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Gasification of waste from coffee and eucalyptus production as an alternative source of bioenergy in Brazil

Jofran Luiz de Oliveira[a], Jadir Nogueira da Silva[b], Marcio Arêdes Martins[b], Emanuele Graciosa Pereira[b,*], Maria da Conceição Trindade Bezerra e Oliveira[a]

[a] Universidade Federal de Mato Grosso, Rod. MT 270 km 06, Rondonópolis, MT, Brazil
[b] Universidade Federal de Viçosa, Av. P.H. Rolfs, Viçosa, MG, Brazil

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ABSTRACT

This paper presents results of a study about the gasification process of waste from eucalyptus production, as wood chips, and wastes from coffee production, as coffee husks and coffee wood. These wastes were subjected to gasification in an open-source commercial small-scale downdraft gasifier, using air as the gasifying agent. The fuel gas composition was monitored in a fuel gas analyzer to determine the volume concentration of CO, CO_2, H_2 and CH_4, and higher heating value (HHV). The coffee husk fuel gas presented the average HHV of 7.76 ± 1.27 MJ Nm^{-3} containing predominantly methane, carbon monoxide and carbon dioxide. The fuel gas from coffee wood gasification reached the lowest HHV (5.45 ± 0.42 MJ Nm^{-3}), containing predominantly carbon monoxide (14.03 ± 0.72%). The gasification of eucalyptus chips presented average HHV of 6.81 ± 0.34 MJ Nm^{-3}, with predominance of carbon monoxide (20.24 ± 0.93%), showing a regular composition during the experimental trials, and superior operational performance among the three biomasses investigated. This study demonstrates that gasification is an attractive alternative for waste-to-energy conversion and the energy upgrade can be used for on farm sustainable activities.

Introduction

Brazil is the largest producer of coffee in the world (2,906,315 tons per year) and the coffee production is mainly concentrated southeastern with approximately 80% of the total production in the country. The production of eucalyptus supports a wide range of applications including furniture, cellulose pulp, charcoal, logs and timber. The eucalyptus production in Brazil accounted for 115,741,531 m^3, and excluding charcoal and logs, about 65% of wood production is characterized as waste generated by the industrial activity. The wastes generated in the production of wood and coffee have great potential for energy production in Brazil and it could be used as inputs for this sector [1].

Brazil is one of the countries with the most advanced biomass energy recovery programs. Gasification technology has many applications and should form the basis of bioenergy [2]. The biomass energy conversion process is a feasible alternative to generate energy for production systems, even in remote locations where access to the electrical distribution network is not yet available. This technology has proven to be sustainable and can contribute to the development of small farms [3,4].

Biomass gasification is a promising green development for a worldwide sustainable energy system, which may decrease our current dependence on fossil fuels [5–8]. The gasification process is defined as the conversion of biomass or any solid fuel to an energetic gas through partial oxidation at high temperatures, using 20–40% of the stoichiometric air, also known as equivalence ratio [9]. This complex process is affected by many parameters including physical and chemical properties of biomass, the gasifying agent and equivalence ratio, operating temperature, catalyst addition and gasifier type. The effects of these parameters on the gasification process must be understood for this system to perform effectively [10,11]. One of the major problems in gasification is the tar formation, which causes operating issues such as downstream fouling due to tar condensation at temperatures below 350 °C resulting in a fuel gas with lower heating value [12].

Research and development of biomass gasification technologies have been encouraged worldwide due to the abundance of raw materials and vast potential for energy [13–15]. However, there is still a lack of information in regard to the energy content of fuel gas from gasification of coffee wood, and applicability of an open-source small-scale downdraft gasifier to generate energy from waste of agricultural production. In this context, the aim of this study was to analyze the

* Corresponding author.
E-mail addresses: jofran@ufmt.br (J.L. de Oliveira), jadir@ufv.br (J.N. da Silva), aredes@ufv.br (M.A. Martins), emanuele.pereira@ufv.br (E.G. Pereira).

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Table 1
Proximate analysis, elemental composition and heating values of biomasses.

Biomass	Proximate analysis				Composition					
	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)	C (%)	H (%)	O (%)	HHV (MJ kg^{-1})	(MJ kg^{-1})	Specific mass (kg Nm^{-3})
Coffee wood	9.61	85.73	0.94	13.33	47.50	6.01	44.86	18.07	16.35	416.70
Eucalyptus chips	9.74	90.55	0.44	9.02	46.94	6.08	45.84	17.30	170	179.80
Coffee husk	9.22	81.87	1.71	16.42	47.71	5.93	43.96	18.56	16.73	138.80

composition and behavior of fuel gas during the gasification of wastes from coffee and eucalyptus production in an open source and low-cost downdraft reactor. This analysis is used to evaluate the feasibility of using the described technology to generate energy from wastes of coffee and eucalyptus crops in order to improve sustainability of agricultural production.

Materials and methods

The gasification process review

The gasification process occurs between 800 and 1800 °C in four basic steps: drying, pyrolysis, reduction, and combustion. The major chemical reactions and the heat released are shown in Eqs. (1)–(8) [16].

Combustion (Eq. (1)(3)) releases heat for subsequent reactions to occur successfully.

$$C + 1/2O_2 \rightarrow CO \quad -111\,MJ/kmol \tag{1}$$

$$CO + 1/2O_2 \rightarrow CO_2 \quad -283\,MJ/kmol \tag{2}$$

$$H_2 + 1/2O_2 \rightarrow H_2O \quad -242\,MJ/kmol \tag{3}$$

The Boudouard reaction is endothermic and heterogeneous reduction–oxidation (redox) reaction of carbon monoxide and carbon dioxide at a given temperature (Eq. (4)).

$$C + CO_2 \leftrightarrow 2CO \quad +172\,MJ/kmol \tag{4}$$

The reaction of water gas or carbon-steam is an endothermic and heterogeneous chemical reaction (Eq. (5)), in which carbon reacts with water vapor to form carbon monoxide and hydrogen.

$$C + H_2O \leftrightarrow CO + H_2 \quad +131\,MJ/kmol \tag{5}$$

The reaction of methane formation (Eq. (6)) is an exothermic and heterogeneous chemical reaction, where carbon reacts with hydrogen to form methane.

$$C + 2H_2 \leftrightarrow CH_4 \quad -75\,MJ/kmol \tag{6}$$

In general, the purpose of any thermal conversion technique, as gasification, is the complete conversion of carbon into products. Thus, the heterogeneous reactions (Eqs. (4)–(6)) can be reduced to the water gas shift reaction (Eq. (7)).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad -41\,MJ/kmol \tag{7}$$

Then, methane reacts with water vapor to form carbon monoxide and hydrogen in an endothermic reaction (Eq. (8)).

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad +206\,MJ/kmol \tag{8}$$

The kinetic of Boudouard reaction is affected by many factors. Previous studies have shown the effects of feedstock, gasification agent and operational conditions of gasifier (especially temperature and pressure of the reactor) on the gas composition and its higher heating value (HHV) [17–20].

Biomasses

Residues from eucalyptus production were used in the form of wood chips (square-shaped with approximately 2.2 cm side and 0.3 cm thick). Residues from coffee production were used in the form of husk (semi-ellipsoid shaped and hollow, with the largest size 0.9 cm and smallest 0.5 cm approximately) and wood (cylindrically-shaped with approximately 2.3 cm of diameter and 3.5 cm of height).

The proximate analyses of biomasses were determined according to the ABNT standards (NBR 8112/83) for moisture (M), volatile matter (VM), ash and fixed carbon (FC) [21]. This method is equivalent to the International Standard ASTM E-871 for moisture, ASTM E-872 for volatile matter, ASTM D-1102 for ash [22]. Fixed carbon is usually determined by difference. Due to laboratory limitations, the heating values and elemental composition were calculated based on the methodologies proposed by Reed and Das [23], Parikh *et al.* [24] and Parikh *et al.* [25], respectively, according to Eqs. 9–13, where:

$$C = 0{,}637\ FC + 0{,}455\ VM\ (\%) \tag{9}$$

$$H = 0{,}052\ FC + 0{,}062\ VM\ (\%) \tag{10}$$

$$O = 0{,}304\ FC + 0{,}476\ VM\ (\%) \tag{11}$$

$$HHV = 0{,}3536\ FC + 0{,}1559\ VM - 0{,}0078\ ASH\ (MJ\cdot kg^{-1}) \tag{12}$$

$$LHV = HHV/(1 + M + ASH)\ (MJ\,kg^{-1})(MJ\cdot kg^{-1}) \tag{13}$$

The proximate analysis, elemental composition and the heating values of the biomasses used in this study are shown in Table 1.

These biomasses analysis and further information were previously presented by Oliveira et al. [1] in the characterization and mapping of agricultural wastes conversion to energy in Brazil.

Reactor and secondary components

The gasification system used in this study consisted of a commercial and open source downdraft reactor, model Allpowerlabs GEK v2, coupled to its secondary components: cyclone, filter, burner, and a Venturi nozzle (Fig. 1).

The reactor was manufactured in steel and insulated with a ceramic fiber blanket. The reaction chamber consists of three concentric cylinders and the thermochemical reactions occur in the inner cylinder (25.4 cm of inner diameter and 40.6 cm high). The cylinder in the middle (30.5 cm of inner diameter and 50.8 cm high) was filled with insulating material and the outer cylinder (37.5 cm of inner diameter and 54.6 cm high) hold the body of the gasifier, acting as a hollow space to transport the producer gas to the cyclone.

The producer gas transports particulates (non-reacted carbon and ashes), which were physically separated by a cyclone (12.7 cm and 4.6 cm of inner top and bottom diameter, respectively, and 51.4 cm high). After passing throughout the cyclone, the gas passed by a filter (20.3 cm of inner diameter and 30.5 cm high) filled with charcoal and steel wool to reduce the remaining concentration of tar.

A Venturi-type ejector (2.54 cm of inner diameter and 15 cm height) aspirates the producer gas with 500 mmca of vacuum using an air jet nozzle of 3.2 mm diameter. This pumping device was installed after the filter and coupled to a 1.5 kW compressor. A peristaltic pump sampled the fuel gas to the tar condenser tank (6 m length copper coil immersed into cold water), before reaching the gas analyzer. A water column displacement manometer monitored pressure inside reactor.