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Energy production from direct combustion of agricultural biomass on farm

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ABSTRACT Rising energy cost pushes toward the development of new sustainable green energy. In that context, biomass combustion of wood, switchgrass or willow could be an interesting way to produce green energy (heat or electricity). Emissions and energy produced from wood combustion are well documented, but it is not the case for other biomass. The main objective of this study is to measure and compare the emissions and energy produced from the direct combustion of wood and three different biomasses (dried solid pig manure, switchgrass and willow). This paper will discuss the energy production aspect. A biomass pellet stove producing between 1.5 and 20 kW, installed in a calorimetric room, is used to burn biomass. The room is isolated and ventilated with fresh air in order to extract heat released by the stove. The room temperature is controlled by varying the fresh air flow. Mass burn rate, air flow rate, and dry-bulb temperature and humidity are measured on a continuous base to carry out a complete heat balance. The biomass calorific value is measured in laboratory for every trial. As result, the agricultural biomasses used had similar heating values than wood without significant differences. Important differences among wood and agricultural biomasses, like the lower heating value and the combustion efficiency, could be avoided by adapting the appliance for these materials. Thus agricultural biomasses showed an important potential as a source of renewable energy production.

Keywords: biomass, combustion, energy balance, heating value.

Nomenclature

C_p = Specific heat, kJ/$kg_{dry\ air}$.K

Cr = Combustion rate, $kg_{biomass}$/h

E = Error, %

F_{air} = Air flow, L/s

H_{air} = Humidity ratio of air, kg_{water}/kg_{air}

H_i = total hydrogen in biomass, %

HHV = Higher heating value, MJ/kg

HR = Relative humidity, %

k = Thermal conductivity, W/m-K

LHV = Lower heating value, MJ/kg

m_a = Mass flow of air, kg/s

P_{atm} = Atmospheric pressure, Pa

P_s = Saturated vapour pressure, Pa

P_v = Vapour pressure of air, Pa

Q_i = Heat calculated at localisation *i*, W

Q_v = Heat evacuated by the ventilation, W

Q_{room} = Heat lost through the walls, the roof and the door of the calorimetric room, W

Q_{gas} = Heat released in combustion gases, W

Q_{total} = Total amount of heat released during combustion, W

T = Temperature of air, °C

t_{in} = Temperature at the inlet, °C

t_{out} = Temperature at the outlet, °C

V_{air} = Specific volume of air, $m^3/kg^{-1}{}_{air}$

INTRODUCTION Rising energy cost and climate change push toward the development of new sustainable green energy. In that context, biomass combustion could be an interesting way to produce heat or electricity. In fact, biomass is a renewable energy source that can contribute to reduce greenhouse gas emissions and replace fossil fuels. With the abundance of woody biomass, the Province of Québec (Canada) has been developing a feedstock supply chain for energy production from woody materials. However, the use of agricultural biomasses as potential solid fuels has just been emerging and studied among last years. Besides energetic and environmental advantages, according to Cantrell et al. (2008), the use of agricultural and livestock waste as bioenergy feedstock for waste-to-bioenergy conversion processes would allow farmers to take advantage of new markets for traditional waste products. Research involving heat production from combustion of agricultural biomasses includes materials such as (1) organic-based waste from agricultural activities e.g. cereal straws and cereal seeds; (2) energy crops e.g. switchgrass, *Miscanthus* and willow; and (3) animal manure e.g. poultry litter and the solid fraction of pig manure.

The higher heating value (HHV) (or gross calorific value) is defined as the heat released during combustion per mass unit fuel under the constraints that the water formed during combustion remains in liquid phase and that the water and the flue gas have the same temperatures as the temperature of the fuel prior to combustion. Meanwhile the lower heating value (LHV) (or net calorific value) is defined as the heat released during combustion per mass unit of fuel under the assumption that the water in the products remains in a gaseous phase and that the water and flue gas have the same temperature as the fuel prior to combustion (Van Loo and Koppejan, 2008). Table 1 presents the HHV and the LHV of different biomasses fuels.

Table 1. Higher and lower heating values of different agricultural biomasses

Biomass	Higher heating value (HHV)	Lower heating value (LHV)	Ref.
	(MJ/kg) (d.b)	(MJ/kg) (d.b)	
Wood pellets	19.8	16.4	1
Wheat straw (winter)	18.7	14.5	1
Pellet wheat straw	18.5	17.2	2
Switchgrass	18.0	16.8	2
Miscanthus	19.1	17.9	2
Poultry manure	17.1	15.8	2
Pig manure	13.8	12.8	2
Willow	18.6	17.2	2
Poplar	20.7	19.3	2

References: 1. Van Loo and Koppejan, 2008. 2. ECN, 2011

There have been many attempts at correlating the heating value with the biomass composition. According to Jenkins et al (1999) the heating value of biomass can be partially correlated with ash concentration, for example. Woods with less than 1% ash typically have heating values near 20 MJ kg^{-1} (8600 Btu lb^{-1}). Each 1% increase in ash translates roughly into a decrease of 0.2 MJ kg^{-1}, because the ash does not contribute substantially to the overall heat released by combustion.

The main objective of this study is to measure and compare the energy produced from the direct combustion of wood and three different biomasses (dried solid pig manure, switch grass and willow). The specific objective of this part of the study is to carry out a complete energy balance related to the four biomasses combustion.

MATERIAL AND METHOD The experiments were carried out in a 60,000 BTU/h (17.58 kW) output biomass pellet stove (Enviro Omega). The input air flow was controlled by a slider damper which restricted the air flow conducted into the combustion chamber. In addition, the burner was installed into a calorimetric room (figure 1) in order to determinate the heat produced from every biomass. The calorimetric room (1.96 m x 1.52 m x 1.91 m) was isolated with polyurethane (figure 2) in order to minimize heat losses. Sampling was conducted when a constant temperature inside the calorimetric room was achieved. A fan continuously forced cold air stream to circulate through the chamber and to evacuate heated air. A second fan was installed at the air intake in order to keep a neutral differential pressure inside and outside the calorimetric room. Additionally, thermocouples were installed on the portions inside and outside of the walls in order to measure conductive heat losses. Measurements were collected every 10 minutes by a data logger.

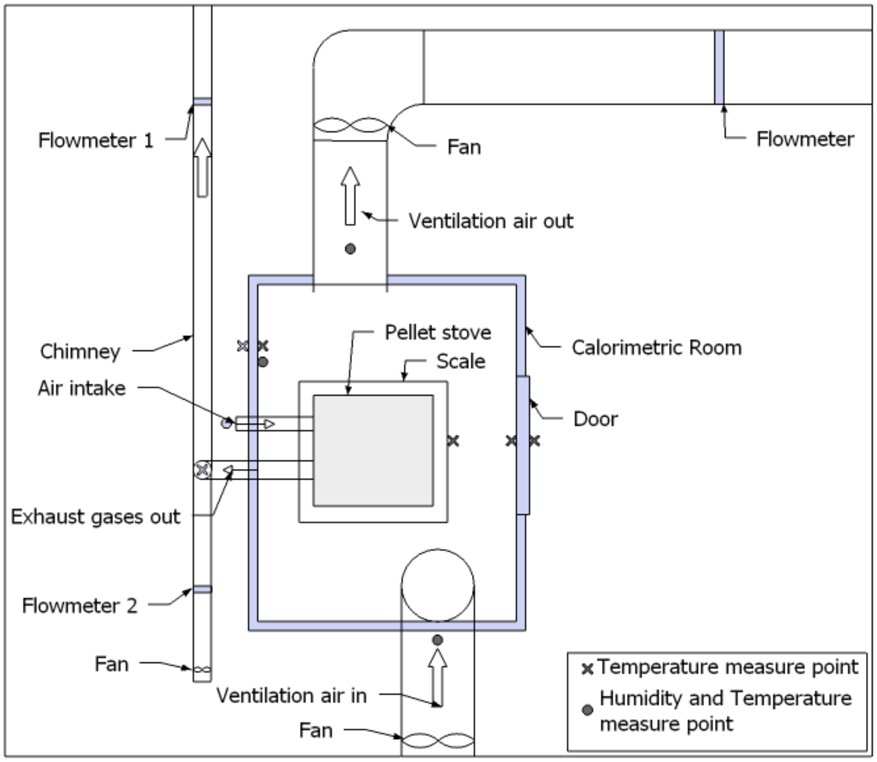

Figure 1: Schema of the experimental setup (top view).

The pellet stove was installed on a scale (± 0.05 kg precision) which collected weight at regular intervals during the combustion process. Combustion rate was determined by the change of the stove's weight at the beginning and the end of the trial, divided by the time period of the burning test. After each test, the bottom ashes in the stove and the fly ashes in the chimney were collected and weighed in order to determine the ash content of the evaluated biomass.

Four biomasses were tested: willow, switchgrass, dried solid fraction of pig manure (SFPM), and commercial wood (a mix of black spruce and gray pine pellets), which was used as reference. All biomasses used had a pellet shape. Properties of biomasses including ash content, higher heating value (HHV), humidity and bulk density were determined. Combustion rate was automatically controlled by the appliance adjusting the heat output level in the control board. There are five heat output levels available, from 1 (minimal rate) to 5 (maximal rate). In order to test the biomasses under the own maximal combustion efficiency, a preliminary experiment were carried out allowing to determinate the ideal input air flow. The slider damper of the pellet stove was adjusted (max., 2/3 and 1/3) to obtain three different flows. Each biomass was burned during two hours at each heat output level for each air flow setting (including one hour for the stabilisation of the burning conditions). Biomasses were burned randomly and CO concentrations in the flue gas were analysed (only one repetition was done for this preliminary test). In fact, CO is produced by the incomplete combustion of the fuel and usually is used as a parameter to indicate the combustion efficiency. The lower is the CO concentration in the flue gas stream; the higher is the combustion efficiency. Final tests were carried out only with the air flow rates showing the lowest CO concentration at the flue gas for each heat output level.

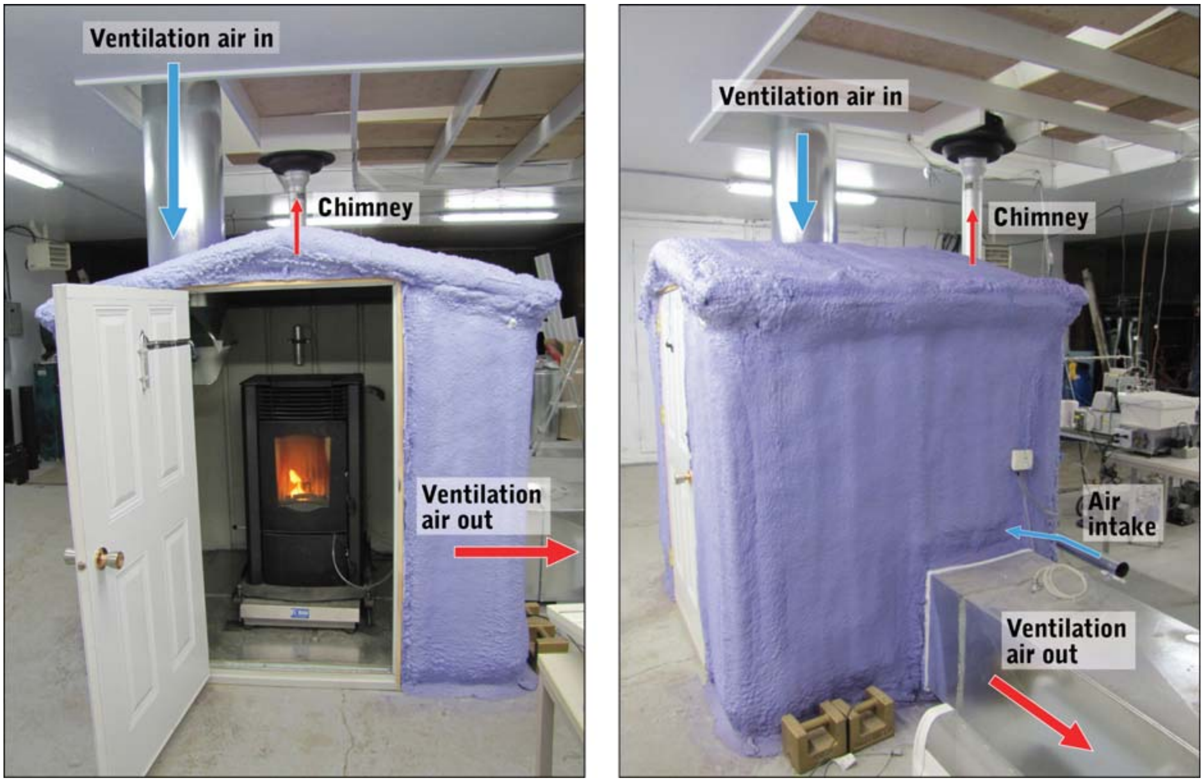

Figure 2. Calorimetric room and experimental setup.

Heat balance was done to determine the heat produced by the stove. To achieve this objective, heat evacuated from the calorimetric room (Q_v) was evaluated from the ventilation flow measured by a flowmeter (figure 1), the temperature at the inlet (t_{in}) and at the outlet (t_{out}) of the room, and the relative humidity at the outlet, as follows:

$$Q_i = m_a C_p \Delta t \quad (1) \qquad \Delta t = t_{out} - t_{in} \quad (2) \qquad C_p = 1 + 1{,}88 H_{air} \quad (3)$$

$$m_a = F_{air} / (V_{air} * 1000) \quad (4) \qquad H_{air} = \frac{0{,}6219 P_V}{P_{atm} - P_V} \quad (5) \qquad V_{air} = \frac{287 \times T}{P_{atm} - P_V} \quad (6)$$

$$P_v = P_s \cdot HR \quad (7) \qquad \ln(P_s / R) = \frac{A + BT + CT^2 + DT^3 + ET^4}{FT - GT^2} \quad (8)$$

R = 22105649; A = -27405.53; B = 97.5413; C = -0.146244; D = 0.0001256; E = -4.85 E-08;

F = 4.34903; G = 0.0039381.

Heat lost in the flue gas (Q_{gas}) was evaluated from the temperature given by a thermocouple inserted into the chimney and the flow of the flue gas. A horizontal chimney was installed at the end of the vertical chimney (fig 1). Additionally a fan was installed at the entrance of the horizontal chimney, taking a flow of fresh air in the attic, measured by the flowmeter 2. Then, a mixture of fresh air and flue gas was evacuated and the flow was measured with the flowmeter 1 (fig. 1). Knowing these values, the flue gas flow can be calculated. Then, the heat evacuated by the chimney was calculated from equation 1, where t_{out} and t_{in} represents the temperature of the flue gas and the temperature in the laboratory, respectively. Vapour pressure of exhaust gases (P_v) was calculated from the H_2O concentration reading at chimney as follows:

$$Pv = \frac{[H_2O]}{1000000} \cdot 101325 Pa \qquad (9)$$

Moreover, heat lost through the walls, the door and the roof of the calorimetric room (Q_{room}) were estimated from the inside and outside temperatures. A thermal conductivity (k) of 0,026 W/m-K for walls and roof insulated with polyurethane foam and a k value of 0,12 W/m-K for the door made of plywood (ASHRAE, 1997) were utilised to calculate heat lost.

The sum of these three heat values (heat evacuated by calorific room ventilation, heat evacuated by flue gas and heat lost through the calorimetric room) gives the total heat produced by the combustion of the pellets and is supposed to equals the lower heating value of the combustible (LHV) (eq. 10). Unit conversion of heat from Watt to MJ/kg is given by equation 11. The combustion efficiency is then found from equation 12.

$$Q_v + Q_{lost} + Q_{gas} = LHV \quad (10) \qquad Q\ (MJ/kg) = \frac{Q_{watt}/10^6}{Cr/3600} \quad (11) \qquad \eta_{combustion} = (Q_v + Q_{lost})/LHV \quad (12)$$

In order to evaluate the measured lower heating values and the used method, higher heating values (HHV) of each biomass were measured in laboratory. Method used was by the bomb calorimeter (ASTM, 2004). Thus lower heating values were estimated (LHVe) from the HHV laboratory results using eq. 13. Total hydrogen in biomass (H_i) in eq. 13 was assumed as 6.22% based on the quantity of H in the cellulose. This assumed value is correct for the wood pellets and it is very close to real total H in switchgrass and willow, but is not the case for SFPM. In fact, SFPM has higher levels of oleic acid were H content is higher. Thus real LHV will be lower than that estimated. Eq. 14 was used to measure the error (E) of experimental results or the difference between the measured heating values and those calculated.

$$LHVe = HHV - 23.96\,(H_i \times 9) \quad (13) \qquad E = \frac{LHVe - LHV}{LHVe} \times 100 \quad (14)$$

RESULTS

Proprieties of biomasses studied. Proprieties of biomasses used were measured in laboratory and results are listed in Table 2. As expected, wood had the lowest ash content among biomasses used (0.5%). In the other hand, ash content of SFPM was significantly higher than other biomasses (8.8%). Ash content of the switchgrass and the willow were less different (2.8 and 3.7% respectively). Literature reports similar values for wood: 0.6% (Samson, 2007); switchgrass: 2—5.2% (Alexander, 2008; van der Berg and de Visser, 2003 and Samson, 2007), and willow (1—5%) (biofuelsb2b, 2007). FAO (1980) documented the ash content of SFPM from 10% to 28%. Calorific value of wood was lower than literature (19—20 MJ/kg). Switchgrass and willow presented a similar calorific value and in accordance with literature (18—18.7 MJ/kg) (table 1). Humidity was lower in wood pellets (6.6%) than other biomasses (10.5—14.1%).

Table 2. Properties of the biomasses

Biomass	Ash content (% d.b.)	Calorific value (HHV) (MJ/kg w.b.)	Humidity (% w.b)	Density (g/cm^3)	Bulk density (kg/m^3)
Wood	0.5%	17.9	6.6	1.1	686
SFPM	8.8%	15.6	10.5	1.26	769
Switchgrass	3.7%	18.7	14.1	0.94	509
Willow	2.8%	18	12.7	1.03	590

Preliminary tests. Preliminary tests allowed determining airflow inlet to appliance producing the maximal combustion efficiency. The combustion processes were relatively stable with all fuels. Average flue gas oxygen ranged from 13.9% to 18.9%. The combustion was performed at flue gas flows from 0.57 to 1.7 m^3/min. Flow varied in function of the input air restriction and the combustion rate (3.01, 1.68 and 0.99 kg/h for the heat output levels 5, 3 and 2). The flue gases temperatures were in average 160, 120 and 82 °C for the heat output levels 5, 3 and 2 respectively.

The resulting CO concentrations are resumed in table 3. No clear correlation was found between CO concentrations and both the heat output level and the air flow. The highest CO concentration (1140 ppm) was measured from wood combustion at the maximal heat output level (5) and the minimal airflow (1/3), which was about 2-fold that of other airflows at level 5, and 4—19-fold that of other heat output levels. In addition, wood combustion presented the highest CO concentration variability ranging from 60 (± 15) to 1,140 ppm (± 316). A similar variability was found by Godbout et al (2010) ranging from 23 to 1400 ppm. Even though, wood and switchgrass produced in general, lower CO concentrations than the other tested biomasses. Emissions were especially low during switchgrass combustion at maximal heat output level (56—86 ppm).

Table 3. CO concentrations (ppm) at the flue gas in preliminary tests

Heat output level	**5**			**3**			**2**		
Air flow	**max.**	**2/3**	**1/3**	**max.**	**2/3**	**1/3**	**max.**	**2/3**	**1/3**
Biomass	**CO concentrations (ppm)**								
Wood	544	490*	1140	134	86	60*	157*	264	170
SFPM	422*	-	477	170*	269	509	336*	415	501
Switchgrass	69	56*	86	100	102	93	154	140*	189
Willow	577	627	516*	319	284*	341	437	372	315*

*Airflow with the lowest CO concentration at each heat output

Experimental tests. The object of experimental tests was to compare the energy produced from each biomass at the conditions where combustion was most efficient. The airflow adjustment for which each biomass got the lowest CO concentration at each heat output level in preliminary tests was selected as the condition of combustion for experimental tests. Three repetitions were executed for each heat output level.

The combustion parameters of experimental tests resulted similar to preliminary tests. Combustion rates were in average 2.98, 1.80 and 1.11 kg/h for the heat output levels 5, 3 and 2 respectively. Average oxygen concentration in flue gas ranged from 14.7% to 19.3%. The range of the averaged flue gas flows was shorter than preliminary tests: from 0.66 to 0.8 m^3/min. The temperatures at the chimney were in average 158, 121 and 93 °C for the heat output levels 5, 3 and 2 respectively. A special attention was ported to the temperature at the calorimetric room in order to maintain it stable during the test period at each heat output level. Nevertheless the temperature differences ranged from 3 to 12°C.

Heat balance results are listed in table 4. The highest total heat measured was from wood (8 422 W), followed by the SFPM and the willow (7 243 W and 7 237 W). The lowest heat measured was from switchgrass (6 442 W). Although when the total heat is related to the combustion rate, willow presented the lowest quantity of heat released per kg (12.7 MJ/kg). Wood remains as the biomass with the highest quantity of heat released (15 MJ/kg). The switchgrass and the SFPM released the same heat quantity (13.9 and 13.8 MJ/kg respectively). In general, the standard deviation of a same heat output level was under 10% of the averaged result. Nonetheless the SFPM and the willow exceeded the 10% (12.2% and 16.1%) both at heat output level 2. Since heat is measured while the water is in the vapour phase, values in table 4 correspond to the lower heating value (LHV). In general, no significant differences were founded about the lower heating values between wood and the agricultural biomasses.

Table 4. Heat balance results

Biomass	**Heat output level**	**Combustion rate** kg/h	**Qv** W	**$Q_{lost\text{-}roof}$** W	**$Q_{lost\text{-}walls}$** W	**$Q_{lost\text{-}door}$** W	**Q_{room}** W	**Q_{gas}** W	**Q_{total}** W	**LHV** MJ/kg
Wood	5	3.25	10606.9	64.8	64.3	101.3	230.5	1652.4	12490	13.9
	3	1.83	7232.2	35.9	13.6	53.4	103.0	913.9	8249	16.3
	2	1.2	4229.2	28.8	4.2	35.2	68.2	849.9	5147	15.4
Average			**7356.08**	**43.2**	**27.4**	**63.3**	**133.9**	**1138.7**	**8629**	**15.2**
SFPM	5	3.08	8065.6	18.8	53.6	81.6	154.1	1780.2	10000	11.7
	3	1.86	6023.4	11.0	29.0	52.6	92.7	1314.6	7431	14.4
	2	1.05	3535.3	4.3	11.2	31.0	46.5	839.2	4421	15.4
Average			**5874.78**	**11.4**	**31.3**	**55.1**	**97.7**	**1311.3**	**7284**	**13.8**
Switchgrass	5	2.62	7605.0	15.9	33.2	75.0	124.1	1731.0	9460	13.1
	3	1.53	5157.0	9.0	19.0	47.9	75.8	789.8	6023	14.2
	2	0.98	3245.9	0.4	-4.8	23.3	18.9	678.2	3943	14.6
Average			**5335.99**	**8.4**	**15.8**	**48.7**	**72.9**	**1066.3**	**6475**	**14.0**
Willow	5	2.98	8617.0	24.3	77.8	103.0	205.1	1306.8	10129	12.2
	3	1.99	6111.93	16.7	49.4	67.7	133.9	1293.7	7539	13.7
	2	1.33	4101.7	8.5	24.1	45.4	77.9	622.6	4802	13.2
Average			**6276.9**	**16.5**	**50.4**	**72.0**	**139.0**	**1074.3**	**7490**	**13.4**

Calorimetric room installation proved to well isolate the temperature, in fact, only 1% of heat was lost through it (Q_{room}). In the other hand, 16% of heat was released through chimney by the flue gases (Q_{gas}). The remaining heat (83%) was recovered by the ventilation system (Q_v).

The table 6 lists the heating values (higher, lower and estimated lower) of each biomass, and also the difference (as the error) between the LHV measured by combustion in the calorimetric room and that estimated (LHVe) from the HHV measured at laboratory. For wood, the reference biomass, the difference between LHV and LHVe was 8%. As described before, LHVe values resulted from the assumption that total hydrogen in biomass (H_i) is based on the quantity of H in the cellulose (6.22%). Concerning the LHVe in the SFPM, it was the lowest as expected. Also the error was the lowest (3%). Evermore, based on the fact that SFPM has a higher H content due to the higher content of oleic acid than wood, the LHVe in the SFPM could be lower than estimated and thus the error also. The switchgrass and willow had the highest difference, both around 20%.

Table 6. Heating values, error and appliance combustion efficiency

Biomass	HHV	LHV	LHVe	Error	Efficiency
	MJ/kg	MJ/kg	MJ/kg	%	%
Wood	17.9	15.2	16.6	8	80
SFPM	15.6	13.8	14.3	3	80
Switchgrass	18.7	14.0	17.4	19	68
Willow	18	13.4	16.7	20	69

In general, no significant relation was found between the measured heating values and any of the biomass properties. Combustion efficiency of the appliance was calculated adding the heat released by the appliance except the heat conduced through the chimney ($Qv + Q_{room}$) and dividing by the LHVe (Table 6). According to the pellet burner specifications, 80% is the optimum efficiency that will vary according to fuel type. As result, wood and SFPM reached the optimal efficiency (80%), whereas the combustion of switchgrass and willow was less efficient (68 and 69% respectively). Nevertheless, switchgrass and willow's efficiency can be considered as important as wood in the way considering these biomasses as source of renewable energy production. Since combustion characteristics depend also on the appliance design, better efficiencies could be obtained by adapting the devise especially for theses biomasses.

CONCLUSION The heat balance of agricultural biomasses (dried solid fraction of pig manure (SFPM), switchgrass and willow) were compared to wood. Heat released by direct combustion of each biomass was measured. As expected, wood had the highest heating value measured (15.2 MJ/kg). The agricultural biomasses used for this study had similar heating values (13.8, 14.0 and 13.4 MJ/kg for dried solid fraction of pig manure, switchgrass and willow respectively). No significant differences were founded among wood and the agricultural biomasses. Additionally, the theoretical lower heating value was estimated and compared with the measured values. Wood and SFPM had better approximations (8 and 3% of difference respectively) than switchgrass and willow (19 and 20% respectively). Finally, switchgrass and willow did not obtain the optimum combustion efficiency as the wood and SFPM did. Some improvements to the experimental setup could allow a more accurate heat balance. First, the losses through the chimney are approximate because the flow measurement instruments are more or less accurate. The Pitot tube in S shape proposed by the CSA-B415.1-10 could be used for the calibration of the flow in the chimney. Several thermocouples could also be installed at the exit of the appliance in order to average temperature values. Lastly, an ultimate analysis, including the hydrogen content, for each biomass, would reduce the relative error of the LHV calculation. In conclusion, agricultural biomasses studied showed similar energetic properties than wood. Important differences among wood and agricultural biomasses, like the lower heating value and the combustion efficiency, could be avoided by adapting the appliance for these materials. Thus agricultural biomasses show an important potential as a source of renewable energy production.

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