

The Production of Gaseous Biofuels Using Biomass Waste from Construction Sites in Recife, Brazil

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Keywords: gaseous biofuels, gasification, WTE, CCbiowaste

Abstract:

Due to climate change problems caused by greenhouse gas emissions generated by fossil fuels and from waste disposition, fuel alternatives for power generation are being extensively researched. Currently, in Brazil and in many countries, wood waste is disposed in landfills. However, due to lignin, one of the major constituents of biomass, which prevents wood waste from suffering microbial degradation, there is no significant mass degradation, even over decades, when landfilled. Hence, landfilling is not a solution to discard wood waste. Hence, one of the solutions to get rid of the great amount of wood waste is to use it as feedstock in waste-to-electricity (WTE) projects. WTE projects are in high demand in the world, as they can replace fossil fuels and they reduce two major environmental problems (greenhouse gas emissions due to the use of fossil fuels and the accumulation of waste in landfills), while generating biofuels and/or electricity. One of the residues that can be used in WTE projects is biomass residue from construction sites (CCbiowaste). CCbiowaste could be converted into gaseous biofuels through pyrolysis or gasification. These gaseous biofuels can be used in Otto engines connected to an electricity generator (gensets) to produce electricity and/or heat (cogeneration applications). Hence, the objective of this research was to characterize (physically, chemically, and energetically) civil construction biomass wastes (CCbiowaste), produced in a residential building construction site in Recife, Brazil, and to use these wastes in a bench-scale gasifier to produce gaseous biofuels at the temperatures of 700 °C, 800 °C, and 900 °C. The gaseous fuels were collected in the gasifier and analyzed in a gas chromatograph equipped with a thermal conductivity detector (TCD) to determine their composition and heating values. The lower heating value (LHV) results varied from 8.07 MJ/m³ to 10.74 MJ/m³ for 700 °C to 900 °C gasification temperature. These gaseous fuels were tested in an adapted Otto cycle engine connected to an electricity generator to prove the feasibility of this application. The highest total energy per ton of biomass was obtained for mixed wood and Pinus at 900 °C, with approximately 13 GJ/ton¹. Hence, the use of CCbiowaste can become an option for the reuse of wasted wood instead of simply dumping in a landfill.

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Article

The Production of Gaseous Biofuels Using Biomass Waste from Construction Sites in Recife, Brazil

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Abstract: Due to climate change problems caused by greenhouse gas emissions generated by fossil fuels and from waste disposition, fuel alternatives for power generation are being extensively researched. Currently, in Brazil and in many countries, wood waste is disposed in landfills. However, due to lignin, one of the major constituents of biomass, which prevents wood waste from suffering microbial degradation, there is no significant mass degradation, even over decades, when landfilled. Hence, landfilling is not a solution to discard wood waste. Hence, one of the solutions to get rid of the great amount of wood waste is to use it as feedstock in waste-to-electricity (WTE) projects. WTE projects are in high demand in the world, as they can replace fossil fuels and they reduce two major environmental problems (greenhouse gas emissions due to the use of fossil fuels and the accumulation of waste in landfills), while generating biofuels and/or electricity. One of the residues that can be used in WTE projects is biomass residue from construction sites (CCbiowaste). CCbiowaste could be converted into gaseous biofuels through pyrolysis or gasification. These gaseous biofuels can be used in Otto engines connected to an electricity generator (gensets) to produce electricity and/or heat (cogeneration applications). Hence, the objective of this research was to characterize (physically, chemically, and energetically) civil construction biomass wastes (CCbiowaste), produced in a residential building construction site in Recife, Brazil, and to use these wastes in a bench-scale gasifier to produce gaseous biofuels at the temperatures of 700 °C, 800 °C, and 900 °C. The gaseous fuels were collected in the gasifier and analyzed in a gas chromatograph equipped with a thermal conductivity detector (TCD) to determine their composition and heating values. The lower heating value (LHV) results varied from 8.07 MJ·m⁻³ to 10.74 MJ·m⁻³ for 700 °C to 900 °C gasification temperature. These gaseous fuels were tested in an adapted Otto cycle engine connected to an electricity generator to prove the feasibility of this application. The highest total energy per ton of biomass was obtained for mixed wood and *Pinus* at 900 °C, with approximately 13 GJ·ton⁻¹. Hence, the use of CCbiowaste can become an option for the reuse of wasted wood instead of simply dumping in a landfill.

Keywords: CCbiowaste; gasification; WTE; gaseous biofuels

1. Introduction

Brazil became an emergent country in the last decade and its development mainly involved infrastructure (refinery, car industry) and habitational projects. These sites have a great impact on

the environment due to fact that some of the waste generated during construction (CCbiowaste) is dumped in landfills with little recycling, especially biomass (plywood, timber, wood poles, cement bags, and sawed biomass) [1]. According to Vanderlei e Silva (2013), there are approximately 200 tons of biomass waste generated daily in Recife, Brazil. In Brazil, most of this biomass waste generated in civil construction sites is dumped in landfills or in inappropriate places (open dumps, left at the construction sites, or even left in the streets). According to Ximenes et al. (2015), prior to 2008, 1,457,000 tons of wood waste was deposited in Australia annually. Approximately 70% of the wood waste was generated in the construction and demolition (C&D) and/or commercial and industrial (C&I) streams [2]. In Europe, all wood waste must be used either in construction as recycled wood or in boilers and in municipal waste incinerators as biofuel, since the disposal of any wood waste in landfills is prohibited [3]. According to Diyamandoglu and Fortuna, 170 million tons of C&D waste was generated in the United States in 2003. Forty-eight percent (48%) of this total was dumped in landfills. Wood represented 33% of this total, i.e., approximately 30 million tons of wood was disposed of in landfills [4]. Wang et al. (2011) observed carbon loss varying from 0% up to 7.8% in hardwood such as red oak and *Eucalyptus pilularis* samples, and in softwood such as spruce and radiata pine from Australia in laboratory experiments [5]. Ximenes et al. concluded that there was little or no sign of decay in the wood samples analyzed from the landfill in Sydney, even in samples extracted from landfills that were 46 years old [2,6]. As a result of this investigation, it was concluded that the biodegradation of wood waste or CCbiowaste in landfills is very low or insignificant [2,5,6].

Cellulose, hemicellulose, and lignin are the major building blocks of lignocellulosic materials or wood biomass. Their percentage varies based on the type of biomass. Cellulose is the most abundant polymer, which corresponds to 20–30% of the primary cell wall's dry mass. Hemicellulose is the other major polysaccharide after cellulose, which corresponds to 20–40% by mass of lignocellulosic materials [7]; it is the third major component, which corresponds to 30% by mass of the cell wall and contributes up to 40% of the energy content [7]. Lignin is the cementing agent for cellulose fibers, holding adjacent cells together [8]. According to Khan and Ahring (2019) and Buendia-Kandia et al., lignin is an important constituent of the cell wall as it provides structural support and prevents microbial attacks and decomposition of the cell wall [7–9]. For this reason, CCbiowaste is not easily degraded by microorganisms in landfills, and, for this reason, environmentally friendly technological routes ought to be found to use this wood waste as a large-scale feedstock.

The most challenging issue in civil construction, in Brazil, as well as in other parts of the world, is to implement sustainable practices and to have an ecofriendly large-scale use of this biomass that can no longer be reused in construction sites due to its physical condition (damaged or broken) or if there is no other construction site to be used, as dumping in landfills was proven to not be a correct solution.

One alternative for the valorization of biomass waste is its use as a feedstock for waste-to-energy technology (WTE). WTE is defined as the process of recovering energy in the form of electricity and/or heat, as well as in the form of biofuels, by using thermal or biological processes [2,9,10]. One of the WTE routes is to use thermochemical processes to convert solid or liquid feedstock into gaseous fuels through gasification, pyrolysis, or hydrothermal liquefaction; the other routes consist of either biological processes comprising anaerobic digestion and alcoholic fermentation or landfilling with biogas recovery [9–11]. All routes convert solid biomass into biofuels. According to Passos et al., incineration is a treatment process that involves the combustion of waste. It can be used for electricity generation or to supply heat. However, due to the pollution control cost and the environmental danger it may represent, incineration has a low acceptance in the society [10].

The moisture content of feedstocks is one of the keys to selecting a proper route. Generally, low-moisture-content biomass is more feasible for use in the gasification and pyrolysis routes, while high-moisture-content biomass may be used as a feedstock for biological and hydrothermal liquefaction [2,3,9–11]. Hydrothermal liquefaction is normally carried out at 280–370 °C, between 10 MPa and 25 MPa, and its main products are biocrude oil with a heating value ranging between 22.8 and 36 MJ·kg⁻¹, char, water-soluble substances, and gas [11]. According to Toor et al., hydrothermal

liquefaction processes have the potential to become an important technology for converting wet biomass or organic waste into bio-oil for fuel and other applications [11]. Hence, due to their lower moisture content, civil construction biomass residues (CCbiowaste) were used as a feedstock in a bench-scale air gasifier to produce gaseous fuels. In the majority of cases, thermal chemical conversions require appropriate pre-treatments like drying, milling, and separation for efficient conversion [10]. In air gasification, biomass is partially oxidized to produce gaseous fuels [2,10,12]. For gasification processes, the temperature range lies within 700 °C and 900 °C in oxygen-deprived environments, typically 25–35% of the stoichiometric ratio for complete combustion [10]. The gaseous fuels' main constituents are carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), methane (CH₄), nitrogen (N₂), and hydrocarbons (HCs) [2,10,12–17]. The lower calorific value of these gaseous fuels may vary from 4–13 MJ·m⁻³ depending on the gasifier temperature and type [10,12–17]. According to Sikarwar et al. (2016), one of the most commonly used gasifiers is a fixed-bed gasifier (FXBG) that can exist as either an updraft (fuel enters from the top, gasifying agent enters from the bottom) or a downdraft gasifier (both fuel and gasifying agent enter from the top) [17]. Gasification enables solid biomass to be used as fuel in internal combustion engines and gas turbine cycles, as well as to produce green liquid fuels [9,11–17]. Kirubakaran et al. reported that gasification is economical at all capacities from 5 kW onwards, and that the rate of gasification is affected by the size, shape, environment, moisture, and ash content of the feedstock, as well as waste flow (batch or continuous) and gasification temperature [18]. For this reason, it is necessary to determine several characteristics of the biomass feedstock prior to the gasification process. The main characteristics to be determined are moisture, volatile matter, fixed carbon content, and ash content, which were obtained through proximate or thermogravimetric analysis (TGA). Furthermore, the effect of temperature and heating rate on biomass weight loss can be analyzed through TGA [18]. Ultimate analysis determines the amount of carbon, hydrogen, nitrogen, oxygen, and sulfur present in the solid biomass. The amount of bio-oxygen helps to convert solid combustible matter into gaseous fuels. Moreover, gasification can be catalyzed by certain metals contained in the ash. Gasification by bio-oxygen in the presence of ash is called auto-gasification [18]. These data obtained are important when analyzing the heat content of CCbiowaste. It is important to mention that gasification technology can use a wide range of feedstocks such as wood, crop residues, peat, black liquor, waste, and so forth. This process can be applied for the production of heat, electricity, and chemical energy, as well as transport fuels [8,11,18–20].

All CCbiowaste characterization and gasification experiments were carried out at the Fuel and Energy Laboratory of the University of Pernambuco, in Recife, Brazil.

The importance of this work lies in the fact that few researchers investigated the gasification of CCbiowaste or landfill-diverted wood. According to Littlejohns et al. (2020), many experimental gasification studies focused on the utilization of clean wood chips, and there is a lack of experimental gasification studies using more challenging feedstocks such as landfill-diverted feedstock or CCbiowaste [19]. Hence, the use of wood waste as a feedstock for distributed biomass gasification cogeneration provides an economical solution to avoid landfilling whilst producing low-carbon energy [19].

As an incentive to produce electricity from renewable sources, starting on 1 March 2018, through Decree 65 of the Ministry of Mines and Energy, the Brazilian Government established a new tariff when purchasing electricity in the decentralized power generation program, called ProGD. The price for MWh generated using residual biomass was R\$349.00 (Brazilian real) and that for municipal solid waste was R\$561.00 [21,22]. For comparison reasons, it is worth noting that the exchange rate was \$1 United States dollar (USD) to R\$4.0805 on 25 December 2019 [23].

This work had the objective of promoting the use of CCbiowaste as fuel, avoiding environmental problems such as the accumulation of CCbiowaste in landfills due to its low biodegradability. Furthermore, this work obtained the physical, chemical, and energetic data for CCbiowaste, as these properties can help understand the thermo-chemical conversion of solid biomass waste to gaseous fuels through gasification, as well as evaluate their potential to generate electricity in civil construction sites.

2. Materials and Methods

This work was based on collecting biowaste samples in civil construction sites in Recife during the construction of a multi-story residential building made of reinforced concrete and masonry, consisting of 40 floors and a constructed area of 11,416.91 m². Reinforced concrete and masonry are the most common type of building construction carried out in Brazil [24].

2.1. CCbiowaste Characterization

A compositional analysis of the biomass waste produced in the construction site was carried out using the Brazilian Standard ABNT NBR 10.007:2004 [25]. Furthermore, it was observed that the biomass used in several phases of the building construction could be divided into four main groups: mixed wood (timber made of several types of wood such as eucalyptus, cedar, and *Pinus*, for instance; the composition is not fixed, as other types of wood can be used), *Pinus* (*Pinus elliotti*), plastic-coated plywood, and resin-coated plywood.

The collected biomass samples were physically treated to obtain their physical, chemical, and energetic data, before being used as a feedstock in the gasifier. The physical treatment consisted of grinding, screening, homogenizing, and manually densifying to form pellets. For grinding, a knife mill made by Marconi (Marconi Equipamentos para Laboratorio, Piracicaba-SP, Brazil -marconi@marconi.com.br), Model MA-048 was used with a screen Mesh 20/30 (0.841–0.595 mm). The ground biomass was densified using a manual press (IKA Werke GmbH, Janke-Kunkel Strasse 10, Staufen im Breisgau, Germany), and the pellets were used in analytical equipment to obtain their data; for the gasification experiments, the pellets were made using a 100-kg·h⁻¹ pelletizer manufactured by Xuzhou Orient Industry Co. Ltd. (Xuzhou – Jiangsu, China).

The experiments to obtain the physical, chemical, and energetic data of the biomass waste were carried out at the Fuel and Energy Laboratory of the University of Pernambuco, in Recife, Brazil. The experiments and the standards used were as follows: density (ABNT NBR 7190, 1997 [26]); moisture content—dry-oven method (ABNT NBR 14929, 2017 [27] and ASTM D 4442-07 [28]); ultimate analysis (ASTM D3176-15 [29]); proximate analysis (ASTM D 3172-12 [30]); ash content (ABNT NBR 8289 [31] and ASTM D 2974-87 [32]); higher and lower heating values (ASTM D 2015-77, 1983 [33]).

For ultimate analysis, the Elemental-Vario-El Cube equipment (Elementar Analysensysteme GmbH, Langenselbold, Germany) was used to determine the carbon, hydrogen, oxygen, nitrogen, and sulfur content, in % *m/m*, of the biomass waste. For approximate analysis, the moisture, as well as the volatile, fixed carbon, and ash content, was determined using a Shimadzu-model DTG-60 (Shimadzu Corporation, Kyoto, Japan). For these experiments, the thermogravimetric balance was set to heat from ambient temperature (30 °C) to 900 °C, using a fixed heating ramp of 10 °C·min⁻¹. From ambient temperature to 850 °C, nitrogen was used as the oven atmosphere to obtain moisture and volatile mass data; then, the oven atmosphere was changed to oxygen, a reactive gas, to burn the fixed carbon and to obtain the ash content of the biomass. An IKA C-2000 calorimeter (IKA Werke GmbH, Staufen im Breisgau, Germany) was used for determining the biomass samples' higher heating value (HHV) and lower heating value (LHV).

2.2. Gasification Experiments

The gasification experiments were carried out using a bench-scale gasifier (BSG), illustrated in Figure 1. This BSG in the experiments was designed by Peres [14] and implemented with monitoring equipment for operation at different gasification temperatures and residence times [34,35]. This BSG consisted of a 30-cm-long, two-inch-diameter, 304 stainless-steel seamless tube gasifier (1). The reactor internal temperature distribution was monitored using three type K thermocouples (2). The bench-scale gasifier was heated externally by two electrical resistors (1000 W total) (3) and thermally isolated with a 2-mm-thick flexible rockwool insulation blanket (4). At one end of the gasifier tube, there was a ball valve (5) where the biomass samples could be placed in the middle of the reactor and the

gasification residues could be removed. On the other end, a needle valve (6) and a pressure gauge (7) were installed. The pressure gauge was used to monitor the pressure increase during the gasification process, and, when there was no increase in pressure, it was assumed that the conversion of solid to gas was complete. Then, after the established residence time (3 min), the needle valve was opened, and the biomass gaseous fuels, after passing through a filter made of oxidized steel wool (not shown in Figure 1), used as a heat sink to remove condensables, were collected in sample bags through the port (8). All experiments were carried out in batch mode in limited aerobic conditions, as only the air trapped inside the reactor was used in the gasification experiments.

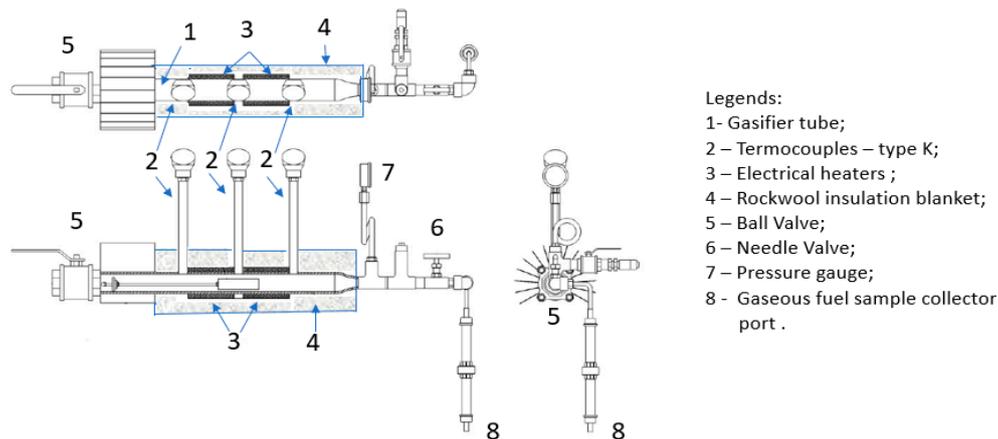


Figure 1. The POLICOM bench-scale gasifier scheme (adapted from Reference [34]).

The air gasification experiments were conducted at 700 °C, 800 °C, and 900 °C using a 3-min residence time, with samples weighing 5 g, as done in the work of Geraldo (2012), Vanderlei e Silva (2014), and Cavalcanti (2017) [1,34,35]. The gaseous fuel content at the given temperatures was analyzed by gas chromatography using a GC SRI-8610C (SRI Instruments, Torrance, CA, USA), equipped with a thermal conductivity detector (TCD). The carrier gases were argon and hydrogen. Hydrogen gas was used for the analysis of all gases except for hydrogen, which was analyzed using argon as the carrier gas. After the determination of the gases produced and their volume, it was possible to work out the volume, gaseous content, and calorific value of gas produced in each experiment at the given temperatures. This procedure was described in Peres (1997) [14].

3. Results and Discussion

In this section, the results are divided into biomass collection and sampling, biomass characterization, and gasification.

3.1. Biomass Collection and Sampling

This first step was to analyze the construction site documents to determine the amount of biomass purchased to construct the multi-story residential building. The results are shown in Table 1.

Table 1. Total purchased biomass for the residential building construction site.

Biomass Type	Mass (ton) *	Mass Percentage (%)
Mixed wood	110	67
<i>Pinus</i>	18	11
Plastic-coated plywood	24	14
Resin-coated plywood	12	8
Total	164	100

* Total biomass mass (on a wet basis).

As observed in Table 1, mixed wood was the most acquired biomass for the construction site. The mixed wood consisted of different types of woods, with no specification of type given by the seller. Mixed wood is used for the construction of concrete mold, scaffolding timbers, slats, and rafters. In Brazil, generally, there are 18 types of woody biomass used for this purpose. The complete list of wood used in construction sites in Brazil can be seen in the work by Zenid (2009) [36]. Examples of types of wood used in Brazil are *Hymenolobium* spp., *Platonia insignis*, *Erisma uncinatum*, *Eucalyptus tereticornis*, *E. citriodora*, *E. saligna*, and *Clophyllum brasiliense* [36]. According to Mello and Vieira (2015), CCbiowaste represents 31% to 42% by volume or 25% to 35% by mass of the waste generated in the construction of residential buildings in Brazil [37]. Due to the large number of types of wood used in civil construction, details on the most common wood type used in building constructions were not found in the literature, as the availability of the different types varies significantly in Brazil and in the world. For this reason, the quantity of wood, shown in Table 1, was determined using a booklog of residues of the studied residential building construction site. This log took into account that most of the biomass was relocated to other construction sites or sold to recycling companies to be used at other construction sites (by other companies) or as fuel for bakeries and pizzerias [1].

3.2. Biomass Characterization

3.2.1. Density, Moisture, and Ash Content

The results of density, moisture, and ash content, on a dry basis and in terms of % m/m , of the construction site biomass waste are shown in Table 2. As observed, the highest density was found for mixed biomass at $800 \text{ kg}\cdot\text{m}^{-3}$, while that for *Pinus* was $414 \text{ kg}\cdot\text{m}^{-3}$. For the two types of plywood, the densities were about the same, at around $520 \text{ kg}\cdot\text{m}^{-3}$.

Table 2. Density, moisture, and ash content by mass.

Biomass Type	Density ($\text{kg}\cdot\text{m}^{-3}$) *	Moisture ¹ (%) *	Ash ² (%) (600 °C) *
Mixed wood	800 ± 12	7.6 ± 0.1	1.08 ± 0.07
<i>Pinus</i>	414 ± 21	7.4 ± 0.1	0.94 ± 0.01
Plastic-coated plywood	519 ± 17	10.3 ± 0.1	2.09 ± 0.10
Resin-coated plywood	521 ± 3	9.2 ± 0.1	2.11 ± 0.12
Weighted average ³	696	8.1	1.29

* On a dry basis; ¹ oven method [27,28]; ² muffle method [31,32]; ³ based on the percentage of each type of biomass (Table 1).

The moisture content varied from 7.6% to 10.3%, by mass, with no prior drying process. The ash content varied from 0.94% to 2.11%, by mass.

The Wood Fuels Handbook states that the density of *Pinus* and plywood lies within the bulk density of beech, spruce, and fir, ranging from $445 \text{ kg}\cdot\text{m}^{-3}$ to $304 \text{ kg}\cdot\text{m}^{-3}$ [38]. Furthermore, the density of conifer wood such as cypress, stone pine, maritime pine, and Aleppo pine varies from $600 \text{ kg}\cdot\text{m}^{-3}$ to $810 \text{ kg}\cdot\text{m}^{-3}$ [38]. Wood ash content may vary from 0.20% to 6.13% by mass; however, the ash content can be much higher for agriculture residues such as sugarcane bagasse and rice hulls, with 13.30% and 15.41–20.60% by mass, respectively [13,14,19,38–41]. Moisture contents of 6.5% and 14.1% (as received) were reported for *Eucalyptus* [38,42], while values of 0.4% and 0.3% were obtained for air-dried spruce and pine, respectively [18]. Additionally, the moisture content was found to vary from 3.03% to 8.65%, by mass, for willow, poplar, maritime pine, and chestnut [39]. However, Littlejohns et al., who used landfill-derived wood waste, reported moisture contents of 10% to 11% and 7% to 8% for air-dried spruce and pine, respectively, while moisture contents of 6% and 20% were obtained for construction and demolition (C&D) wood. The ash content for C&D wood varied from 0.7% to 0.8%, by mass, as received [19]. According to Basu (2010) and Ruiz et al. (2013), thermal gasification typically requires a moisture content of less than 15% [8,13]. Every kilogram of moisture needs about 2300 kJ of heat to

vaporize and an additional 1500 kJ to be raised to a typical gasifier temperature of 700 °C. Therefore, lower moisture results in more heat available in the product gas [8]. Hence, it is desirable to keep moisture as low as possible to enhance the gaseous product heating value.

3.2.2. Ultimate Analysis

The biomass composition in terms of carbon, hydrogen, nitrogen, sulfur, and oxygen was determined as shown in Table 3.

Table 3. Ultimate analysis results.

Biomass Type	Content (% by mass) *				
	C	H	O	N	S
Mixed wood	46.27 ± 0.55	6.59 ± 0.03	45.67 ± 0.56	0.16 ± 0.01	0.21 ± 0.02
<i>Pinus</i>	46.29 ± 0.19	6.58 ± 0.03	46.32 ± 0.22	0.10 ± 0.01	0.11 ± 0.01
Plastic-coated plywood	48.08 ± 1.03	6.57 ± 0.13	43.72 ± 1.17	0.24 ± 0.01	0.10 ± 0.01
Resin-coated plywood	47.60 ± 0.50	6.56 ± 0.08	44.04 ± 0.59	0.21 ± 0.01	0.11 ± 0.01
Weighted average ¹	46.63	6.58	45.34	0.17	0.18

* On a dry basis; ¹ based on the percentage of each type of biomass (Table 1).

According to the Wood Fuels Handbook and the Atlas of Thermal Data, the typical values for coniferous wood ultimate analysis, by mass, are as follows: C (47–54%), H (5.6–7.0%), O (40–44%), N (0.1–0.5%), and S (0.01–0.05%) [34,38]. For woody energy crops such as *Eucalyptus* and *Casuarina*, the results are as follows: C (48.5–49%), H (5.83–6.04%), O (43.32–45.13%), N (0.15–0.59%), and S (0.30–0.59%) [39]. Similar results for the ultimate analysis of C&D wood waste were reported for woody biomass by other authors [19,39–43].

3.2.3. Proximate Analysis

The proximate analysis results are shown in Table 4.

Table 4. Proximate analysis results.

Biomass Type	Content (% by mass) *			
	Volatiles *	Fixed carbon *	Ashes (900 °C) *	Moisture *
Mixed wood	98.59 ± 0.19	0.53 ± 0.11	0.88 ± 0.11	11.35 ± 0.32
<i>Pinus</i>	98.68 ± 0.04	0.50 ± 0.03	0.82 ± 0.06	13.68 ± 0.34
Plastic-coated plywood	99.42 ± 0.13	0.41 ± 0.07	0.17 ± 0.03	11.88 ± 0.78
Resin-coated plywood	99.4 ± 0.16	0.34 ± 0.05	0.26 ± 0.07	12.78 ± 0.22
Weighted average ¹	98.78	0.49	0.72	11.79

* On a dry basis; ¹ based on the percentage of each type of biomass (Table 1).

Several authors reported values for the proximate analysis of woody biomass as follows: volatiles (67.92–90.60%) and fixed carbon (9.20–23.01%), by mass [36–43]. These values were smaller than those obtained in this research, probably due to different test conditions, especially the temperature range. In this research, the heat ramp was set to 10 °C·min⁻¹, and the inert nitrogen atmosphere was changed to an oxygen atmosphere at 850 °C, while the experiment finished at 900 °C. Some authors carried out their experiments in temperatures up to 660 °C [39,43] and 280 °C [40], or using the oven-dry method [38]. For this reason, the ash results reported in Table 4 were lower than those found in the literature [38–44].

3.2.4. Calorimetric Analysis

The higher heating value (HHV) and lower heating value (LHV) for each type of biomass used in the construction site are illustrated in Table 5.

Table 5. Biomass higher heating value (HHV) and lower heating value (LHV).

Biomass Type	HHV * (MJ·kg ⁻¹)	LHV * (MJ·kg ⁻¹)
Mixed wood	18.205 ± 97	17.988 ± 113
<i>Pinus</i>	17.701 ± 153	17.509 ± 172
Plastic-coated plywood	17.723 ± 101	17.487 ± 124
Resin-coated plywood	17.804 ± 84	17.560 ± 88
Weighted average ¹	18.050	17.831

* On a dry basis; ¹ based on the percentage of each type of biomass (Table 1).

The HHV for *Pinus* was 5% lower than that reported by Pintor-Ibarra et al. (2017) [44], with similar results obtained by other authors [19,39,43]. However, as a whole, the values in Table 5 were within the values of 13.3 to 19.2 MJ·kg⁻¹ reported in the literature for different biomass [19,35–45].

The higher energy content of biomass, lower ash content, and higher content of hydrogen and oxygen, combined with the high volatile matter, indicate that the biomass can be easily converted to gaseous fuel and it can combust more easily than coal, for instance [43].

3.3. Biomass Waste Gasification

The gaseous formation results are shown in Table 6, Table 7, and Table 8 for the 700 °C, 800 °C, and 900 °C gasification experiments, respectively. The bench-scale gasification experiment investigated the effect of reactor temperature on the gaseous fuels formed for each type of biomass used from the construction site.

Table 6. Gaseous fuel composition for the 700 °C gasification.

Biomass Type	(% mol/mol)					LHV (MJ·m ⁻³)
	H ₂	CO	CO ₂	CH ₄	N ₂	
Mixed wood	25.2 ± 0.8	13.1 ± 1.3	27.5 ± 1.2	11.7 ± 0.1	21.8 ± 1.3	8.07 ± 0.15
<i>Pinus</i>	22.5 ± 2.2	14.1 ± 1.0	28.1 ± 0.9	13.9 ± 0.3	20.0 ± 1.0	8.99 ± 0.47
Plastic-coated plywood	24.1 ± 1.5	11.7 ± 0.2	28.4 ± 0.5	13.3 ± 0.7	21.3 ± 0.3	8.55 ± 0.22
Resin-coated plywood	22.8 ± 2.0	12.4 ± 0.9	27.2 ± 2.0	13.3 ± 0.9	23.1 ± 1.9	8.53 ± 0.41
Weighted average ¹	24.6 ± 1.1	13.0 ± 0.9	27.6 ± 0.5	12.3 ± 0.8	21.6 ± 1.1	8.28 ± 0.35

¹ Based on the percentage of each type of biomass (Table 1).

Table 7. Gaseous fuel composition for the 800 °C gasification.

Biomass Type	(% mol/mol)					LHV (MJ·m ⁻³)
	H ₂	CO	CO ₂	CH ₄	N ₂	
Mixed wood	25.4 ± 2.4	14.9 ± 0.6	31.1 ± 2.0	14.8 ± 0.3	12.3 ± 1.0	9.72 ± 0.43
<i>Pinus</i>	21.8 ± 1.7	15.9 ± 0.3	31.9 ± 2.4	16.8 ± 1.6	12.0 ± 0.8	10.18 ± 0.68
Plastic-coated plywood	31.5 ± 0.4	13.4 ± 0.5	25.8 ± 2.4	16.1 ± 0.3	11.4 ± 0.9	10.70 ± 0.11
Resin-coated plywood	30.2 ± 2.3	14.5 ± 1.3	24.1 ± 2.4	15.5 ± 0.3	14.3 ± 0.8	10.28 ± 0.40
Weighted average ¹	26.2 ± 3.9	14.7 ± 0.9	29.9 ± 3.3	15.3 ± 0.7	12.3 ± 1.1	9.95 ± 0.39

¹ Based on the percentage of each type of biomass (Table 1).

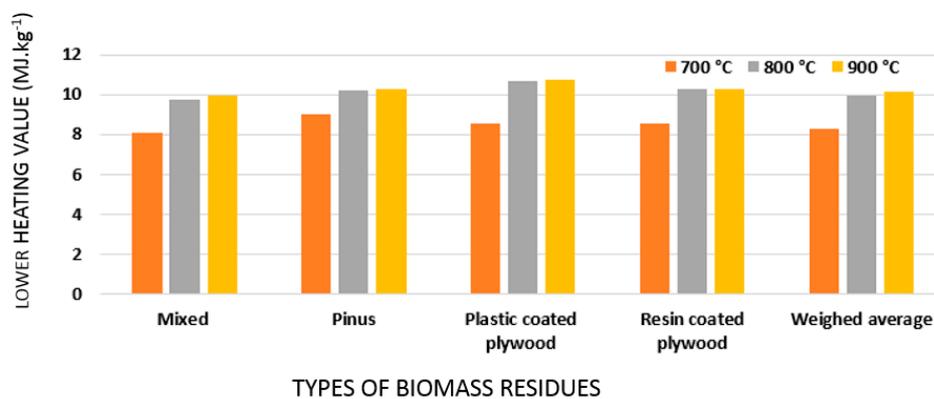
Table 8. Gaseous fuel composition for the 900 °C gasification.

Biomass Type	(% mol/mol)					LHV (MJ·m ⁻³)
	H ₂	CO	CO ₂	CH ₄	N ₂	
Mixed wood	19.7 ± 1.9	20.4 ± 1.4	18.9 ± 1.0	17.0 ± 0.2	23.5 ± 1.3	9.97 ± 0.21
Pinus	19.1 ± 1.8	21.4 ± 1.3	20.4 ± 1.6	17.0 ± 1.4	21.0 ± 1.8	10.31 ± 0.68
Plastic-coated plywood	24.8 ± 1.9	23.3 ± 1.7	20.7 ± 1.2	14.4 ± 1.0	14.7 ± 1.3	10.74 ± 0.29
Resin-coated plywood	24.6 ± 2.1	21.8 ± 1.6	19.0 ± 0.8	13.1 ± 0.6	19.2 ± 1.9	10.28 ± 0.26
Weighted average ¹	20.7 ± 2.7	21.0 ± 1.1	19.3 ± 0.8	16.3 ± 1.7	21.6 ± 2.2	10.14 ± 0.31

¹ Based on the % of each type of biomass (Table 1).

Tables 6–8 illustrate the results of the gaseous conversion for the four types of CCbiowaste studied. These tables show that the production of hydrogen, carbon monoxide, and methane varied with the gasification temperature. Taking into account the weighted average results, it is possible to observe that the percentage of carbon monoxide in the syngas increased by 61.5% from 700 °C to 900 °C, while there was a reduction in carbon dioxide percentage from 700 °C to 900 °C. Additionally, the methane content increased with temperature, whilst there were reductions in the hydrogen and carbon dioxide contents in the syngas. Ruiz et al. (2013) stated that raising the temperature increases the concentration of CO and H₂ in syngas and reduces that of CO₂, CH₄, and H₂O [13]. However, similar behaviors were observed only for CO and CO₂ using the CCbiowaste. In the CCbiowaste experiments, the production of H₂ decreased and that of CH₄ increased with temperature. These results can be modeled using the main gasification reactions that occur simultaneously inside the reactor. These reactions are char reactions, oxidation reactions, water-shift reactions, methanization reactions, and steam reactions [13].

Figures 2 and 3 illustrate the effect of temperature on the LHV and volume generation of gaseous fuels produced during gasification of the four types of biomass waste used from the construction site.

**Figure 2.** Effect of the gasification temperature on the LHV of the gaseous fuels.

The LHV results obtained in the CCbiowaste gasification at 700 °C, 800 °C, and 900 °C ranged from 8.07 to 10.74 MJ·m⁻³. These results were higher than those reported by Basu, Ruiz et al., Littlejohns et al., and Martinez et al., which ranged from 4.5–6.34 MJ·m⁻³ using several types of biomass such as wood chips, spruce, wood pallets, rice husk, sawdust, pine wood blocks, wood waste, and construction and demolition biomass, in temperatures ranging from 700 °C to 1000 °C [8,13,19,20]. In this same temperature range, experiments using dried sugarcane bagasse obtained higher heating values ranging from 9.77 to 13.82 MJ·m⁻³ [14,15]. Passos et al. obtained results for the LHV of syngas at 8.62 MJ·m⁻³, which was similar to that obtained at 700 °C using construction and demolition waste with 12.7% moisture (by mass) [10]. However, Passos et al. did not mention the temperature at which gasification was carried out. As mentioned by Littlejohns et al., there is a lack of experimental studies

on CCbiowaste and landfill-diverted wood, which makes the comparison of results with other authors rather difficult, thus showing the originality of this work [19].

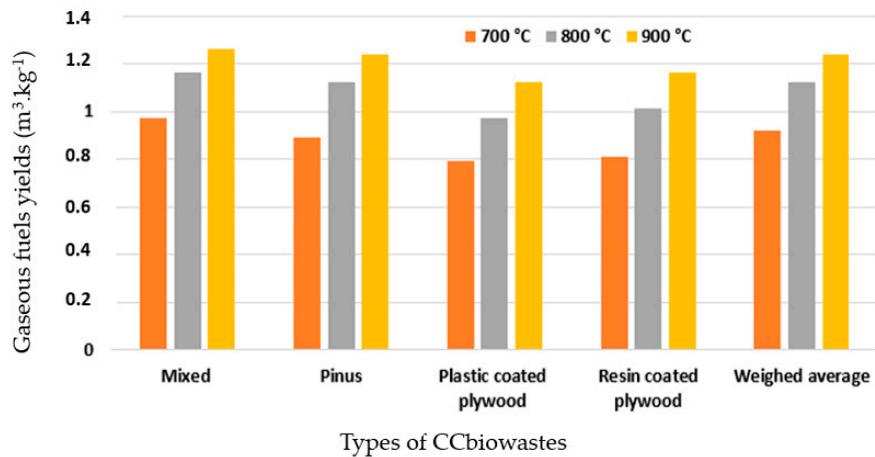


Figure 3. Effect of the gasification temperature on the gaseous fuel yields.

As shown in Figure 3, the gaseous fuel yields varied with temperature. Passos et al. reported a production of $0.916 \text{ Nm}^3 \cdot \text{kg}^{-1}$ in the gasification of C&D waste, similar to that produced with mixed wood [10]. Ruiz et al. stated that the amount of syngas produced per kilo of biomass varied from $2.2\text{--}2.4 \text{ Nm}^3 \cdot \text{kg}^{-1}$ with pelletized biomass used in downdraft gasifiers [13]. Martinez et al. reported gaseous yields ranging from $1.62 \text{ Nm}^3 \cdot \text{kg}^{-1}$ for wood waste to $1.99 \text{ Nm}^3 \cdot \text{kg}^{-1}$ for sawdust and $1.44 \text{ Nm}^3 \cdot \text{kg}^{-1}$ for wood chips [20]. Arena et al. reported yields of 2.34 and $2.56 \text{ Nm}^3 \cdot \text{kg}^{-1}$ for solid recovered fuel (paper and plastic mixed solid fuel) at 880 °C and 989 °C gasification temperature, respectively [46].

Based on the results obtained for the LHV and gaseous fuel yields (Figures 2 and 3), it was possible to determine the total energy available (TEA) per ton of the four CCbiowaste types gasified at the given gasification temperatures (700 °C, 800 °C, and 900 °C), as shown in Figure 4.

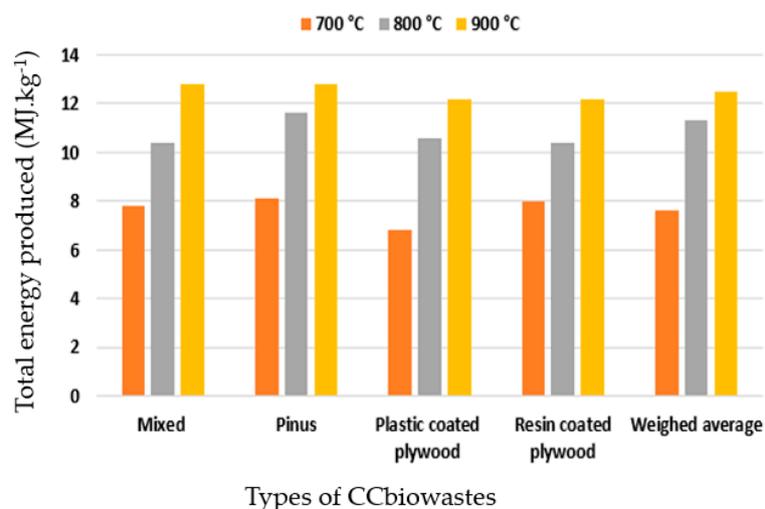


Figure 4. Effect of temperature on the total energy available (TEA) ($\text{MJ} \cdot \text{kg}^{-1}$) of the gasified CCbiowaste.

Figure 4 illustrates that the total energy produced, in $\text{MJ} \cdot \text{kg}^{-1}$, increased significantly with temperature. This can be explained by the greater volume of gaseous fuels produced and the higher heating values, which increased with temperature. All four types of CCbiowaste studied presented similar behaviors. At 700 °C, the total energy varied from 6.4 to $8 \text{ MJ} \cdot \text{kg}^{-1}$; at 800 °C, the total energy

was above $10 \text{ MJ}\cdot\text{kg}^{-1}$ for all types of feedstock; at $900 \text{ }^\circ\text{C}$, the total energy reached values above $12 \text{ MJ}\cdot\text{kg}^{-1}$.

It was not possible to find the TEA for wood waste or C&D waste in the literature, even though some authors reported values of the LHV ($\text{MJ}\cdot\text{m}^{-3}$) and yield ($\text{Nm}^3\cdot\text{kg}^{-1}$) [10,13,20,46]. To enable a comparison with the CCbiowaste TEA, the authors multiplied the values of LHV and gaseous yield using the values found in the literature to determine the TEA of several types of biomass, as shown in Table 9 [10,14,15,20,46].

Table 9. TEA calculation for biomass gasification.

Biomass	Temperature ($^\circ\text{C}$)	Yields ($\text{Nm}^3\cdot\text{kg}^{-1}$)	LHV ($\text{MJ}\cdot\text{m}^{-3}$)	TEA * ($\text{MJ}\cdot\text{kg}^{-1}$)	Reference
C&D waste	n.a.	0.916	8.62	7.90	[10]
Sugarcane bagasse	900	0.55	12.25	6.74	[14,15]
Sugarcane bagasse	1000	0.65	12.84	8.35	[14,15]
Wood chips	n.a.	1.44	5.06	7.29	[20]
Sawdust	900	1.99	6.32	12.58	[20]
Wood waste	1050	1.62	6.34	10.27	[20]
Hazelnut shells	1025	1.97	4.55	8.96	[20]
Solid recovered fuel (SRF)	800	2.34	5.16	12.07	[46]
Solid recovered fuel (SRF)	898	2.56	4.91	12.57	[46]

C&D—construction and demolition; n.a.—not available; * calculated by the authors.

Hence, when analyzing the TEA for the different types of CCbiowaste with respect to the values in Table 9, it is possible to verify that the values obtained at $700 \text{ }^\circ\text{C}$ gasification were closer to those for sugarcane bagasse at $900 \text{ }^\circ\text{C}$, wood chips, and C&D waste. For the CCbiowaste gasification at $800 \text{ }^\circ\text{C}$, the results were similar to those for wood waste at $1050 \text{ }^\circ\text{C}$ (much higher temperature). The best results for CCbiowaste gasification were obtained at the gasification temperature of $900 \text{ }^\circ\text{C}$. The TEA results varied from 12 to $12.8 \text{ MJ}\cdot\text{kg}^{-1}$ which were similar to the TEA results for solid recovered fuel (SRF) and sawdust. This means that the use of CCbiowaste as a feedstock for gasification processes is very promising, and it is a good way to valorize the biomass waste generated at construction sites, as well as significantly reduce the environmental impact.

3.4. Energy Production and the Brazilian ProGD

If we considered that the 200 tons of construction wood wasted daily in Recife is used for power production, this would generate 6400 MWh monthly. As mentioned, the Brazilian ProGD program established values to purchase the electricity generated using residual biomass as R\$349.00/MWh (USD \$85.5287/MWh) and that using municipal solid waste as R\$561.00 (USD \$137.48315) [18,19]. Hence, the electricity generated can be sold to power companies through the Brazilian ProGD Program. This would generate a revenue of R\$2,233,600.00 (USD \$547,383.90) per month if the CCbiowaste or landfill-derived fuel is used as a feedstock in Recife, Brazil. This revenue may attract power and civil construction companies to invest in such technology to produce electricity.

Hence, the gasification of wasted biomass from construction sites and its use as a fuel for power generation in internal combustion engines (Otto cycle engines) seems to be an interesting solution to valorize the biomass waste while providing electricity and reducing or even eliminating the environmental problems caused by the dumping of biomass.

4. Conclusions

CCbiowaste can be used as a feedstock for the gasification process to generate electricity. If all 200 tons of construction wood wasted daily in Recife is used for power production, this would generate 6400 MWh monthly, which may have a revenue of R\$2,233,600.00 (USD \$547,383.90) per month, and which may attract investors to use this technology.

Gasification produced gaseous fuels with an average LHV ranging from 8.28 MJ·m⁻³ for experiments carried out at 700 °C to 9.95 MJ·m⁻³ at 800 °C and 10.14 MJ·m⁻³ at 900 °C.

The best energy results were obtained when gasifying CCbiowaste at 900 °C, with values above 12 GJ·ton⁻¹.

Among the different types of CCbiowaste studied, the best results were obtained for mixed wood and *Pinus* at 900 °C, with values of approximately 13 GJ·ton⁻¹.

The use of gasification could be an interesting way to valorize CCbiowaste, while providing sustainable electricity and reducing (or even eliminating) the environmental problems caused by the dumping of biomass in landfills, where it does not degrade significantly.

Author Contributions: S.P. designed the experiments, discussed the results, and prepared the original paper; A.G. helped with the data on construction biomass waste and analyzed the results; F.V.e.S., H.S., and E.L. managed the experimental tests. All authors helped in discussing the results and formatting the paper. All authors have read and agreed to the published version of the manuscript.

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