Article

Alternative Energy Potential and Conversion Efficiency of Biomass into Target Biofuels: A Case Study in Ethiopian Sugar Industry- Wonji-Shoa

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Abstract: Global energy security relies on fossil-based resources that are affiliated with the source of global warming, apart from punches of political and economic instabilities. Biomass is a promising alternative carbonaceous feedstock used for the production of clean energy that could have the potential to substitute for fossil fuels. This study aims to present a conceptual design that considers the criteria to identify the upper theoretical limits of biomass conversion, thus providing the potential approach to the conversion of three biomass (by-products: dry molasses, dry bagasse, and dry filter cake) through gasification, in order to contribute the biomass carbon-capturing by the model assessment of stoichiometric mass conversion and energy efficiency indicators into simple thermodynamic energy vectors, such as alcohols, alkanes, and syngas (a mixture of carbon monoxide and hydrogen). Modeling plays up the importance of stoichiometric efficiency of biomass conversion with the supply of oxygen and hydrogen. This realizes that the multi-product diversification of feedstock into syngas, hydrocarbons, and alcohol through integrated process schemes could have the potential to fill the energy gap and help to manage environmental load. In regard to biomass conversion results, the mass conversion and energy conversion efficiencies of dry bagasse have better conversion potential than molasses and F. cake (% mass conversion = 129 in syngas, 54.4 in alkane, and 43.4 in alcohol; % energy conversion = 94.3 in syngas and 93.3 in alkane and alcohol).

Keywords: biomass conversion; energy; gasification; efficiency; moisture content

1. Introduction

Among national-level socio-economic development spices, energy is one of the pre-requisites [1] and a pillar for establishing a strategically frame for challenges in state-building scenarios. Countries adjust their vision to fill the energy gap by invoking forward merited development strategies to settle demand. Alternative biofuel resources, such as lignocellulosic biomass, have been among the chief potential sources recognized as the bloom of biofuels and other precious products [2]. Currently, researches on bioenergy around the globe addressed the questions regarding the cost-effectiveness of biofuels, conversion efficiency, and reduced cost of production through broad research and development, in order to mitigate greenhouse gases emission [3]. Biomass-to-biofuel conversion can provide environmental, economic, and strategic benefits, due being processed from non-food competitive sources [4]. Depending on the adopted conversion technology, desired products, and accessibility of feedstock's, fuels which are derived from biomass may be solid, liquid, or gas [5].

Different variety of biofuels, including hydrogen, long-chain alcohols, and alkanes, can be produced from lignocellulosic biomass [6]—even electricity, through an integrated

approach. The conceptual schematic presented in Figure 1 consists of the following main components: the quantity and quality of feedstock subject to chosen conversion technology; the lower heating value, LHV, of representative biomass for this study, within the range of operating variables (operating agent, pressure, temperature, etc.); the conversion pathway for technical application. The desired products are aligned in this regard. For this research, the same generic species of by-products, namely molasses, sugarcane bagasse, and filter cake, were involved. Molasses are ready-made by-products from sugar industries and promising feedstock with a high conversion yield at a low cost, compared with cellulosic biomass in biofuel production [7]. Sugarcane bagasse is a potential solid substrate obtained after juice extraction, mainly from the polymeric biochemical components of lignin (22–25%), cellulose (45–47%), and hemicellulose (24–26%) [8]. Filter cake is a solid substrate generated, after clarification steps, with a significant amount of sugar and finely mixed bagasse [9]. In the current scenarios, the filter cake is partly used for cane farm field soil amendment as a fertilizer, with the remaining damping to the nearby water source river causing significant environmental pollution in the downstream area, as well as cost of disposal [10]. With due credit to the depth of problems, industries should have to take readiness to valorize the available biomass from a social, economic, and environmental benefit point of view. Regarding biomass solely, bagasse is defined from its ultimate (elemental) analysis accordingly, as of the Phillis database description, as carbon (52.70%), hydrogen (6.86%), and oxygen (40.26%); molasses and filter cake took an average value from the same database.
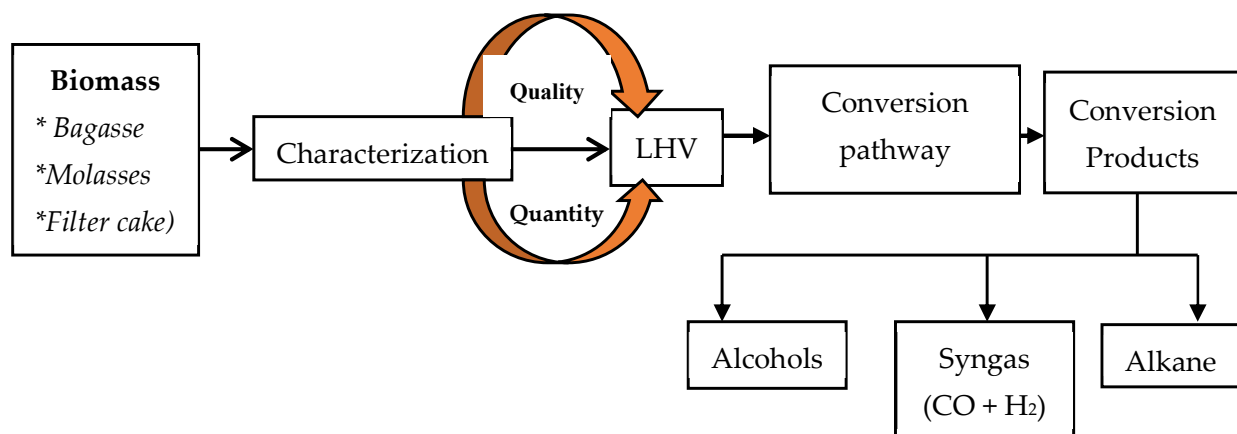

Figure 1. Conceptual block diagram biomass to bio-fuel conversion scheme.

For the dramatic improvement of energy security, economy, and the entire environment, biomass valorization into useful energy indicators would have created a step forward dimension, regarding the research output. Several authors studied the energy potential of feedstocks that are not food competitive by nature and of guaranteed sustainability [11], as well as the power of mixed substrate-to-biofuel production quality and quantity and the challenges to achieving cost-competitive biofuel from biomass, compared with fossil-based fuels [12]. Moreover, [13] stated that biomass originating from forest and agricultural residues has better engine efficiency and new stimulus in the biofuel market. In this case, the two critical strategic questions, such as quality and quantity issues, are key to the biomass conversion setup. The quality of biomass predominately refers to the material and energy conversion efficiency, while the quantity of biomass provides insight regarding the capacity of biofuel production.

Biomass-to-biofuel conversion strategies are synchronized in a set of conceptual steps, as described in Figure 1. The biomass is linked with the characterization step to determine the key energy-generating paradigm, known as the "heating value", in the boundary of expected quality and quantity for the intended conversion pathway. To adopt biofuel production technology and implement viable economic and environmental-oriented policies,

it is important to determine the LHV of biomass substrate. The LHV is a key to measuring the quality of feedstocks and selection of appropriate conversion technology [14], following biomass composition. However, the heating value of biomass is affected by a high moisture value. Thus, the pairing of appropriate technology with optimum moisture value helps to increase the desirable quality of biomass conversion products.

Depending on various conditions, such as the biomass conversion technology, quality of feedstock, and desired products, biomass can be converted by thermochemical and biochemical pathways. The thermochemical pathway includes several possible solutions to produce useful chemicals or fuels from the initial biomass feedstocks. Those different solutions are distinguished by the desired products to produce, their operating parameters, and their products [6]. In contrast to the thermochemical pathway toward chemicals and fuels, the biochemical pathway includes physical, chemical, and biological biomass pretreatments to hydrolyze cellulosic components to produce bioethanol with lower energy consumption at high efficiency [15]. Studies have shown that the use of multiple pretreatment strategies constitutes an emerging approach and can significantly increase the efficiency of the process [16], since there is no single and harmonized biomass pretreatment strategy.

The link between biomass characterization and conversion technology selection speculates the same, as the two faces of a coin's monetary value in action. The quality and quantity of biomass feedstock, specific project factors, economic conditions, environmental standards, and type of desired products are keen for directing towards technology selection [17]. Thus, technology selection is a step toward profitable project investment from particular biomass to recover the maximum possible energy [18]. Extending the research outputs into syngas, liquid hydrocarbons, or alcohol production paradigms, as described in the conceptual diagram (Figure 1), is an explicit directive to follow adaptive conversion technology supported by multiple chemical reactions. Hence, the influence of process parameters and derived target products in biomass conversion, insight into the power of conversion technology choice, and inspired chemical reactions to a promising alternative energy shift from fossil dominant market sphere.

The choice of conversion technology mainly depends on the level of desired products to be produced, overall biomass components stoichiometric balance [19], influence of operating conditions [20], moisture level of feedstock [6], and supply of conversion agents in biomass conversion process [21]. Having all the influential factors and choice of technology in the biomass-to-biofuel conversion, the thermochemical pathways are aligned to prone pyrolysis, combustion, hydrothermal combustion (HTC), and gasification. In pyrolysis biomass-to-biofuel, the conversion is carried on, without supplying oxygen as an oxidizing agent to form solid, liquid, and gaseous fuels, within the range of temperature 600–800 °C [22]. Additionally, biomass combustion could be subject to the supply of excess oxygen to form combustion products (CO_2 and H_2O). A series of steps, such as biomass drying, volatilization, gas, and solid-phase oxidation chemical reactions, are conducted prior to water-gas-shift reactions [23]. Similarly, biomass gasification is conducted with a limited supply of oxygen to produce solid fuel (char) and gas, which is further converted into syngas and bio-oils [24]. Gasification technology is the preferred technology, compared with the other two (pyrolysis and combustion), to produce clean fuel gases from low moisture content biomass. In all the above three conversion technologies, the yield and quality of products also vary with a stoichiometric oxidizing agent (oxygen) supplement.

On the other hand, the hydrothermal carbonization process is more viable for producing target solid fuel (bio char) with better efficiency. Hydrothermal carbonization (HTC) could play a significant role in the valorization of organic waste and biomass residues. HTC is a thermochemical process occurring in subcritical water under relatively mild conditions, with a reaction temperature commonly maintained in a range of about 180–250 °C and pressure between 10 and 50 bar [25]. Under these conditions, liquid water is used as both a reactant and solvent/reaction medium for the biomass, thus leading to its degradation through heterogeneous chemical reactions, which include hydrolysis, dehydration, and polymerization. The result is a solid fuel rich in carbon (hydro char), a liquid by-product,

and gas phase rich in CO_2. The advantage of HTC, over the other thermochemical conversion methods, is that it can convert wet input material into carbonaceous solid at relatively high yields, without the need for an energy-intensive drying process. We strongly believe that the use of the HTC method can help to encourage a greater use of biomass and, in particular, hydrocarbons as biofuels, as well as to increase carbon conversion efficiency. Moreover, HTC has the potential to provide specific chemical and/or structural characteristics, depending on the targeted application.

The combined or individual supplement of oxygen and hydrogen atoms helps to determine the energy intake of the desired products and conversion efficiencies. In this case, not more than 30% of biomass is converted into energy indicator terms by pyrolysis or combustion means. Meanwhile, more than 70% energy efficiency of biomass can be recovered by gasification [8].

A simplified generic circular bio-economy approach to valorize mixed substrate is an initiative to provide opportunities and develop sustainable use of byproducts into biofuel to alleviate energy scarcity and safeguard the entire environment. Adapting gasification as a circular bio-economic approach and developed platform might be an alternative and constructive biofuel production facility to biomass diversification. Because of the current technological advancement, the major focus of this study is to investigate the stoichiometric material conversion potential and energy indicator terms in available feedstocks. The operating conditions were evaluated by the stoichiometric material conversion ratio (elemental constituent), as a measure of efficiency. All the strategies provide sustainability and enhance the efficiency of the system, thereby enriching the energy index and economic benefit of the factory, with the possibility of producing biofuels in an integrated way.

For this research, the same generic species of by-products, namely molasses, sugarcane bagasse, and filter cake, were involved. Molasses are ready-made by-products from sugar industries and promising feedstock with high conversion yield at low cost, compared with cellulosic biomass in biofuel production [7]. Sugarcane bagasse is a potential solid substrate obtained after juice extraction and mainly from polymeric biochemical components of lignin (22–25%), cellulose (45–47%), and hemicellulose (24–26%) [8]. Additionally, filter cake is a solid substrate, generated after clarification steps, with a significant amount of sugar and finely mixed bagasse [9]. In a current scenarios, the filter cake is partly used for cane farm field soil amendment as a fertilizer, and the remaining damping to the nearby water source river causes significant environmental pollution in the downstream area and cost of disposal [10]. Given credit to the depth of problems, industries should have to take readiness to valorize the available biomass from a social, economic, and environmental benefit point of view. The biomass solely, bagasse defined from its ultimate (elemental) analysis accordingly, as of the Phillis database description, carbon (52.70%), hydrogen (6.86%), and oxygen (40.26%); molasses and filter cake took an average value from the same database.

Thus, Gasification systems are a promising approach for clean and efficient power generation, as well as for polygeneration of a variety of products, such as hydrocarbons, synthetic gas (syngas), and alcohol, in stoichiometric biomass conversion employed with the supply of oxygen and hydrogen. This realizes that multi-product diversification of feedstock through integrated process schemes could have the potential to fill energy gap and helps to manage environmental load.

2. Materials and Methods

The system boundary of this study includes a typical chemical composition of 41.57 wt.% C, 6.50 wt.% H, and 51.92 wt.% O dry molasses ($C_{30}H_{56}O_{28}$); 46.80 wt.% C, 6.60 wt.% H, and 46.60 wt.% O dry filter cake ($C_{30}H_{51.14}O_{22.7}$); 52.70 wt.% C, 6.86 wt.% H, and 40.26 wt.% O dry bagasse ($C_{30}H_{46.65}O_{17.11}$), and wet bagasse (moisture = 48.9%) ($C_{30}H_{120}O_{53.84}$). They are subject to endothermic reactions, in which it provides heat energy input to the reactants and products to drive the process. The material conversion efficiency and energy indicator terms are viable to the product shift dimension from the available biomass feedstock. The subscripts in the formula are taken based on the assumed

carbon number 30. One kilogram per second of input is used in the desired reaction system to compare results taken from each biomass feedstock presented in Table 1. The characteristics of input biomass have been introduced from the Phyllis database recorded in the Netherlands energy research center focused on biomass and waste [26].

Table 1. The biomass used in the case factory under study (adapted from Equation (1)).

Biomass	Formula	C (%)	H (%)	O (%)	Production [t/yr]
Molasses	$C_{30}H_{56.24}O_{28.11}$	41.57	6.50	51.92	20.30
Sugarcane bagasse	$C_{30}H_{46.65}O_{17.11}$	52.70	6.86	40.26	141.3
Filter cake	$C_{30}H_{51.14}O_{22.7}$	46.80	6.60	46.60	34,344

2.1. Alternative Conversion Products

The quantity and quality of final conversion products are due to the function of thermochemical and physical properties of the feedstock. From the operating conditions and the feedstock composition repartition, corresponding products are produced. The desired products are obtained from the packs of elements making the chain family in the defined feedstock. The conversion efficiency of biomass into desired products in the model chemical reactions can be measured by constituent materials capturing efficiency from their basis and the supply level of oxidizing agents. The main conventional products produced from long-chain carbon-containing biomass are alcohol, dodecanol ($C_{12}H_{26}O$), liquid hydrocarbon, and dodecane ($C_{12}H_{26}$). Moreover, thermochemical carbon-capturing of biomass to syngas production emerged with traces of methane and carbon dioxide that could be separated by purification.

For the chosen methodology, the biomass and product(s) studied in this research by conceiving inputs, namely molasses, filter cake, and sugarcane bagasse, whose attributes are taken from the Phyllis database. In the biomass-to-biofuel conversion scenario, the LHV and moisture content of the biomass influences material conversion efficiency. The LHV of involved fuels (reported in mass) can be estimated using different correlations. The basis of classification of correlation is based on fuels type (solid, liquid, or gaseous), and source of origin (organic, coal, municipal waste, etc.). Thus, the chosen correlations for this research paper are based on the source of origin of the fuel (organic), and the target products adopted the Boie prototype relation [16], as described in Equation (1); the modified prototype relation, described in Equation (2), used for higher carbon-containing products (alcohol and alkanes).

$$LHV_{Boie} = 348.35C + 938.70H - 108.00O + 62.80N + 104.65S \tag{1}$$

$$LHV_{modified\ correlation} = 349.1C + 958.3H - 103.4O - 15.10N - 100.50S \tag{2}$$

where, C, H, and O are wt.% of corresponding atoms of carbon, hydrogen, and oxygen in biomass composition. Nitrogen and Sulphur components are insignificant and ignored. High moisture value convertible biomass affects the material conversion efficiency, due to the large run out of deliverable energy for biomass drying. Hence, high moisture content affects the heat energy balance in biomass-to-biofuel conversion system. Therefore, the LHV of available feedstock was analyzed into dry and wet bases to define the impact of physically bound water on the overall energy quality and energy consumption for feedstock drying, described in Table 2.

Table 2. Biomass composition and its estimated LHV in wet and dry basis used for the study (using Equation (1)).

Wet Biomass						Dry Biomass					
Biomass	Formula	C%	H%	O%	LHV	Biomass	Formula	C%	H%	O%	LHV
Molasses	$C_{30}H_{93.78}O_{46.90}$	22.37	5.83	46.63	11.00	Molasses	$C_{30}H_{56}O_{28}$	41.57	6.50	51.92	14.96
Bagasse	$C_{30}H_{120}O_{53.84}$	26.83	8.95	64.22	10.81	Bagasse	$C_{30}H_{46.65}O_{17.11}$	52.70	6.86	40.26	20.45
F. cake	$C_{30}H_{313}O_{154}$	11.44	9.96	78.20	4.91	F. cake	$C_{30}H_{51.14}O_{22.70}$	46.80	6.60	46.60	17.46

The wt.% compositions of wet F. cake (filter cake), and wet molasses calculated without considering ash and other components (less by 0.4 wt.% wet F. cake, and 25.17 wt.% wet molasses).

2.2. Effect of Moisture Content on Biomass-to-Biofuel Conversion

For a wide variety of biomass feedstock handling, gasification is a crucial and effective energy conversion technology [27]. Biomass gasification is a partial combustion of solid biomass to convert into gaseous fuels, mainly consisting of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and traces of carbon dioxide (CO_2). However, the product yield and conversion efficiency are affected by many physical and chemical factors such as moisture content, ash content, bulk density, gasifying agent, air-to-fuel ratio, reactor temperature in gasifier stages, and feed particle size ... etc. [28]. Among the factors, the biomass moisture content is the major influential factor in reactor temperature on the composition and calorific value of syngas [29]. Moreover, higher moisture content biomass gasification results in a non-uniform temperature profile, due to tar formation [30]. The range of moisture content suitable for thermochemical biomass-to-biofuel conversion technologies is a research challenge to find optimum moisture level [31]. Due to the heterogeneous moisture level between involved biomass feedstock in this research, molasses 21%, sugarcane bagasse 49%, and filter cake 75% require a substantial amount of heat energy for drying prior to feed in pyrolysis. In general, 85% of the available moisture content of the respective biomass is assumed to be drying by solar energy, and 10% of moisture value is the upper limit to start gasification. This upper limit value can answer the question of economic feasibility issue, due to the raises in the cost of drying.

Because of significant concern in the gasification process worldwide, it is necessary to anticipate the energy requirement for biomass drying over the remaining moisture content. The energy required for the drying process is supplied substantially by heat produced within the process (exhaust heat) from the evaporation condensate. In this case, the knowledge of latent heat is compulsory for the complete dryness of the biomass, as described in Equation (3).
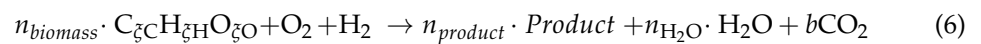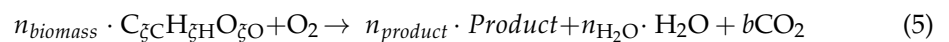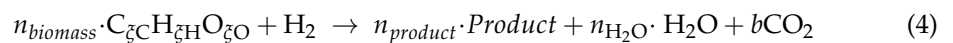
$$q = m \cdot \Delta H_v \qquad (3)$$

where q is the heat energy necessary for vaporization, and ΔH_v and m are the heat of vaporization in kJ/kg and mass of water vaporized in kg, respectively. The heat energy is primarily required to vaporize moisture in biomass-to-biofuel conversion scenarios. In this view, gasification can be more efficient with the simultaneous involvement of steam and air as gasifying agents which causes organic degradation by combustion and release of energy.

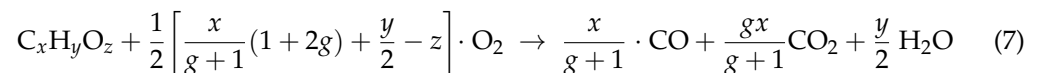### 2.3. Modeling and Parametric Effect

This section presents the overall biomass-to-biofuel conversion models and possible performance measures from its methodological data analysis in the MATLAB simulation result. Depending on the different gasification stages, material conversion and energy efficiency indicators are the pacemakers of the combustion process. As described in Section 2.2, regarding the influence of moisture content in biomass conversion, there are additional parametric factors, such as the source of energy supply, calorific value (LHV) of biomass, and level of deoxygenation in biomass conversion that affect the yield of the final products.

2.3.1. Modeling and Material Conversion: From Carbon Perspective

On the basis of multi-component decomposition reactions, the models that include simple combustion reaction strategies, in general, permit the material conversion into desired products, with an exclusive assumption of tar and soot production. The general biomass into biofuel conversion reactions can be measured by the conversion efficiency of stoichiometric component atoms in a composition. More precisely, the carbon and hydrogen atoms in a biomass composition were recognized as the role players for conversion reactions, with the provision of hydrogen and oxygen simultaneously or individually, as described in Equations (4)–(6) for the general scheme. The general model equations are considered from the premises of the biomass carbon conversion scenario.
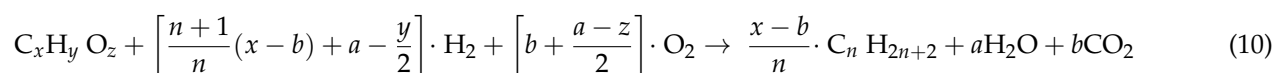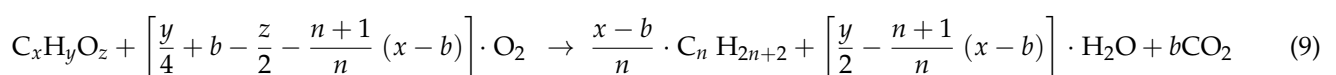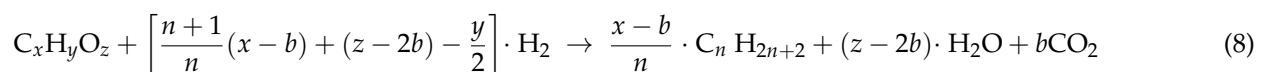
$$n_{biomass} \cdot C_{\zeta C} H_{\zeta H} O_{\zeta O} + H_2 \; \rightarrow \; n_{product} \cdot Product + n_{H_2O} \cdot H_2O + bCO_2 \tag{4}$$

$$n_{biomass} \cdot C_{\zeta C} H_{\zeta H} O_{\zeta O} + O_2 \rightarrow \; n_{product} \cdot Product + n_{H_2O} \cdot H_2O + bCO_2 \tag{5}$$

$$n_{biomass} \cdot C_{\zeta C} H_{\zeta H} O_{\zeta O} + O_2 + H_2 \; \rightarrow \; n_{product} \cdot Product + n_{H_2O} \cdot H_2O + bCO_2 \tag{6}$$

where (*b*) and (*ξ*) are parameters in biomass carbon conversion for CO_2 production adjustment, as well as the extent of biomass conversion reaction when equilibrium has been reached. The partial oxidation of biomass with a limited amount of oxygen is in favor of the gasification process, as described in Equation (7).

$$C_x H_y O_z + \frac{1}{2}\left[\frac{x}{g+1}(1+2g) + \frac{y}{2} - z \right] \cdot O_2 \; \rightarrow \; \frac{x}{g+1} \cdot CO + \frac{gx}{g+1} CO_2 + \frac{y}{2} H_2O \tag{7}$$

where *g* is the deviation factor from ideality.
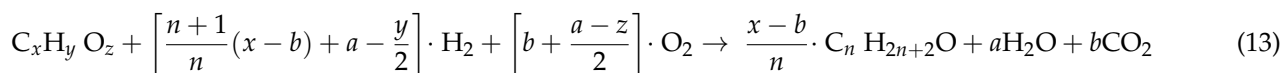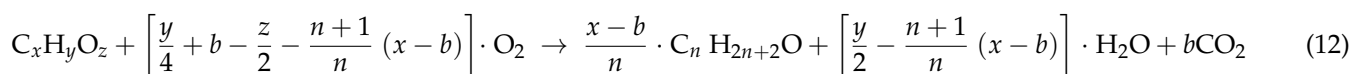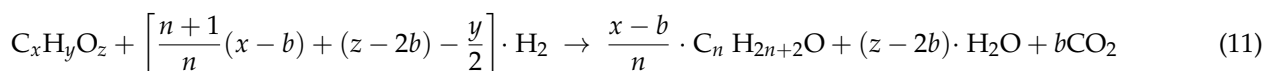
Biomass to Hydrocarbon Fuels Conversion

Conversion of biomass to hydrocarbon fuels process consists of the subsequent product gas cleaning and conditioning after the stoichiometric amount of oxygen consumed in pyrolysis and gasification, followed by Fischer–Tropsch (F-T) synthesis for liquid fuels production [17]. The Fischer–Tropsch process is a set of catalytic processes for converting synthesis gas (syngas, carbon monoxide, hydrogen and/or other gaseous mixture) into liquid hydrocarbons (BTL-FT). Liquid fuels from biomass via Fischer–Tropsch (BTL-FT) synthesis have three main steps: (1) Biomass converted into biomass-derived bio-syngas (syngas) by gasification (synthesis gas production). (2) Cleaning process is applied to the bio-syngas to meet the Fischer–Tropsch synthesis requirements, in order to remove impurities, resulting in clean bio-syngas (Fischer–Tropsch synthesis). (3) The cleaned bio-syngas is then conducted into Fischer–Tropsch catalytic reactor to produce green gasoline, diesel, and other clean biofuel (product upgrading) [25]. The resultant percentage yield from the degradation of biomass-to-biofuel is equivalent to the range of carbon atoms converted in the biomass feedstocks to higher carbon containing products, such as Fischer–Tropsch diesel and dimethyl ether [32]. The general modeling reactions in biomass conversion, $C_x H_y O_z$ into alkanes within the premise of simultaneous and separate provision of hydrogen and oxygen atoms are described in Equations (8)–(10).

$$C_x H_y O_z + \left[\frac{n+1}{n}(x-b) + (z-2b) - \frac{y}{2} \right] \cdot H_2 \; \rightarrow \; \frac{x-b}{n} \cdot C_n H_{2n+2} + (z-2b) \cdot H_2O + bCO_2 \tag{8}$$

$$C_x H_y O_z + \left[\frac{y}{4} + b - \frac{z}{2} - \frac{n+1}{n}(x-b) \right] \cdot O_2 \; \rightarrow \; \frac{x-b}{n} \cdot C_n H_{2n+2} + \left[\frac{y}{2} - \frac{n+1}{n}(x-b) \right] \cdot H_2O + bCO_2 \tag{9}$$

$$C_x H_y O_z + \left[\frac{n+1}{n}(x-b) + a - \frac{y}{2} \right] \cdot H_2 + \left[b + \frac{a-z}{2} \right] \cdot O_2 \rightarrow \frac{x-b}{n} \cdot C_n H_{2n+2} + aH_2O + bCO_2 \tag{10}$$

where *a* is adjustable parameter to water production during the provision of hydrogen. The supply of hydrogen to the reaction is due to the insufficient amount of hydrogen atoms in the biomass.
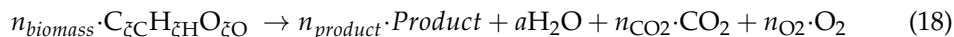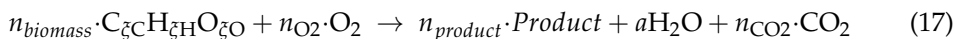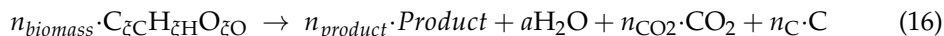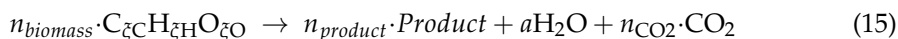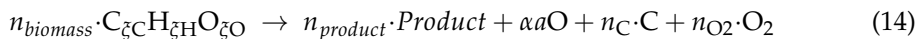
Biomass to Alcohol Conversion

Despite the economic viability and technical hurdles related to product diversification from the same or/and different sources, there are new emerging approaches expected to synergistically combine the different biomass conversion technologies dealing with the economic and technical barriers. Among the key technologies, the Fischer–Tropsch (FT) process is the predominant method suitable for the production of a range of liquid fuels in the presence of suitable metal catalysts within the optimum ranges of operating conditions (temperature and pressure). Similarly, as stated in hydrocarbon formation, the general biomass into alcohol conversion modeling equations are described in Equations (11)–(13). It is unlikely that there is an addition of oxygen atom from the general alkane series chemical formula ($C_n H_{2n+2}$) in alcohol ($C_n H_{2n+2}O$).

$$C_xH_yO_z + \left[\frac{n+1}{n}(x-b) + (z-2b) - \frac{y}{2}\right] \cdot H_2 \rightarrow \frac{x-b}{n} \cdot C_n H_{2n+2}O + (z-2b) \cdot H_2O + bCO_2 \tag{11}$$

$$C_xH_yO_z + \left[\frac{y}{4} + b - \frac{z}{2} - \frac{n+1}{n}(x-b)\right] \cdot O_2 \rightarrow \frac{x-b}{n} \cdot C_n H_{2n+2}O + \left[\frac{y}{2} - \frac{n+1}{n}(x-b)\right] \cdot H_2O + bCO_2 \tag{12}$$

$$C_xH_y O_z + \left[\frac{n+1}{n}(x-b) + a - \frac{y}{2}\right] \cdot H_2 + \left[b + \frac{a-z}{2}\right] \cdot O_2 \rightarrow \frac{x-b}{n} \cdot C_n H_{2n+2}O + aH_2O + bCO_2 \tag{13}$$
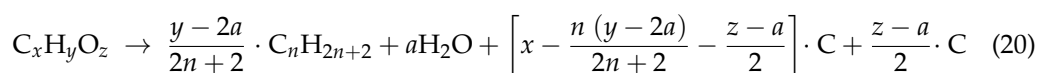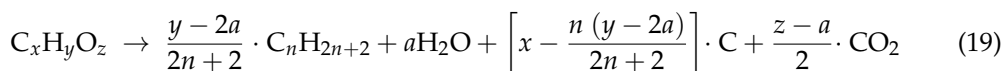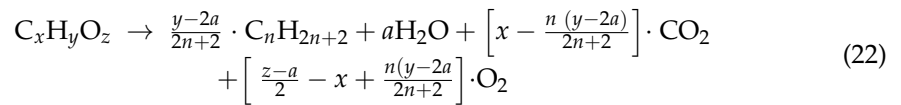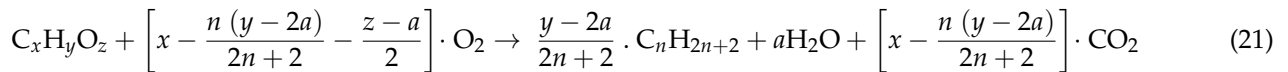
2.3.2. Modeling and Material Conversion: From Hydrogen Perspective

In the biomass conversion process, hydrogen is produced due to water-gas shift, reforming, and cracking reactions using catalysts under exothermic conditions [33]. The hydrogen production for direct integration in the sugar processing plant and installed cogeneration plant is enhanced by dehydration (H_2O removal) and decarboxylation (CO_2 removal) segmented schemes. Depending on the reaction conditions and oxidants in biomass gasification, the product gas may contain as much as 98% hydrogen (H_2) [21]. The simultaneous reactions of product gas yields are mainly influenced by factors such as CO and H_2 fractions in the product gas, air-to-biomass ratio, steam-to-biomass ratio, and operating conditions (temperature and pressure). Hence, during the pace of biomass conversion, two or more simultaneous reactions, such as hydrothermal carbonization reactions, have been taken place for stoichiometric conversion products and intermediate products. As in the hydrothermal carbonization process in biomass conversion, the stoichiometric addition of water and production of hydrogen can be corrected by an adjustable factor "a" for the benchmark carbon and hydrogen atoms conversion efficiency over the selectivity and yields of desirable products, as described in Equations (14)–(18).

$$n_{biomass} \cdot C_{\xi C}H_{\xi H}O_{\xi O} \rightarrow n_{product} \cdot Product + \alpha aO + n_C \cdot C + n_{O2} \cdot O_2 \tag{14}$$

$$n_{biomass} \cdot C_{\xi C}H_{\xi H}O_{\xi O} \rightarrow n_{product} \cdot Product + aH_2O + n_{CO2} \cdot CO_2 \tag{15}$$

$$n_{biomass} \cdot C_{\xi C}H_{\xi H}O_{\xi O} \rightarrow n_{product} \cdot Product + aH_2O + n_{CO2} \cdot CO_2 + n_C \cdot C \tag{16}$$

$$n_{biomass} \cdot C_{\xi C}H_{\xi H}O_{\xi O} + n_{O2} \cdot O_2 \rightarrow n_{product} \cdot Product + aH_2O + n_{CO2} \cdot CO_2 \tag{17}$$

$$n_{biomass} \cdot C_{\xi C}H_{\xi H}O_{\xi O} \rightarrow n_{product} \cdot Product + aH_2O + n_{CO2} \cdot CO_2 + n_{O2} \cdot O_2 \tag{18}$$
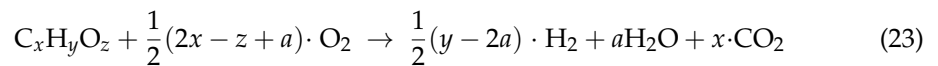
In the biomass-to-biofuel conversion process, the constituent atoms are converted into desirable products as carbon harvest and hydrogen production. In this case, the removal of H_2O and CO_2 resulted from the production of hydrocarbons under exothermic reaction schemes, without the provision of external heat sources described in Equations (19)–(22).

$$C_xH_yO_z \rightarrow \frac{y-2a}{2n+2} \cdot C_nH_{2n+2} + aH_2O + \left[x - \frac{n(y-2a)}{2n+2}\right] \cdot C + \frac{z-a}{2} \cdot CO_2 \tag{19}$$

$$C_xH_yO_z \rightarrow \frac{y-2a}{2n+2} \cdot C_nH_{2n+2} + aH_2O + \left[x - \frac{n(y-2a)}{2n+2} - \frac{z-a}{2}\right] \cdot C + \frac{z-a}{2} \cdot C \tag{20}$$

$$C_xH_yO_z + \left[x - \frac{n(y-2a)}{2n+2} - \frac{z-a}{2} \right] \cdot O_2 \rightarrow \frac{y-2a}{2n+2} \cdot C_nH_{2n+2} + aH_2O + \left[x - \frac{n(y-2a)}{2n+2} \right] \cdot CO_2 \quad (21)$$

$$C_xH_yO_z \rightarrow \frac{y-2a}{2n+2} \cdot C_nH_{2n+2} + aH_2O + \left[x - \frac{n(y-2a)}{2n+2} \right] \cdot CO_2 \\ + \left[\frac{z-a}{2} - x + \frac{n(y-2a)}{2n+2} \right] \cdot O_2 \quad (22)$$

In general, in the decarbonization and dehydration process steps in the biomass conversion scenario, product gas hydrogen (H_2), can be produced and considered a limiting reagent for the entire reaction, as described in Equation (23).

$$C_xH_yO_z + \frac{1}{2}(2x - z + a) \cdot O_2 \rightarrow \frac{1}{2}(y - 2a) \cdot H_2 + aH_2O + x \cdot CO_2 \quad (23)$$

2.4. Biomass Conversion Efficiency and Energy Indicators

Biomass-to-biofuel conversion efficiency mainly depends on the conversion technology, methods of approach, variety of feedstocks, and intended purpose of product use. In conversion efficiency, renewability and neutral carbon footprint are the key features associated with it. In general, efficiency refers to a percentage value comparable to the ratio between the input of energy content of biomass and output of heat produced or electricity generated in the output [34]. To indicate the overall biomass-to-biofuel conversion efficiency, the different reaction stages and efficiency indicators are presented in the simulation model. The conversion efficiency is defined from the corresponding trends of material conversion and energy efficiency indicators of inputs and desirable products. In material conversion performance indicators, either the products or biomass itself were involved in the potential carbon harvest scale. If only biomass is involved as an interpreter index for combustion reactions, the carbon-capturing ratio (carbon harvest) can be defined as described in Equation (24).

$$\eta_{carbon\ capturing\ ratio} = \frac{n_{product\ obtained} \cdot M_{product}}{(n_{biomass\ conversion} + n_{biomass\ burned}) \cdot M_{biomass}} \quad (24)$$

In addition, if products are considered the source of energy supply during the combustion process system, the amount of convertible biomass to the desired products can be described in Equation (25).

$$\eta_{carbon\ capturing\ ratio} = \frac{\left(n_{product\ obtained} - n_{product\ burned} \right) \cdot M_{product}}{(n_{biomass\ conversion} \cdot M_{biomass})} \quad (25)$$

where M_i and n_i denotes the molar mass and mole number of "i" components, respectively. The terms $(((n_{biomass\ burned} + n_{biomass\ conversion}) \cdot M_{biomass}))$ are used for carbon-capturing indicator in the input quantity. As described in Section 1, Figure 1, the LHV is a key component to energy conversion efficiency and technology choice during the steps of biomass-to-biofuel conversion. Considered either biomass or products as the source of energy supply to the system, the energy ratio indicator measures the energy value from the biomass carbon-capturing value. Equations (26) and (27) describe the energy ratio indicator, regarding the system energy supplied from the product(s) and biomass, respectively.

$$\eta_{energy} = \frac{\left(n_{product\ obtained} - n_{product\ burned} \right) \cdot LHV_{product}}{n_{biomass\ conversion} \cdot LHV_{biomass}} \quad (26)$$

$$\eta_{energy} = \frac{n_{product\ obtained} \cdot LHV_{product}}{(n_{biomass\ burned} + n_{biomass\ conversion}) \cdot LHV_{biomass}} \quad (27)$$

Despite the need for further integrated process development and optimization, the operational variables are the functional results of the product quality and quantity in

biomass conversion efficiency. In this context, the potential conversion efficiency of the involved biomass focuses on the model implementation of harmonized optimum carbon harvest to the desired product formation. The carbon harvest enhances the product gas (CO and H_2) efficiency as the stoichiometric air-to-biomass ratio decreases. Indeed, a limited amount of oxygen is supplied to the system; thus, the adjustable parameter "b" is incorporated to control the referable amount of CO_2 generation. The adjustable parameter "b" varied, as to the assigned number of carbon atoms in the biomass chemical formula, i.e., "b" varied between 0 and 30 for all the involved biomass components for this research work. The number of carbon atoms for the optimum material and energy conversion efficiencies extended from 0 to 30 potential factors. This refers to that "b" is the limit point of carbon harvest from the involved biomass to desired products production and selectivity. As "b" is equal to zero, the carbon harvest is the same as the carbon reported in the biomass; additionally, "b" is equal to 30, the excess amount of oxygen supplied to the system and converted into CO_2. Similarly, the generation of water and conversion of the stoichiometric hydrogen atom in the biomass were adjusted by the "a" factor, standing from an arbitrary constant (0.15) to some limit value calculated from H:O ratio in the simulation.

2.5. Biomass-to-Biofuel Conversion Technologies and End Products Use

Due to the high consumption of resources and quantity of landfill wastes [24], the environmental burden increases alarmingly. To alleviate the burden and create a clean environment in the manufacturing sectors, appropriate technology selection is the prime assignment for respected stakeholders, in order to exploit useful materials. The technology selection is mainly based on feedstock physico-chemical properties and desired products. Due to the growing concerns regarding energy security, biomass-to-biofuel conversion strategies to exploit embedded energy for multi-purpose use can be categorized as biochemical or thermochemical pathways.

The thermochemical pathway is a high-temperature operation to convert biomass into solid, liquid, and gaseous intermediate fuels with the pairing of two or more conversion methods. The coupling of two or more conversion technologies could increase the product diversification and identify optimum process parameters, while the biochemical pathway refers to the production of pure, clean, and efficient products within the premises of enzymatic matrices [5]. Hence, coupling two or more process technologies and a variety of feedstocks could enhance the energy production and supply chain in the global energy market security. Integrated biomass in the biofuel conversion process and affiliated technology arrangements, final products, and uses are described in Figure 2.
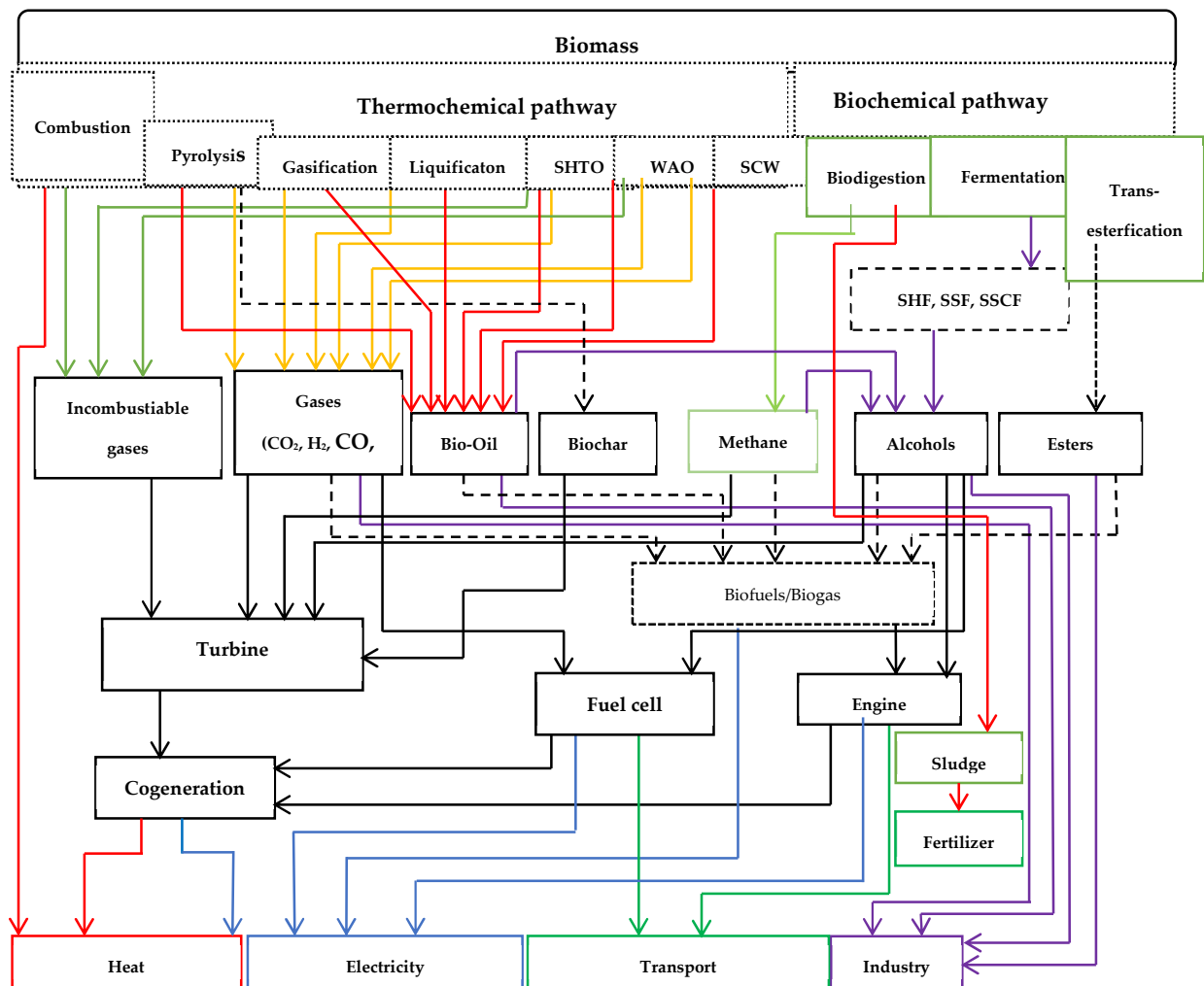
Figure 2. Main integrated biomass-to-biofuel conversion processes and technology affiliation for final products uses, adapted by [35].

3. Results and Discussion

3.1. Biomass Fuel Characterization

The transformation succession of biomass into biofuels mainly depends on the fuel characteristics and technology aspiration. The fuel characteristics, including fuel moisture content parallel to the chosen conversion technology and calorific value (LHV), can determine the efficiency of the conversion process to the desired products. The moisture content of the biomass shown in Table 2 affects the calorific value of the biomass feedstocks. Contrary to the low calorific value, the moisture content increases the bulk density of the biomass feedstocks. It implies that the increase in bulk density is evident in a lesser amount of energy generated from the decomposition of biomass in the chosen conversion technology. The partial heat energy is wasted on moisture evaporation and results in a temperature drop in different stages of the gasifier. The temperature drops in the gasifier affect the overall conversion efficiency of the components, regarding the desired products, since most of the heat energy is attributed to being spent on biomass drying.

The charge of the biomass remains a considerable margin of the leading energy source, and the allowable upper limit moisture content value must meet the intended process, as per the choice of conversion technology. Considering the 10% upper limit moisture content of biomass involved in the conversion reactions, there is a significant variation in calorific value. The percentage of the variation of the calorific value with moisture and moisture-free

biomass, as seen in Table 3, shows that there is a significant amount of heat energy required for evaporation, other than the other verge of biomass conversion to target products.

Table 3. Impact of moisture content in calorific value of biomass conversion.

Wet Biomass	LHV [MJ/kg]	Dry Biomass	LHV [MJ/kg]	LHV% Variation
Wet molasses	11	Dry molasses	14.96	26.47
Wet bagasse	10.81	Dry bagasse	20.45	47.14
Wet F. cake	4.91	Dry F. cake	17.46	71.88

The variation in calorific value refers to the fact that high moisture content biomass has an inefficient carbon-capturing efficiency in the yield of the products. In model reactions, Equations (14), (16), (19) and (20) showed that there are unconverted carbon atoms that emerged in the product streams, due to the high moisture content and limited supply of oxygen in the conversion process. The upper limit of moisture in the biomass could define the amount of water evaporated from the raw biomass and required amount of heat energy for this specific purpose.

3.2. Heat Energy Requirement for Biomass Moisture Evaporation

To remove intrinsic surface water from the biomass and recover the carbon loss in the available feedstocks of combustible matter, the heat energy required for evaporation is assumed to be an equimolar gain of cellulose during the hydrolysis process. Hence, the total amount of heat energy required to evaporate is considered a function of the mass of water removed from the biomass and its enthalpy at the operating conditions. Equations (28) and (29) describe the amount of water evaporated and heat energy required for the gasification process at the upper moisture limit.

$$\dot{m}_{H_2O} = n_{cellulose} \cdot M_{water} \tag{28}$$

$$E_{vap.} = \dot{m}_{H_2O} \cdot \Delta H \tag{29}$$

For the complete drying of biomass feedstocks, we have to consider partial or complete thermal action over the gain of solar drying. This thermal action could enhance the carbon-capturing efficiency from the input biomass during the gasification process. However, the energy requirement for incorporated thermal action could not be above the energy potential of the biomass executed in the conversion reactions. Table 4 presents the heat energy required for evaporation and possible extractable amount of biomass energy in the designed conversion reactions. In this case, the drying process was conducted from the interest of 85% drying by solar energy, as well as the upper limit for gasification (10%) value, in which the specific latent heat of evaporation for water was considered as 2250 kJ/kg.

Table 4. Heat energy requirement for biomass moisture remove and available biomass energy after treatment.

Biomass	Initial Moisture [%]	m_{H_2O} Evaporated [t/yr]	$Q_{required}$ [kJ/yr]	$E_{Biomass}$ after Treatment [kJ/yr]
Bagasse	48.9	130,367.16	2.905×10^{12}	8.2276×10^{11}
Molasses	21	7748.42	3.769×10^{8}	1.65475×10^{15}
F. cake	75	1445.61	3.25×10^{9}	1.11945×10^{16}

In fact, the importance of biomass treatment can be seen in the ratio of energy available after treatment-to-energy required for the evaporation of water from the biomass. From an economic point of view, the useful energy (EB)-to-required energy for evaporation (Ev) is a factor of 2.8. Moreover, the useful energy after treatment is a factor of 0.28 energy

contained in the original biomass. Hence, the amount of energy required for evaporation to the amount of energy contained in the treated biomass (bagasse) is about a factor of 10.

3.3. Process Energy Consumption Scenario and Available Useful Energy

3.3.1. Process Energy Conversion Scenario

During the biomass-to-biofuel conversion process, energy is dissipated to moisture removal. However, considering the integrated cogeneration plant, the available biomass is partly used for steam production and electricity generation, and the remaining goes to biofuel production in the designed conversion process. The amount of steam produced and MW of electricity produced from the bagasse feed ring can be measured from the essence of steam-to-bagasse and electricity-to-bagasse ratios. The steam-to-bagasse ratio ($\frac{m_{st}}{m_{bag}}$) from the current on-going operation is 1.87, and the electricity generation-to-bagasse consumption ratio ($\frac{MW_{Elec}}{kg_{bag}}$) is equal to 0.67 from the annual production of 906 thousand tons of bagasse. For the annual operation period of 4680 h per year, the power generation can be calculated by Equation (30).

$$P = \frac{\dot{m}_{st} \cdot H_{v,\,H_2O}}{t_{operation}} \qquad (30)$$

where $\dot{m}_{st}$ and H_{v,H_2O} are annual steam production and specific latent heat of vaporization of water (kJ/kg) at the operating temperature (180 °C). Based on recorded data taken from the factory under study, there is a deviation of energy demand for steam production and electricity generation between moisture and moisture-free biomass, as described in Appendix A and Tables A1 and A2; it is supposed to be 1 kg/s wet and dry, biomass, respectively. In general, the moisture content of the biomass affects biomass-to-biofuel conversion as the energy requirement for electricity generation and steam production rises. Table 5 shows the impact of moisture content in biomass-to-biofuel conversion from an energy requirement views on an annual basis.

The steam-to-bagasse ratio and MW power of electricity generation per kg of bagasse determine the potential capacity of the bagasse consumption for firing and remaining bagasse for biofuel production. Thus, the bagasse consumed for firing is conducted at a finite time series production basis of $(1 - (\sqrt{\frac{T_c}{T_h}}))$, where T_c and T_h are the cold and hot temperature values of 300 and 573 K, respectively.

Table 5. Impact of moisture content in energy requirement for electricity generation and steam production in annual basis.

Electricity Generation to Bagasse Consumption		**Steam Production to Bagasse Consumption**	
Biomass	[MW/Kg]	Biomass	Steam/bagasse
Wet bagasse	0.67	Wet bagasse	1.87
Dry bagasse	1.31	Dry bagasse	3.59

3.3.2. Available Useful Energy (E_B)

Upon the bagasse consumption scenario in the burning process, the useful powers from dry and wet bagasse were computed to 84 and 40 MW. This is a reservation for the designed biomass-to-biofuel conversion strategies and potential requirement of the remaining biomass to produce substantial MW power. Hence, the useful energy from the remaining bagasse, as shown in Tables A4 and A5 (Appendix B), is subject to the upper limit moisture value.

3.4. Alternative Biomass-to-Biofuel Conversion Potential

Based on the method of approach(es), the biomass-to-biofuel conversion process yields two or more products from the same or different feedstocks species. The most

important point here is the material and energy conversion efficiency from the available feedstocks, concerning the adopted method of conversion. Regarding the packs of a range of technologies, the thermochemical biomass conversion route was chosen for this research. Three input components, namely dry molasses, bagasse, and filter cake were used for the quantitative and qualitative analysis of biomass-to-biofuel conversion. The conversion products were measured from the efficiency indicators (material (material conversion, and energy conversion) point of view. In this regard, syngas, alkane, and alcohol were designed as alternative potential products.

3.4.1. Biomass to Syngas Conversion Efficiency

The conversion efficiency of biomass-to-syngas refers to a percentage comparison of the ratio between the input of energy content of feedstocks and output of product gas. The product gas (syngas) formation was measured in mass conversion and energy efficiency indicators from the quantitative use of feedstocks. Table 6 shows the mass conversion and energy efficiency of input components from the optimum stoichiometric carbon capturing process.

Table 6. Stoichiometric carbon capturing efficiency in biomass to syngas conversion process.

Biomass	$\dot{m}$ [kg/s]	LHV [MJ/kg]	% Energy Conversion	% Mass Conversion
Dry molasses	1.20	14.96	94.60	1.00
Dry bagasse	3.17	20.45	93.40	129.00
Hydrolysed bagasse	2.37	19.60	94.00	123.00
Dry F. cake	1.97	17.46	94.30	1.12

* Except molasses, in all cases, the stoichiometric carbon atom 12 is the optimum carbon conversion, while, in molasses, it reduced to carbon number 10.

In terms of energy conversion efficiency, all feedstock components have almost the same recorded value, while the material conversion efficiency of bagasse (dry and hydrolyzed) has the better conversion efficiency. This is due to the classical reduction of carbonized biomass, which rich in its carbon nature composition, regarding the desired products. The formation of H_2, CO, water, and traces of CO_2 occurs when the biomass reacts with sub-stoichiometric quantities of oxygen in the air, as well as steam, as an oxidized agent. The use of steam as an oxidizing agent during gasification reaction causes the hydrogen in the biomass to oxidize to generate water via the dehydration process, thus yielding a product with a high calorific value. Therefore, the mass conversion efficiency and energy conversion efficiency of biomass highly depend on the moisture content and smart stoichiometric supply of oxidizing agent(s).

3.4.2. Biomass to Hydrocarbon Conversion Efficiency

The sustainable processing of biomass to hydrocarbon biofuels extends an all-in-one, state-of-the art process development and systematic pairing of resources to deliverable end-product users. The efficiency of biomass into hydrocarbon conversion is determined based on stoichiometric carbon-capturing contained in biomass, within the sense of the harmonized advanced gasification system utilized at a high-temperature range of (450–800 °C). As shown in Table 7, the carbon conversion efficiency is close to the optimum mass conversion and energy efficiency indicator from the involved biomass components.

Table 7. Stoichiometric carbon capturing efficiency in biomass to hydrocarbon conversion.

Biomass	$\dot{m}$ [kg/s]	LHV [MJ/kg]	C ATOM Number	% Mass conversion	% Energy Conversion
Dry molasses	1.20	14.96	10	31.00	92.30
Dry bagasse	3.17	20.45	12	43.40	93.30
Hydrolysed bagasse	2.37	19.60	12	41.40	93.30
Dry F. cake	1.97	17.46	12	36.50	93.10

The % carbon mass conversion of components into hydrocarbon formation results considerably differ from syngas (Table 6), due to carbon-capturing efficiency, in favor of gaseous yields in the designed operating conditions, since biomass gasification in applying steam as a gasifying agent with air is more appreciable to stoichiometric carbon conversion to product gases.

3.4.3. Biomass to Alcohol Conversion Efficiency

A comparable trend has been noticed for biomass to alcohol, hydrocarbon, and syngas conversion efficiencies. This could be the % mass conversion efficiency and % energy conversion efficiency of inputs. Due to the stoichiometric carbon and hydrogen atoms in the biomass, there is a slight deviation in % mass conversion in alcohol formation, compared with hydrocarbon formation (Table 8).

Table 8. Stoichiometric carbon capturing efficiency in biomass to alcohol conversion.

Biomass	$\dot{m}$ [kg/s]	LHV [MJ/kg]	C Atom Number	% Mass Conversion	% Energy Conversion
Dry molasses	1.20	14.96	9	46.70	93.30
Dry bagasse	3.17	20.45	12	54.60	93.30
Hydrolysed bagasse	2.37	19.60	12	56.20	93.30
Dry F. cake	1.97	17.46	10–12	52.60	93.30

The carbon conversion efficiencies of dry bagasse, hydrolyzed bagasse, and filter cake have almost the same % mass conversion efficiencies, while dry molasses is comparably lower than others. This is due to the lesser amount of referable carbon atoms in the biomass. However, the % energy conversion of all involved components is potentially equal. Thus, from an energy efficiency indicator point of view, there is a better chance, regarding the tendency of biomass selectivity to alcohol production.

3.5. Conversion Efficiency of Preferable Products

In general, the mass conversion and energy conversion efficiencies of dry and hydrolyzed bagasse have better conversion potential than molasses and F. cake in all desired products formation, from the respective input mass flowrates. The sustainability and flexibility of the conversion strategy could decide the approach to multiple useable product generations from the mixed inputs. The multiple product generation strategies depend on the stoichiometric conversion efficiency of component atoms in the domain of the system. Unless handling all the involved input biomass in one technological setup, we have been forced to choose the alternative product to be produced for the intended purpose. This is due to the limitation of investment costs for implementing all the desired products strategically. Hence, the biomass to syngas conversion process is favored by dry and hydrolyzed bagasse, from the percent mass conversion perspective (Figure 3).

Fiber-containing biomass feedstocks, inspired by gaseous products, yield when the method of approach prefers the gasification process. Whereas, in the case of dry molasses and dry filter cake, the mass conversion to syngas formation is very low. On the contrary, the percent energy conversion to syngas production for all product yields is higher. Therefore, in order of preference from the available biomass, the syngas > hydrocarbon **>** alcohol for fibrous feedstocks are shown in Figure 4.
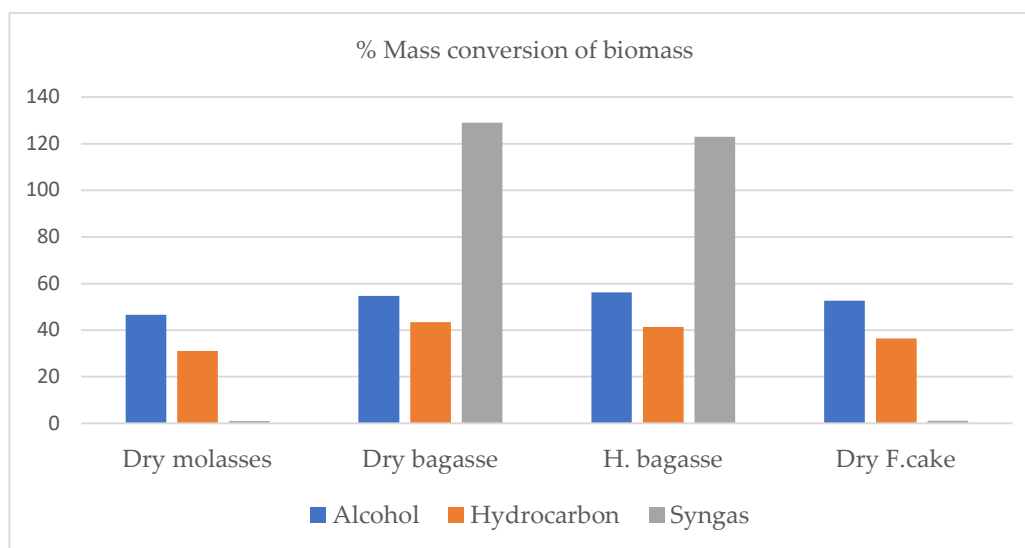
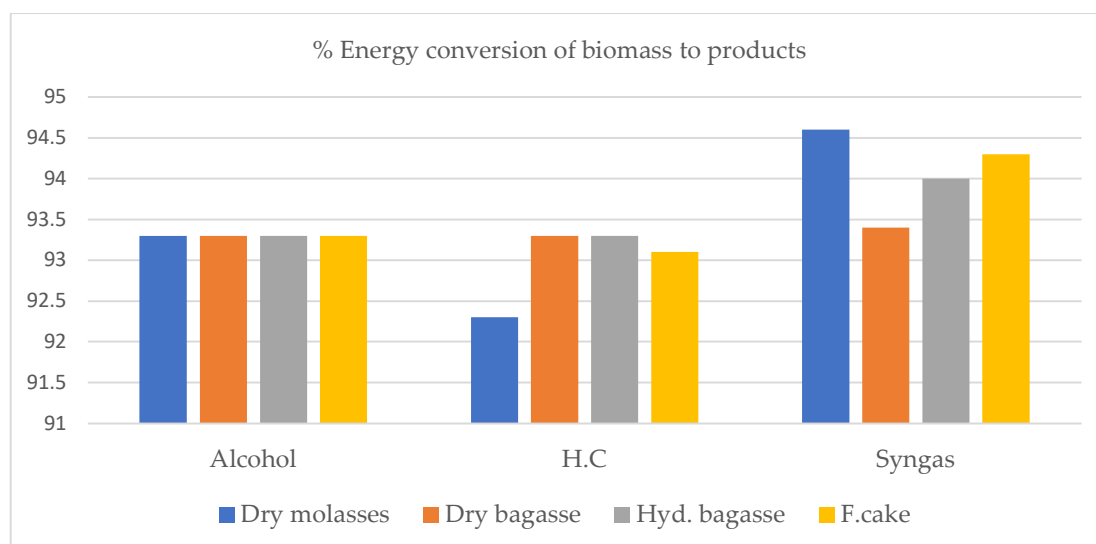**Figure 3.** Percent mass conversion of input biomass into desired products.

Figure 4. Percent energy conversion of input biomass into desired products.

4. Conclusions

The potential of alternative fuels production from biomass could allow for establishing the comparison between conversion technologies and the momentum to satisfy the quality and quantity of conversion products. The thermochemical biomass-to-biofuel conversion process, including pyrolysis, combustion, gasification, hydrothermal carbonation (HTC), and liquefaction (HTL), has a greater orientation to multi-products valorization technological packs. One of the promising thermochemical routes for converting biomass into to multi-products valorization is biomass gasification, as the upstream step to extended liquid transportation fuels production via Fischer–Tropsch synthesis has been discussed. Pretreatment of the biomass should be properly performed to create suitable gasification feed with low cost and efficient carbon chain conversion. Several parameters, such as the gasification temperature and pressure, gasifying agent, calorific value, moisture content, and so on, should be optimized to convert biomass into hydrogen-sufficient raw bio-syngas, alcohol, and hydrocarbons with a satisfactory carbon conversion rate. In FT-synthesis, in the cleaning process, the organic and inorganic impurities, such as tar, sulfur, chloride, and oxygen, will need to be removed to meet requirements in the following catalytic conversion.

The following are some of the presented results, in terms of mass % conversion and energy % conversion indicators, respectively, hydrogen or syngas: bagasse (43.4, 129), molasses (1, 94.6), filter cake (1.12, 94.3); alcohol: bagasse (54.6, 93.3), molasses (46.7, 93.3), and filter cake (52.6, 93.3); and hydrocarbon: bagasse (43.4, 93.3), molasses (31, 92.3), and filter cake (36.5, 93.1). The fuel gas can be later used to produce heat and electricity, or even hydrogen, by means of the separation process for direct application in steam production boiler plant. Thus, the stoichiometry of the limiting reaction elements with optimum operating conditions determines the mass and energy conversion efficiencies of the desired products. Therefore, attempting to valorize by-products into energy indicator drives an efficient and sustainable economy in the long run.

Abbreviations

The following abbreviations are used in this manuscript:

LHV_i	Lower heating value of component I (MJ/kg)
$\eta_{carbon\ capturing}$, η_{energy}	Carbon capturing and energy ratio
n_i	Mole number of components I (kmole)
M_i	Molar mass of component I (kg/kmole)
Q	Required heat energy (kJ)
$\Delta H_{,st}$	Heat of vaporization of water in vapor state (kJ/kg)
a, b	Control parameters
$\dot{m}_{st}$	Steam mass flowrate (kg/h)
$T_c,\ T_h,$	Cold and hot temperature (K)
$E_{,B}$	Useful energy in the biomass
ξO_2	Stoichiometric ratio of oxygen in total oxidation
SHF	Separate hydrolysis and fermentation
SSF	Simultaneous saccharification and fermentation
$SSCF$	Simultaneous saccharification and co-fermentation

Appendix A

Table A1. Dry bagasse consumption to electricity generation and steam production (1 kg/s).

Activities	MW/kg	Calculation Relation
Electricity	4.75	$\frac{P_{consumption}}{\dot{m}_{,dry\ bagasse}} \cdot \frac{1}{\left(1 - \sqrt{\frac{T_o}{T_{st}}}\right)}$ where, $T_o = 27\ °C$ and $T_{st} = 300\ °C$
Steam	9.99	$\frac{\dot{m}_{st}}{\dot{m}_{,dry\ bagasse}} \cdot \Delta H_{st}[T_{steam} = 180\ °C]$

Table A2. Wet bagasse consumption to electricity generation and steam production (1 kg/s).

Activities	MW/kg	Calculation Relation
Electricity	2.41	$\frac{P_{consumption}}{\dot{m}_{bagasse}} \cdot \frac{1}{\left(1 - \sqrt{\frac{T_o}{T_{st}}}\right)}$ where, $T_o = 27\ °C$ and $T_{st} = 300\ °C$
Steam	5.07 MW	$\frac{\dot{m}_{st}}{\dot{m}_{bagasse}} \cdot \Delta H_{st}\ [T_{st} = 180\ °C]$

Table A3. Heat requirement for drying and steam production (1 kg/s wet bagasse).

Heat for drying	1.87 MW/kg	$\left(\frac{P_{consumption}}{\dot{m}_{bagasse}}\right) / \left(1 - \sqrt{\frac{T_c}{T_h}}\right)$, $T_c = 300k$ and $T_h = 723k$
Heat for steam	5.07 MW	$\left(\frac{\dot{m}_{steam}}{\dot{m}_{bagasse}}\right) \cdot \Delta H_{st,T_{st}} = 180\ °C$

Appendix B

Table A4. Wet bagasse consumption to electricity generation and steam production (16.5 kg/s), as well as bagasse left for biofuel production.

Consumption	[kg/s]	Calculation Relation
For electricity	3.68	$\left(\frac{P_{consumption}}{\dot{m}_{wet\ bagasse}} \cdot \frac{1}{\left(1 - \sqrt{\frac{T_o}{T_{st}}}\right)}\right) \cdot (\dot{m}_{bagasse}) \cdot \left(\frac{1}{LHV_{,bagasse}}\right)\ (1^*)$
For steam	7.75	$\left(\frac{\dot{m}_{steam}}{\dot{m}_{wet\ bagasse}}\right) \cdot \Delta H_{steam}(\dot{m}_{bagasse}) \cdot \left(\frac{1}{LHV_{bagasse}}\right)\ (2^*)$
Bagasse left	5.10	$\dot{m}_{bagasse\ feed} - (eq.\ 1^* + eq.\ 2^*)$

Table A5. Dry bagasse consumption to electricity generation and steam production (8.4 kg/s), as well as bagasse left for biofuel production.

Consumption	[Kg/s]	Calculation Relation
For electricity	1.94	$\left(\frac{P_{consumption}}{\dot{m}_{dry\ bagasse}} \cdot \frac{1}{\left(1 - \sqrt{\frac{T_o}{T_{st}}}\right)}\right) \cdot (\dot{m}_{bagasse}) \cdot \left(\frac{1}{LHV_{,bagasse}}\right)\ (1^{**})$
For steam	4.08	$\left(\frac{\dot{m}_{st}}{\dot{m}_{dry\ bagasse}}\right) \cdot \Delta H_{st} \cdot \left(\dot{m}_{bagasse}\right) \cdot \left(\frac{1}{LHV_{bagasse}}\right)(2^{**})$
Bagasse left	2.36	$\dot{m}_{dry\ bagasse} - (eq.\ 1^{**} + eq.\ 2^{**})$

References

1. Pachauri, S.; Cherp, A. Energy security and energy access: Distinct and interconnected challenges. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 199–201. [CrossRef]
2. Brandin, J.; Hulteberg, C.; Ku, H. *A Review of Thermo-Chemical Conversion of Biomass into Biofuels-Focusing on Gas Cleaning and Up-Grading Process Steps*; TRITA-CHE Report 2017:24; KTH Royal Institute of Technology (KTH): Stockholm, Sweden, 2017; Volume 1. [CrossRef]
3. Frankó, B.; Galbe, M.; Wallberg, O. Bioethanol production from forestry residues: A comparative techno-economic analysis. *Appl. Energy* **2016**, *184*, 727–736. [CrossRef]
4. Ortiz, P.S.; de Oliveira, S. Exergy analysis of pretreatment processes of bioethanol production based on sugarcane bagasse. *Energy* **2014**, *76*, 130–138. [CrossRef]

5. Hassan, B.A.R.; Yusoff, Z.B.M.; Othman, M.A.H.; Bin, S. *Supportive and Palliative Care in Solid Cancer Patients*; IntechOpen: London, UK, 2013. [CrossRef]

6. Rastegari, A.A.; Yadav, A.N.; Gupta, A. (Eds.) *Prospects of Renewable Bioprocessing in Future Energy Systems: Production by Cyanobacteria*; Springer: Berlin/Heidelberg, Germany, 2019.

7. Day, C.; Tseng, Y.-C.; Puyol, R.; Nissan, J. Efficiency Comparisons of Secondary Biofuels. *PAM Rev. Energy Sci. Technol.* **2015**, *1*, 70–89. [CrossRef]

8. Ardila, Y.C.; Figueroa, J.E.J.; Lunelli, B.H.; Filho, R.M.; Maciel, W.M.R. *Syngas Production from Sugar Cane Bagasse in a Circulating Fluidized Bed Gasifier Using Aspen Plus^{TM}: Modelling and Simulation*; Elsevier: Amsterdam, The Netherlands, 2012; Volume 30.

9. Subia, B.; Kundu, J.; Kundu, S.C. Biomaterial scaffold fabrication techniques for potential tissue engineering applications. *Tissue Eng.* **2010**, *141*, 13–18.

10. Jenkins, B.M.; Baxter, L.L.; Miles, T.R.; Miles, T.R. Combustion properties of biomass. *Fuel Process. Technol.* **1998**, *54*, 17–46. [CrossRef]

11. Joshi, B.; Raj, M.; Dinita, B.; Jarina, S.; Rajani, J. Lignocellulosic ethanol production: Current practices and recent developments. *Biotechnol. Mol. Biol. Rev.* **2011**, *6*, 172–182.

12. Wilke, C.R.; Maiorella, B.; Sciamanna, A.; Tangnu, K.; Wiley, D.; Wong, H. *Enzymatic Hydrolysis of Cellulose: Theory and Applications*; Noyes Pubns: Norwich, UK, 1978.

13. Oke, M.A.; Annuar, M.S.M.; Simarani, K. Mixed Feedstock Approach to Lignocellulosic Ethanol Production—Prospects and Limitations. *Bioenergy Res.* **2016**, *9*, 1189–1203. [CrossRef]

14. Dashtban, M.; Schraft, H.; Qin, W. Fungal bioconversion of lignocellulosic residues; Opportunities & perspectives. *Int. J. Biol. Sci.* **2009**, *5*, 578–595. [CrossRef]

15. Osman, A.I.; Mehta, N.; Elgarahy, A.M.; Al-Hinai, A.; Al-Muhtaseb, A.H.; Rooney, D.W. *Conversion of Biomass to Biofuels and Life Cycle Assessment: A Review*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 19.

16. Tanger, P.; Field, J.L.; Jahn, C.E.; DeFoort, M.W.; Leach, J.E. Biomass for thermochemical conversion: Targets and challenges. *Front. Plant Sci.* **2013**, *4*, 1–20. [CrossRef]

17. Chen, Y. Biomass to Fuels: Thermo-chemical or Bio-chemical Conversion? *Ferment. Technol.* **2012**, *1*, 7972. [CrossRef]

18. Jahirul, M.I.; Rasul, M.G.; Chowdhury, A.A.; Ashwath, N. Biofuels production through biomass pyrolysis—A technological review. *Energies* **2012**, *5*, 4952–5001. [CrossRef]

19. Achinas, S.; Euverink, G.J.W. Consolidated briefing of biochemical ethanol production from lignocellulosic biomass. *Electron. J. Biotechnol.* **2016**, *23*, 44–53. [CrossRef]

20. Hassan, S.S.; Williams, G.A.; Jaiswal, A.K. Emerging technologies for the pretreatment of lignocellulosic biomass. *Bioresour. Technol.* **2018**, *262*, 310–318. [CrossRef]

21. Rauch, R.; Hrbek, J.; Hofbauer, H. Biomass gasification for synthesis gas production and applications of the syngas. *Wiley Interdiscip. Rev. Energy Environ.* **2014**, *3*, 343–362. [CrossRef]

22. Feedstocks, B. Biomass Feedstocks. In *Biofuels*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 45–85. [CrossRef]

23. Shukla, A.; Kumar, S.Y. A comparative study of sugarcane bagasse gasification and direct combustion. *Int. J. Appl. Eng. Res.* **2017**, *12*, 14739–14745.

24. Corona, F.; Hidalgo, D.; Díez-Rodríguez, D.; Urueña, A. Conversion as the Key Step for the Production of Value-Added Products from Waste. *Biofuels* **2016**, 1–26. Available online: http://www.smgebooks.com/biofuels/chapters/BF-16-01.pdf (accessed on 21 August 2022).

25. Hu, J.; Yu, F.; Lu, Y. Application of fischer-tropsch synthesis in biomass to liquid conversion. *Catalysts* **2012**, *2*, 303–326. [CrossRef]

26. Ravaghi-Ardebili, Z.; Manenti, F.; Pirola, C.; Soares, F.; Corbetta, M.; Pierucci, S.; Ranzi, E. Influence of the effective parameters on H2:CO Ratio Of Syngas At Low-Temperature Gasification. *Chem. Eng. Trans.* **2014**, *37*, 253–258. [CrossRef]

27. Sheth, P.; Babu, B. Effect of Moisture Content on Composition Profiles of Producer Gas in Downdraft Biomass Gasifier. In Proceedings of the International Congress Chemistry and Environment (ICCE), Madhya Pradesh, India, 24–26 December 2005; pp. 356–360. Available online: https://www.researchgate.net/profile/Bontha_Babu/publication/228616005_Effect_of_Moisture_Content_on_Composition_Profiles_of_Producer_Gas_in_Downdraft_Biomass_Gasifier/links/0deec521907331b690000000.pdf (accessed on 21 August 2022).

28. Sukthang, N.; Liplap, P.; Arjharn, W.; Hinsui, T. The potential of high moisture biomass for energy production using plasma—Assisted gasification. *Orient. J. Chem.* **2017**, *33*, 1805–1814. [CrossRef]

29. Atnaw, S.M.; Sulaiman, S.A.; Yusup, S. Influence of fuel moisture content and reactor temperature on the calorific value of Syngas resulted from gasification of oil palm fronds. *Sci. World J.* **2014**, *2014*, 121908. [CrossRef] [PubMed]

30. Fonseca, F.G.; Funke, A.; Niebel, A.; Dias, A.P.S.; Dahmen, N. Moisture content as a design and operational parameter for fast pyrolysis. *J. Anal. Appl. Pyrolysis* **2019**, *139*, 73–86. [CrossRef]

31. Eke, J.; Onwudili, J.A.; Bridgwater, A.V. Influence of Moisture Contents on the Fast Pyrolysis of Trommel Fines in a Bubbling Fluidized Bed Reactor. *Waste Biomass Valorization* **2020**, *11*, 3711–3722. [CrossRef]

32. Prins, W.; Dahmen, N. Processes for Thermochemical Conversion of Biomass. In Proceedings of the 10th European Conference on Industrial Furnaces and Boilers, Porto, Portugal, 7 April 2015; pp. 1–8.

33. Ciferno, J.P.; Marano, J.J. *Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production*; U.S. Department of Energy National Energy Technology Laboratory: Pittsburgh, PA, USA, 2002; 58. Available online: https://netl.doe.gov/sites/default/files/netl-file/BMassGasFinal_0.pdf (accessed on 21 August 2022).

34. EU Biomass Availability and Sustainability Information System. *Report on Conversion Efficiency of Biomass*; BASIS Project; Evropean Commission: Brussels, Belgium, 2015; pp. 1–20. Available online: http://www.basisbioenergy.eu/fileadmin/BASIS/D3.5 _Report_on_conversion_efficiency_of_biomass.pdf (accessed on 21 August 2022).

35. Goffé, J.; Ferrasse, J.H. Stoichiometry impact on the optimum efficiency of biomass conversion to biofuels. *Energy* **2019**, *170*, 438–458. [CrossRef]