



Comparative study for hardwood and softwood forest biomass: Chemical characterization, combustion phases and gas and particulate matter emissions



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HIGHLIGHTS

- Hardwood and softwood forest biomass were burned in the laboratory.
- Combustion behavior under flaming and smoldering was analyzed.
- CO₂, CO, NO_x and PM_{2.5} emission factors were determined.
- Softwood biomass emitted a higher concentration of PM_{2.5}.
- Lignin content influenced on CO₂ and CO emission.

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ABSTRACT

Two different types of typical Brazilian forest biomass were burned in the laboratory in order to compare their combustion characteristics and pollutant emissions. Approximately 2 kg of Amazon biomass (hardwood) and 2 kg of Araucaria biomass (softwood) were burned. Gaseous emissions of CO₂, CO, and NO_x and particulate matter smaller than 2.5 μm (PM_{2.5}) were evaluated in the flaming and smoldering combustion phases. Temperature, burn rate, modified combustion efficiency, emissions factor, and particle diameter and concentration were studied. A continuous analyzer was used to quantify gas concentrations. A DataRam4 and a Cascade Impactor were used to sample PM_{2.5}. Araucaria biomass (softwood) had a lignin content of 34.9%, higher than the 23.3% of the Amazon biomass (hardwood). CO₂ and CO emissions factors seem to be influenced by lignin content. Maximum concentrations of CO₂, NO_x and PM_{2.5} were observed in the flaming phase.

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1. Introduction

Biomass combustion is one of the recommended technologies for reducing fossil fuel consumption (Kistler et al., 2012) and improving energy security (Sims et al., 2010) because of the current climate situation. According to Pasangulapati et al. (2012), biomass from agricultural waste and woody materials has widely been used as feedstock for energy. However, use of forest biomass as an energy source is only sustainable when renewable biomass is used. This mainly consists of waste from forest harvesting and

lumber mills. According to Hauglin et al. (2012), in most countries only the tree trunks have been harvested and processed by lumber mills and the pulp and paper industries, while branches and tree tops have been left in the forest.

Van Caneghem et al. (2012) studied thermal treatment techniques that have been used to convert waste in order to re-utilize it as an energy source. Combustion, pyrolysis, and gasification are among thermal treatment techniques. The authors concluded that combustion is the best established technology among the three.

Biomass combustion, however, is a source of pollutants such as PM₁₀, PM_{2.5}, NO_x, and SO₂ (based on fuel composition) and CO (based on combustion quality) (Villeneuve et al., 2012). Brassard et al. (2014) highlighted the importance of more studies in order to fill the gaps in knowledge regarding both gas and PM emissions.

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The emissions of compounds in biomass combustion are related to the operational characteristics of the burning equipment used (Van Caneghem et al., 2012) and to fuel composition (Brassard et al., 2014).

Van Caneghem et al. (2012) discussed the operational characteristics of combustion equipment. They state that in fluidized bed combustion, the high level of turbulence created improves combustion and encourages heat transfer and uniform mixture. Use of fluidized beds for combustion of a mixture of forest waste was one part of the studies of Chakrithakul and Kuprianov (2011). The authors obtained combustion efficiency of 99.6%.

In fluidized bed burners, various techniques have been developed in order to reduce the emissions from the process. To minimize CO in combustion gases, Van Caneghem et al. (2012) suggested using an optimal proportion of excess air in which the quantity of oxygen provided is high enough to guarantee the burn time of the volatile material. According to the authors, this optimal proportion can be obtained through projects relating to the height of the burner. Duan et al. (2014) proposed secondary combustion air injection to ensure complete combustion of the volatile gases dragged along with the primary air. This would minimize CO emissions. Munir et al. (2011) recommended air staging to control formation of NO_x and N₂O. This technique limits availability of oxygen in the high temperature zone, creating a low-oxygen primary combustion zone. Because of this, most of the N in the fuel is liberated as N₂. Chyang et al. (2010) suggested adding calcium-based substances to the burner in order to eliminate gaseous acidic compounds such as SO_x and HCl. In calcinations, chalk is rapidly converted to porous calcium oxide, which can subsequently capture acidic compounds. However, Van Caneghem et al. (2012) report that particulate matter must be removed from combustion gases before acid-removal treatment. The authors mention that particulate matter is normally removed using electrostatic precipitators or sleeve filters.

Andreae and Merlet (2001) characterize fuel composition of lignocellulosic biomass. It is made up of cellulose and hemicellulose (holocellulose), lignin and other compounds. For Pasangulapati et al. (2012), polymer structure and length, and cross-linkage of cellulose, hemicellulose and lignin vary substantially, resulting in different thermal decomposition characteristics and products during gasification and pyrolysis.

Telmo and Lousada (2011) report that increases in lignin content increase the heating value of the material. According to these authors, lignin is the component of plant cell walls that is richest in carbon and hydrogen, which are the main elements involved in heat generation. In biomass with high lignin content, combustion tends to be more efficient due to the higher heating value, as discussed by Telmo and Lousada (2011).

According to Rowell (2012), wood biomass is grouped into two large groups: hardwood and softwood. Softwood generally has higher lignin content (26–34%) than hardwood (23–30%), so softwood is expected to lead to higher CO₂ emissions.

The objective of this study was to quantify and to compare gas and PM_{2.5} emissions generated in the burning of biomass from hardwood and softwood trees that are found in Brazilian forests in order to increase understanding for use of forest biomass waste.

2. Methods

2.1. Biomass fuels and chemical characterization

In this work, biomass from the Amazon rainforest and from Araucaria (*Araucaria angustifolia*) was burned. The Amazon biomass was composed of a mixture of different species. For the laboratory burning experiments, there were a total five repetitions

for Amazon biomass and four for Araucaria biomass. In the burning experiments, approximately 1.5 kg of each biomass were used per repetition.

The biomass was made up of 90% branches by mass, with a maximum of 2 cm² cross section. The remaining 10% of the mass was made up of finer branches and leaves, as in Neto et al. (2011). The combustion experiments were carried out at the Associated Combustion and Propulsion Laboratory at INPE in Cachoeira Paulista in the state of São Paulo, Brazil.

For chemical characterization of the two types of biomass, random samples were taken of branches with bark with a cross section less than 2 cm², since that made up 90% of the burnt material. These branches were air dried for around two months. The material retained by the 60 mesh sieve was used for the chemical analyses. Determination of lignin contents was carried out as defined in regulation T 222 (Tappi, 1998), extractive contents as defined in regulation T 204 (Tappi, 1997), and holocellulose content was obtained by difference. The proximate analysis was performed according to the ASTM D3172 (1983), and moisture content was determined at 103 ± 5 °C. The pump calorimeter method (ASTM E 711-87, 2004) was used to evaluate HHV (IKA C-5000). There were a total of six repetitions for chemical characterization.

2.2. Combustion experiment

2.2.1. Experimental setup

The experimental device (Fig. 1a) basically consisted of a burn tray placed on a scale that was used to register mass loss throughout the combustion process. The scale had a 1 s response time. A computer running LabView received the signals from the scale. The tray/scale ensemble was set up on a table located in the center of a container directly under a hood connected to a chimney. An axial exhaust fan generated vertical airflow in the chimney outlet by convection, which forced the gases out, especially in the smoldering phase. The apparatus also included a temperature sensor, a Pitot tube, and absolute and differential pressure transducers. The measurements taken were transmitted to a mass flow controller that calculated air flow through the biomass on the tray during the burning experiments. The flow rate was corrected for Standard Temperature and Pressure (STP). Fig. 1b shows specifications according to US EPA (2012) for the location of connections where the sampling probes were installed. The vertical distance between the connections was established considering internal chimney diameter (D).

2.2.2. Gas and PM_{2.5} measurement

Gas measurement was carried out using analyzers from Rosemount Analytical. Details of calibration of the analyzers, positioning of the sampling probes, and how the gas flow to the reading by the analyzers was dealt with can be found in the studies of Neto et al. (2011). These authors utilized the same equipment to determine emissions factors of CO₂, CO, NO_x, and unburnt hydrocarbons resulting from biomass burnt in the laboratory.

Measurement of particulate matter was carried out using a DataRam4 and an Andersen Cascade Impactor. The DataRam (DR4) Model DR4000 is certified by the FCC (Federal Communications Commission) and EC (European Community). It is able to collect particulate matter with diameters between 0.04 and 4 μm and provides average mass concentration of the sample particle in the range from 0.1 to 400,000 μg/m³. In order to guarantee isokinetic sampling, the suction speed of the particulate matter was kept equal to the speed of the gas inside the tube. In this study, the flow speed was set at 4.2 m/s for all of the tests carried out. Data collection took place for 10–15 min in flaming and 10–15 min in smoldering. Sampling at each point lasted 3 min, which was the

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