780857097415.1.85.

[64] Zhang C, Su H, Baeyens J, Tan T. Reviewing the anaerobic digestion of food waste for biogas production. Renew Sustain Energy Rev 2014;38:383–92. https://doi.org/10.1016/j.rser.2014.05.038.

[65] Woon KS, Lo IMC, Chiu SLH, Yan DYS. Environmental assessment of food waste valorization in producing biogas for various types of energy use based on LCA approach. Waste Manag 2016;50:290–9. https://doi.org/10.1016/j.wasman.2016.02.022.

[66] Koornneef J, van Breevoort P, Noothout P, Hendriks C, Luning uchien, Camps A. Global potential for biomethane production with carbon capture, transport and storage up to 2050. Energy Procedia 2013;37:6043–52. https://doi.org/10.1016/j.egypro.2013.06.533.

[67] Caballero A, Pérez PJ. Methane as raw material in synthetic chemistry: The final frontier. Chem Soc Rev 2013;42:8809. https://doi.org/10.1039/c3cs60120j.

[68] Bagi Z, Ács N, Böjti T, Kakuk B, Rákhely G, Strang O, et al. Biomethane: The energy storage, platform chemical and greenhouse gas mitigation target. Anaerobe 2017; 46:13–22. https://doi.org/10.1016/j.anaerobe.2017.03.001.

[69] Rezaiyan J, Cheremisinoff NP. Gasification technologies: A primer for engineers and scientists. Taylor & Francis; 2005.

[70] Matsakas L, Gao Q, Jansson S, Rova U, Christakopoulos P. Green conversion of municipal solid wastes into fuels and chemicals. Electron J Biotechnol 2017;26: 69–83. https://doi.org/10.1016/j.ejbt.2017.01.004.

[71] Gasification and Syngas Technologies Council (GSTC). The gasification industry. http://www.gasification-syngas.org/resources/the-gasification-industry/, Accessed date: 1 August 2017.

[72] Bach Q-V, Tran K-Q. Dry and wet torrefaction of woody biomass — A comparative study on combustion kinetics. Energy Procedia 2015;75:150–5. https://doi.org/10.1016/j.egypro.2015.07.270.

[73] Uzun BB, Pütün AE, Pütün E. Fast pyrolysis of soybean cake: Product yields and compositions. Bioresour Technol 2006;97:569–76. https://doi.org/10.1016/j.biortech.2005.03.026.

[74] Bain R, Broer K. Gasification. In: Brown RC, editor. Thermochemical processing of biomass: Conversion into fuels, chemicals and power. Wiley; 2011. p. 47–77.

[75] Cardona Alzate CA, Solarte Toro JC, Peña ÁG. Fermentation, thermochemical and catalytic processes in the transformation of biomass through efficient biorefineries. Catal Today 2018;302:61–72. https://doi.org/10.1016/j.cattod.2017.09.034.

[76] Barman NS, Ghosh S, De S. Gasification of biomass in a fixed bed downdraft gasifier — A realistic model including tar. Bioresour Technol 2012;107:505–11. https://doi.org/10.1016/j.biortech.2011.12.124.

[77] Gil J, Corella J, Aznar MP, Caballero MA. Biomass gasification in atmospheric and bubbling fluidized bed: Effect of the type of gasifying agent on the product distribution. Biomass Bioenergy 1999;17:389–403. https://doi.org/10.1016/s0961-9534(99)00055-0.

[78] McKendry P. Energy production from biomass (part 3): Gasification technologies. Bioresour Technol 2002;83:55–63. https://doi.org/10.1016/s0960-8524(01)00120-1.

[79] Molino A, Chianese S, Musmarra D. Biomass gasification technology: The state of the art overview. J Energy Chem 2016;25:10–25. https://doi.org/10.1016/j.jechem.2015.11.005.

[80] Couto N, Rouboa A, Silva V, Monteiro E, Bouziane K. Influence of the biomass gasification processes on the final composition of syngas. Energy Procedia 2013; 36:596–606. https://doi.org/10.1016/j.egypro.2013.07.068.

[81] Ahmed TY, Ahmad MM, Yusup S, Inayat A, Khan Z. Mathematical and computational approaches for design of biomass gasification for hydrogen production: A review. Renew Sustain Energy Rev 2012;16:2304–15. https://doi.org/10.1016/j.rser.2012.01.035.

[82] Jang DH, Kim HT, Lee C, Kim SH, Doherty W, Reynolds A, et al. Gasification of hazelnut shells in a downdraft gasifier. Energy 2002;27:415–27. https://doi.org/10.1016/j.energy.2010.04.051.

[83] Patra TK, Sheth PN. Biomass gasification models for downdraft gasifier: A state-of-the-art review. Renew Sustain Energy Rev 2015;50:583–93. https://doi.org/10.1016/j.rser.2015.05.012.

[84] Kirubakaran V, Sivaramakrishnan V, Nalini R, Sekar T, Premalatha M, Subramanian P. A review on gasification of biomass. Renew Sustain Energy Rev 2009;13:179–86. https://doi.org/10.1016/j.rser.2007.07.001.

[85] Rollinson A, Williams O. Experiments on torrefied wood pellet: study by gasification and characterization for waste biomass to energy applications. R Soc Open Sci 2016; 3:150578. https://doi.org/10.1098/rsos.150578.

[86] Demirbas A. Effects of moisture and hydrogen content on the heating value of fuels. Energy Sources Part A Recover Util Environ Eff 2007;29:649–55. https://doi.org/10.1080/009083190957801.

[87] Yin C-Y. Prediction of higher heating values of biomass from proximate and ultimate analyses. Fuel 2011;90:1128–32. https://doi.org/10.1016/j.fuel.2010.11.031.

[88] Mallick D, Mahanta P, Moholkar VS. Co-gasification of coal and biomass blends: Chemistry and engineering. Fuel 2017;204:106–28. https://doi.org/10.1016/j.fuel.2017.05.006.

[89] Soponpongpipat N, Sittikul D, Comsawang P. Prediction model of higher heating value of torrefied biomass based on the kinetics of biomass decomposition. J Energy Inst 2016;89:425–35. https://doi.org/10.1016/j.joei.2015.02.011.

[90] Konda R, Sulaiman S, Ariwahjoedi B. Syngas production from gasification of oil palm fronds with an updraft gasifier. J Appl Sci 2012;12:2555–61. https://doi.org/10.1063/1.4704311.

[91] Atnaw S, Sulaiman S, Yusup S. Syngas production from downdraft gasification of oil palm fronds. Energy 2013;61:491–501.

[92] Kitzler H, Pfeifer C, Hofbauer H. Pressurized gasification of woody biomass — Variation of parameter. Fuel Process Technol 2011;92:908–14. https://doi.org/10.1016/j.fuproc.2010.12.009.

[93] Berrueco C, Recari J, Güell BM, del Alamo G. Pressurized gasification of torrefied woody biomass in a lab scale fluidized bed. Energy 2014;70:68–78. https://doi.org/10.1016/j.energy.2014.03.087.

[94] Cayan FN, Zhi M, Pakalapati SR, Celik I, Wu N, Gemmen R. Effects of coal syngas impurities on anodes of solid oxide fuel cells. J Power Sources 2008;185: 595–602. https://doi.org/10.1016/j.jpowsour.2008.06.058.

[95] Lee SH, Yoon SJ, Ra HW, Son Y Il, Hong JC, Lee JG. Gasification characteristics of coke and mixture with coal in an entrained-flow gasifier. Energy 2010;35:3239–44. https://doi.org/10.1016/j.energy.2010.04.007.

[96] Murthy BN, Sawarkar AN, Deshmukh NA, Mathew T, Joshi JB. Petroleum coke gasification: A review. Can J Chem Eng 2014;92:441–68. https://doi.org/10.1002/cjce.21908.

[97] Niu M, Huang Y, Jin B, Wang X. Simulation of syngas production from municipal solid waste gasification in a bubbling fluidized bed using aspen plus. Ind Eng Chem Res 2013;52:14768–75. https://doi.org/10.1021/ie400026b.

[98] Grace JR, Chaouki J, Pugsley T. Fluidized bed reactor. In: Lee S, Henthorn KH, editors. Part. Technol. Appl. CRC Press; 2012. p. 208. https://doi.org/10.1017/cbo9781107415324.004.

[99] Asadullah M. Barriers of commercial power generation using biomass gasification gas: A review. Renew Sustain Energy Rev 2014;29:201–15. https://doi.org/10.1016/j.rser.2013.08.074.

[100] García CA, Betancourt R, Cardona CA. Stand-alone and biorefinery pathways to produce hydrogen through gasification and dark fermentation using Pinus Patula. J Environ Manage 2017;203(2):695–703. https://doi.org/10.1016/j.jenvman.2016.04.001.

[101] Brown RC. Thermochemical processing of biomass: Conversion into fuels, chemicals and power. Wiley; 2011 https://doi.org/10.1002/9781119990840.

[102] Quintero JA, Moncada J, Cardona CA. Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: A process simulation approach. Bioresour Technol 2013;139:300–7. https://doi.org/10.1016/j.biortech.2013.04.048.

[103] Daza Serna LV, Solarte Toro JC, Serna Loaiza S, Chacón Perez Y, Cardona Alzate CA. Agricultural waste management through energy producing biorefineries: The colombian case. Waste Biomass Valorization 2016:1–10. https://doi.org/10.1007/s12649-016-9576-3.

[104] Ahmad AA, Zawawi NA, Kasim FH, Inayat A, Khasri A. Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. Renew Sustain Energy Rev 2016;53: 1333–47. https://doi.org/10.1016/j.rser.2015.09.030.

[105] Graaf GH, Sijtsema PJJM, Stamhuist EJ, Joostes GEH. Chemical equilibria in methanol synthesis. Chem Eng Sci 1986;41:2883–90. https://doi.org/10.1016/0009-2509(86)80019-7.

[106] Graaf GH, Stamhuis EJ, Beenackers AACM. Kinetics of low-pressure methanol synthesis. Chem Eng Sci 1988;43:3185–95. https://doi.org/10.1016/0009-2509(88)85127-3.

[107] Wooley RJ, Putsche V. Development of an aspen plus property database for biofuels components. National Renewable Energy Laboratory; 1996.

[108] Sharma AK. Modeling and simulation of a downdraft biomass gasifier 1. Model development and validation. Energy Convers Manag 2011;52:1386–96. https://doi.org/10.1016/j.enconman.2010.10.001.

[109] Patra TK, Nimisha KR, Sheth PN. A comprehensive dynamic model for downdraft gasifier using heat and mass transport coupled with reaction kinetics. Energy 2016;116:1230–42. https://doi.org/10.1016/j.energy.2016.10.036.

[110] Tinaut FV, Melgar A, Pérez JF, Horrillo A. Effect of biomass particle size and air superficial velocity on the gasification process in a downdraft fixed bed gasifier. An experimental and modelling study. Fuel Process Technol 2008;89:1076–89. https://doi.org/10.1016/j.fuproc.2008.04.010.

[111] Goh CS, Tan HT, Lee KT. Pretreatment of oil palm frond using hot compressed water: An evaluation of compositional changes and pulp digestibility using severity factors. Bioresour Technol 2012;110:662–9. https://doi.org/10.1016/j.biortech.2012.01.083.

[112] Razak AMY. Industrial gas turbines: performance and operability; 2007. https://doi.org/10.1533/9781845693404.

[113] Zheng L, Furimsky E. Aspen simulation of cogeneration plants. Energy Convers Manag 2003;44:1845–51. https://doi.org/10.1016/s0196-8904(02)00190-5.

[114] Cardona CA, Aristizábal V, Solarte Toro JC. Improvement of palm oil production for food industry through biorefinery concept. In: Taylor JC, editor. Adv. Chem. Res., vol. 32. Nova Science Publishers; 2016.

[115] Moncada J, El-Halwagi MM, Cardona CA. Techno-economic analysis for a sugarcane biorefinery: Colombian case. Bioresour Technol 2013;135:533–43. https://doi.org/10.1016/j.biortech.2012.08.137.