BIOMASS GASIFICATION AND PHYSICAL ANALYSIS OF PLANT BIOMASS AND AGRICULTURAL WASTE PRODUCTS IN LOUISIANA

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Abstract. There are many properties that can affect the quality of syngas generated from biomass gasification. Among the most critical are ash, heating value, moisture, and density of the feedstock. The focus of this study is to analyze the characteristics of different woody biomass materials and agricultural wastes typically found in Louisiana or similar regions. The energy content of combustible gases produced by gasification is also quantified. The feedstocks analyzed are pine, hardwood pellets, alfalfa, switchgrass, sugarcane bagasse, corn, cypress mulch, chipped bark nuggets, dairy manure, and poultry litter. Analyzing and comparing the different feedstock characteristics indicates that the differences in physical properties are largely responsible for varying energy generation capabilities from gas produced through gasification. Ultimately, it is determined that pine and hardwood are the best candidates for energy production through gasification, based on their high density, relatively low MC, and low ash content. Producer gas generated from pine gasification had the highest concentration of hydrogen, carbon monoxide, and methane and resulted in the greatest energy output when combusted.

Keywords: Biofuel, syngas, switchgrass, wood, manure, alfalfa, bagasse.

INTRODUCTION

Over the past few decades, biomass has been recognized as a major sustainable contributor to energy generation across the world. Numerous studies have been conducted to understand the different properties of biomass feedstocks and bio-based waste products, and many have concluded that biomass can be a major component among energy resources that are both renewable and environmentally compatible (Babu and Whaley 1992; McKendry 2002). Renewable fuels are cleaner, from an environmental perspective, when compared with traditional petroleum and coal sources and can reduce overall air pollution and lower greenhouse gas emissions (Tavasoli et al 2009). Because biomass is clean and renewable, it has the potential to be an excellent substitute for conventional fuels. When consuming biomass as an energy source, it is important to understand and quantify the thermal, physical, and chemical aspects that characterize the overall quality of different feedstocks for energy generation. This study focuses specifically on

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how these characteristics affect the quality of producer gas from the gasification of different feedstocks. Gasification is the high-temperature, oxygen-lean thermochemical conversion process of a solid fuel, such as biomass, to gaseous products primarily composed of hydrogen, carbon dioxide, and carbon monoxide, with a much smaller amount of methane; a schematic of a biomass gasifier is shown in Fig 1, with typical reactions occurring during gasification summarized in Table 1. The different physical and chemical properties examined are calorific value, ash percentage, moisture percentage, density, and ultimate and proximate analysis.

Understanding the various properties of biomass feedstocks relevant for energy conversion is essential for identifying the optimum use of each product. In a study surveying biomass properties, Erol et al (2010) state that calorific value is an indication of the energy chemically bound in a biomass sample that can be converted to heat energy through a combustion process. Calorific value is therefore the most important property of a fuel for energy generation. In Erol's study, 20 different samples were analyzed for moisture, ash, volatile matter, fixed carbon, and organic matter percentages. It is noted that the MC of the samples varied from 1.25% and 12.5%, ash percentage between 1.04% and 8.98%, and volatile matter between 73.5% and 92.0%. The heating value of the feedstocks analyzed ranged from 15.4 to 19.5 MJ/kg. Thirteen different correlations were developed to estimate heating value from physical properties (volatile matter, fixed carbon, ash, and organic matter) and have regression coefficients from 0.829 to 0.898, indicating a relatively high degree of accuracy (Erol et al 2010). Similarly, Raveendran and Ganesh (1996) studied the heating value of biomass and biomass pyrolysis products to determine the suitability of different feedstocks for pyrolysis, carbonization, liquefaction, and gasification. They determined that the heating value of char was primarily a function of the lignin and ash content, whereas the heating values of liquid and gaseous products were functions of the cellulose, lignin, and silica-free ash content. Demirbas (1997) also studied 16 different biomass samples for their calorific value and reported that it was a function of fixed carbon content and volatile matter present in the feedstocks. They used the results of ultimate analysis to calculate the calorific value of the samples. In a study focusing on the elemental composition of biomass as it relates to calorific value, Friedl et al (2005) tested various samples for heating value, carbon, hydrogen, nitrogen, sulfur, chlorine, and ash content. Some studied samples include miscanthus, wood waste, wood chips, briquettes, sunflower straw, sugar and brewing waste, poultry litter, and sewage sludge. Sunflower straw resulted in the highest calorific value of 26 MJ/kg, woody materials were approximately 18 MJ/kg, and poultry litter resulted in the lowest calorific value at 10.2 MJ/kg. Using a similar approach, Sheng and Azevedo (2005) proposed 15 correlations for estimating biomass calorific value from ash, carbon, hydrogen, and oxygen

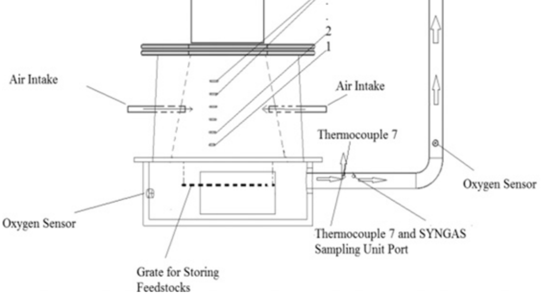

Figure 1. Schematic of downdraft biomass gasifier.

Table 1. Gasification reactions inside a downdraft biomass gasifier.

Designation	Mechanism
Oxidation	$C + O_2 \leftrightarrow CO_2$
	$C + ½\,O_2 \leftrightarrow CO$
Boudouard	$C + CO_2 \leftrightarrow 2CO$
Water gas, primary	$C + H_2O \leftrightarrow CO + H_2$
Water gas, secondary	$C + 2H_2O \leftrightarrow CO_2 + 2H_2$
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$
Steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$
	$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$
CO_2 reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$
H_2 reforming	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$

content. They report that calorific value decreases with the increase of ash and oxygen content, whereas calorific value increases with an increase in carbon and hydrogen. Geyer and Walawender (1999) tested 20 random samples of catalpa for calorific value, ash content, and specific gravity, reporting an average calorific value of approximately 19 MJ/kg. Specific gravity was determined to be 0.39 and ash content at 0.38%. Engler et al (2010) identified dairy manure as a sample feedstock for downdraft biomass gasification, and analyzed for relevant physical and chemical properties. It was found that pelletized manure yielded approximately 16 MJ/kg and 30% ash, of which 33% was silicon dioxide, 28% calcium oxide, 11% magnesium oxide, and 6% sulfur trioxide. Ultimate analysis indicated that C, H, N, O, and S contents were 43%, 6.2%, 2.2%, 48%, and 0.5%, respectively. All these studies are strong indications that quantifying the various physical and chemical properties of biomass is a useful tool for characterizing feedstocks for future processing. If biomass samples can be effectively characterized, then researchers will be significantly more well informed about how certain feedstocks will behave during various thermochemical conversion techniques. Ultimately, this can allow for more efficient fuel and chemical production from biomass in the future.

The primary purpose of this research is to identify and document the energy productivity of different feedstocks with respect to their application in biomass gasification. This will be achieved through analyzing their physical and thermal behavior responses under different experimental tests. Experimentation of the selected feedstocks in a biomass gasification unit was also conducted to analyze the generated combustible gases. There were five tests conducted on the feedstocks. High heating value (HHV) was calculated for each biomass sample, MC and density was determined, ash concentration was quantified, ultimate and proximate analysis was carried out for the feedstocks, and each feedstock underwent biomass gasification. The resulting gasifier-derived syngas was analyzed using gas chromatography. The 10 different feedstocks tested are pine pellets, hardwood pellets, alfalfa pellets, switchgrass pellets, sugarcane bagasse pellets, corn pellets, chipped cypress mulch, chipped bark nuggets, dairy manure, and poultry litter.

MATERIALS AND METHODS

Testing Methods

Feedstocks were tested for their physical and chemical properties at Louisiana State University laboratories. The ultimate and proximate analysis was conducted at Louisiana State University (LSU) AgCenter's WA Callegari Environmental Center. The feedstocks were either purchased in a pelletized or mulched form, or acquired from producers within the LSU AgCenter.

High heating value. Quantification of HHV was done using American Society for Testing and Materials (ASTM) D2015 Standard Method for finding calorific value of a feedstock (ASTM 1996).

Bulk density. Bulk density of biomass was calculated by dividing the measured feedstock sample mass by its calculated volume. Mass was measured using an electronic balance. The volume was calculated by averaging 10 random samples measured for their diameter and height in case of pellets or their length, breadth, and height in case of chips.

MC. Moisture of the feedstocks was calculated using ASTM D4442-07 standard test method for direct MC of wood (ASTM 2007b). Ten random samples were weighed before and after a muffle furnace treatment at 105°C (±2°C) for 2 h. The MC was calculated by dividing the difference in final and initial weight measurements by the initial weight measurement.

Ash percentage. Ash content was calculated following ASTM D1102-84 (ASTM 2007a). Ten moisture-free samples were weighed and placed in preweighed crucibles in a high-temperature furnace at 550°C (±5°C) for 30 min. After the heat treatment, these samples (now ash) were placed in a desiccated environment for cooling close to ambient temperature. The mass of the ash samples was then measured and averaged with an electronic balance. Volatile solid percent can be determined, if desired, by calculating the difference in mass between the dry sample and ash sample for a given feedstock and then dividing by the dry sample mass.

Energy content generated from gasification. Energy content of the produced gas is represented by the HHV of the gas mixture. The HHV of the total mixture was calculated by adding the products of each constituent gas mole fraction with its respective HHV. Mole fraction of each constituent gas in the mixture was determined through gas chromatography analysis of the biomass gasifier product from the given feedstocks.

Power produced from combustion. Power quantification generated from biomass gasification was determined by multiplying the measured flow rate of the gasifier with the calculated heating value of the produced gas mixture. Mass flow rate was found by measuring the volumetric flow rate of the gasifier and multiplying by the gas mixture density.

Ultimate and proximate analysis. As a part of elemental analysis, carbon and nitrogen were determined following the Environmetal Protection Agency (EPA) Method 440 (EPA 1997), whereas inductively coupled plasma analysis was performed following EPA method 6010-C (EPA 2000). The equipment used for testing following the abovementioned methods were Elementar Vario EL III (Langenselbold, Germany) and Varian Vista MPX (Palo Alto, CA), respectively. These tests were performed at the LSU AgCenter's WA Callegari Environmental Center.

RESULTS

Summary of Results

Results from the analysis of the six different feedstock pellets (pine, hardwood, corn stover, alfalfa, switchgrass, and sugarcane bagasse), two animal waste products (dairy manure and poultry litter), and two raw plant-based feedstocks (cypress mulch and bark nuggets) are presented individually and discussed subsequently.

Calorimetry of feedstock. Figure 2 compares the heating values of different feedstocks. Pine pellets, with an HHV of 18.7 MJ/kg, resulted in highest calorific value among the tested feedstocks. A similar calorific value was observed

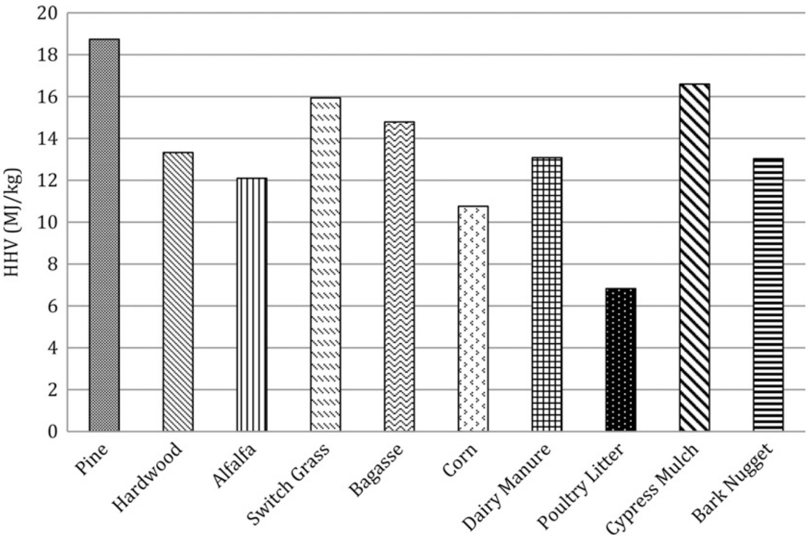

Figure 2. High heating value of different biomass feedstocks.

in tests conducted by Gil et al (2010), who found that pine pellets resulted in approximately 19.3 MJ/kg. Arshanitsa et al (2009) also tested softwood granules for higher heating value and found approximately 19.5 MJ/kg, similar with findings documented here. Compared with pine pellets, hardwood pellets resulted in a relatively lower HHV. These results are consistent with findings shown by Telmo and Lousada (2011), who observed that softwood pellets (*Pinus radiata*) resulted in a greater HHV than hardwood pellets. Calorimetry of dairy manure pellets resulted in approximately 13.5 MJ/kg. However, Young and Pian (2003) reported approximately 18 MJ/kg, which is significantly higher than the findings documented here. This can most likely be attributed to variations in MC of samples used in experimentation. Mukhtar and Capareda (2012) reported the calorific value of ash-free dairy manure to be approximately 19.8 MJ/kg. Alfalfa resulted in approximately 16.3 MJ/kg, and similar results for calorific value were observed in the findings of Boateng et al (2006) when alfalfa stems, reed canary grass, and eastern gamagrass were compared as energy crops. Calorimetry of switchgrass pellets resulted in approximately 16.0 MJ/kg. McKendry (2002) reported a larger value for switchgrass at 17.4 MJ/kg. Bagasse (14.8 MJ/kg) and pine pellets (18.7 MJ/kg) in this analysis also resulted in lower calorific value than what were reported by McKendry, who gives 19.4 MJ/kg for bagasse and 21.2 MJ/kg for pine. Bark nuggets resulted in a comparatively low calorific value of approximately 13.3 MJ/kg. The low calorific value observed in case of alfalfa, poultry litter, and dairy manure pellets is attributed to high ash percentage in the fuel pellets. Sheng and Azevedo (2005) reported a similar pattern when calorific values of biomass fuels were plotted against their ash percentage.

Moisture and density of feedstock. Determination of moisture percentage and pellet and chip density is significant for biomass gasification because feedstock moisture and density help in predicting the biomass feed rate and its effect on successful gasification. Results are shown in Figs 3 and 4. Pine pellets exhibited a pellet density of approximately 950 kg/m^3 and moisture at approximately 6%. Corn pellets resulted in the highest MC of approximately 13% at the time of laboratory examination; these pellets were then subjected to air-drying to lower moisture percentage to approximately 6% before they were used in a gasifier. The bulk density of corn pellets was determined to be approximately 900 kg/m^3. These values were somewhat similar to

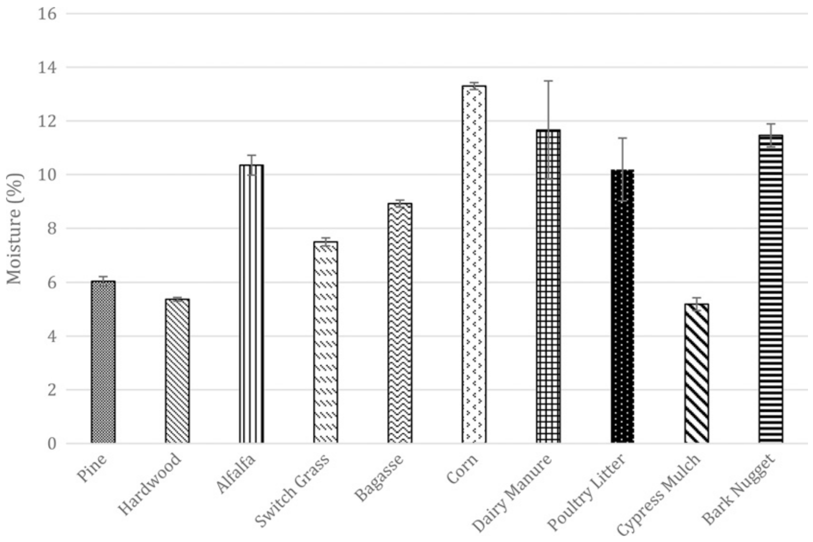

Figure 3. MC of different biomass feedstocks.

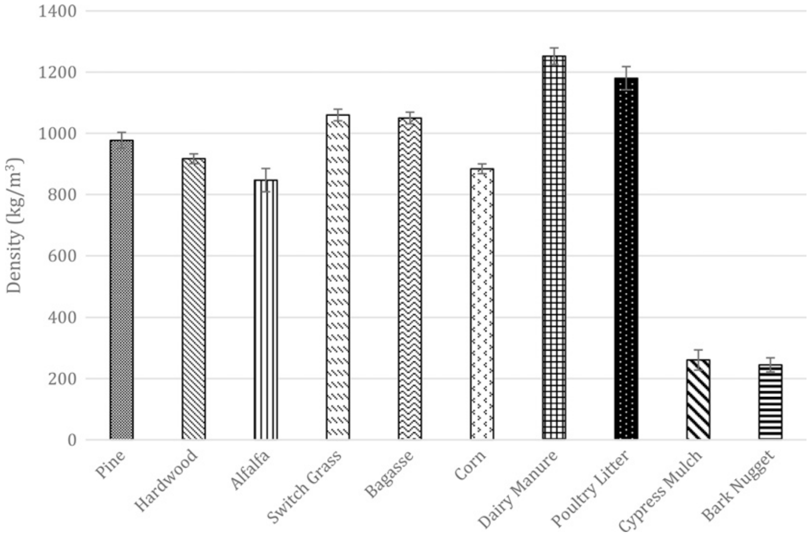

Figure 4. Density of different biomass feedstocks.

findings documented by Mani et al (2006) who tested the effects of compressive force, particle size, and MC on mechanical properties of biomass pellets. They reported a density of approximately 130 kg/m^3 and moisture at 6.2% for corn stover. They also reported pellet density and MC of switchgrass pellets to be approximately 1150 kg/m^3 and 8%, which was consistent with findings observed here. Similarly, softwood and hardwood are approximately 9% and 8% MC. Igathinathane et al (2010) reported density of hardwood pellets and softwood chips as 1200 kg/m^3 and 400 kg/m^3, respectively, consistent with values found in this study. Alfalfa resulted in approximately 8% MC, which is consistent with Tabil and Sokhansanj (1997) who reported approximately 7% moisture. However, the density of alfalfa pellets in this study was found to be approximately 850 kg/m^3 which was less than the reported value near 1250 kg/m^3 by Sohansanj and Tabil. Bagasse resulted in approximately 8% MC and 1000 kg/m^3. Similar values were documented by Erlich et al (2005) who studied 6-mm Brazilian bagasse species resulting in approximately 7% moisture and 1100 kg/m^3. Dairy manure and poultry litter pellets both resulted in approximately 10% moisture and a pellet density of approximately 1300 kg/m^3.

Ash percentage of feedstock. The results from determining feedstock ash content are summarized in Fig 5. Pine pellets resulted in lowest ash content of approximately 0.2%. The same results were observed in the findings of Gil et al (2010) who tested pine sawdust and reported 0.2% ash. Garcia-Perez et al (2007) compared pine pellets to pine chips and observed 1.1% and 0.5% ash, respectively. Cypress mulch resulted in 0.7% ash, which was higher than McKendry's (2002) finding of 0.4%. It was also reported that switchgrass resulted in 4.5% ash which is higher than the value of 3.2% ash observed in this study. Alfalfa also resulted in a significantly high ash percentage of 12.16%. Similar observations were made by Delong et al (1995) while comparing various species of alfalfa leaves (highest 11.01%). Bagasse, corn, and switchgrass pellets all resulted in less than 10% ash. These findings were similar to the ones made by Raveendran et al (1995) who found only 2.9% ash in bagasse and 6.8% ash in corn. Erlich et al (2005) also found approximately 6.7% ash while comparing three different species of bagasse. Bark nuggets resulted in extremely low ash content of 0.79%, which was consistent with Obernberger and Thek (2004) who observed an average of 0.88% ash. Highest ash content of 42% and 40% was observed in

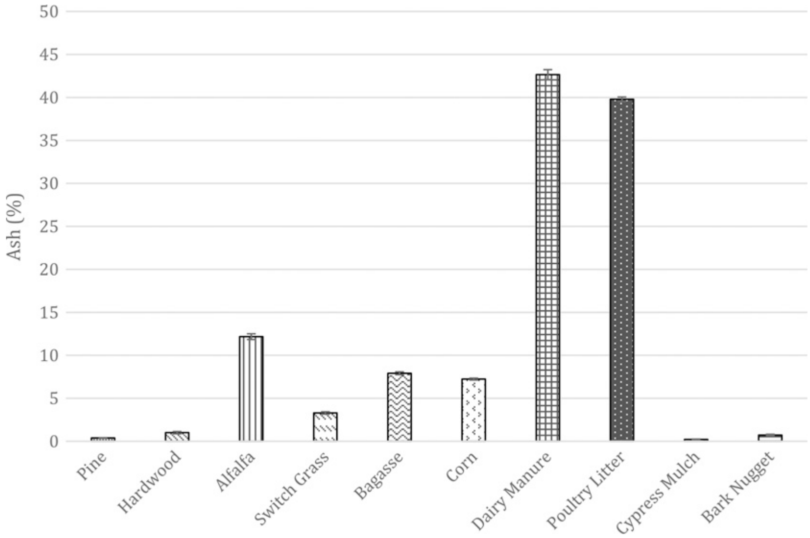

Figure 5. Ash content of different biomass feedstocks.

dairy manure and chicken (poultry) litter pellets, respectively. Similar results were observed by Fantozzi and Buratti (2009) while comparing poultry litter, bovine manure, and their mixture for anaerobic digestion.

Ultimate and proximate analysis of feedstocks. Ultimate and proximate analysis was carried out to verify the difference in ash percentage and calorific values of feedstocks. The carbon (C), hydrogen (H), and nitrogen (N) analysis was done on different feedstocks and is represented in Fig 6. Pine pellets resulted in approximately 40%, 4%, and 0.5% of C, H, and N content by weight, respectively. These results were similar to the findings of Garcia-Perez et al (2007) and Sensoz (2003), which showed the values of C, H, and N to be approximately 50%, 5%, and 0.4%. Gil et al (2010) observed similar results for C, H, and N (45%, 6.3%, and 0.1%,

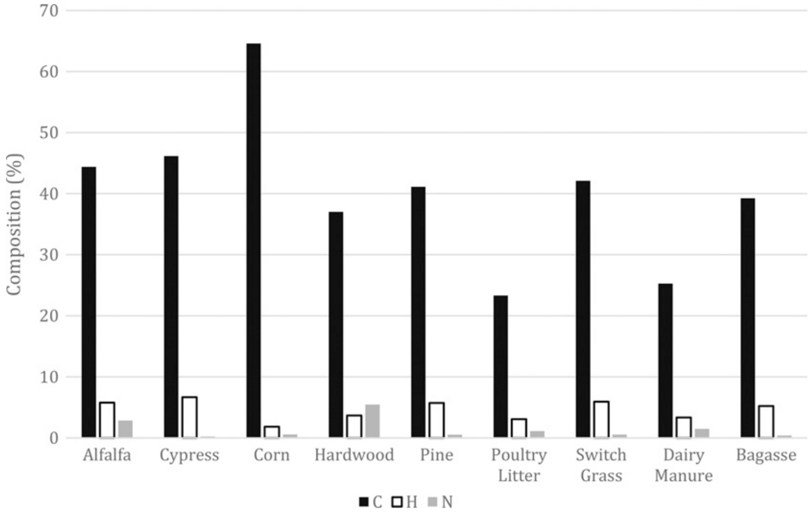

Figure 6. Ultimate analysis of different biomass feedstocks.

respectively). Hardwood and corn resulted in 37%, 3%, and 5% and 64%, 2%, and 0.5% of C, H, and N, respectively. Bagasse resulted in 39.42% of C, 5.2% of H, and 0.4% of N, similar to the findings reported by Kirubakaran et al (2009) while conducting ultimate analysis of bagasse. Similar results were confirmed by Raveendran et al (1995) and Erlich et al (2005) who recorded C, H, and N percentages for bagasse as 43.8%, and 46.9%, 5.8% and 5.49%, and 0.4% and 0.18%, respectively. Cypress mulch resulted in 46.15%, 6.6%, and 0.23%, which was similar to the values reported in McKendry's (2002) analysis (55% C and 6.5% H).

Comparison of energy efficiency of producer gas from different feedstocks. The comparison of gas composition of gasified feedstocks is shown in Fig 7. The gas composition with highest energy content is represented by the highest combustible gas percentage. Figure 8 compares the power produced by syngas combustion from different feedstocks. Pine pellets produced the highest combustible gas composition mixture with approximately 18% CO and H_2 and 4% of CH_4. Hardwood pellets also produced approximately 17% CO; however, it only produced 11% H_2 and 4% CH_4. Hardwood does have a slightly lower MC than pine, which would result in a higher corresponding energy efficiency following gasification. However, hardwood has a lower hydrogen content than pine (37% and 41%) and a significantly higher nitrogen content (5.5% and 0.5%). This could be a possible explanation for why the resulting syngas from hardwood gasification has a lower overall energy content than that of pine gasification. Cypress mulch, bark nuggets, and alfalfa were amongst the lowest combustible gas composition producers, averaging a value of 19% of the total composition. In comparison, pine pellets produced approximately 40% of producer gas.

DISCUSSION

Based on the presented results, pine and hardwood biomass feedstocks show the most potential among the studied feedstocks for effective energy generation in a biomass gasification application. This is primarily based on the fact that these two samples yielded a fuel-gas mixture following gasification with the highest energy content. Although hydrogen and carbon monoxide are the most abundant combustible products of biomass gasification, methane content plays a significant role in the overall calorific value of the gas

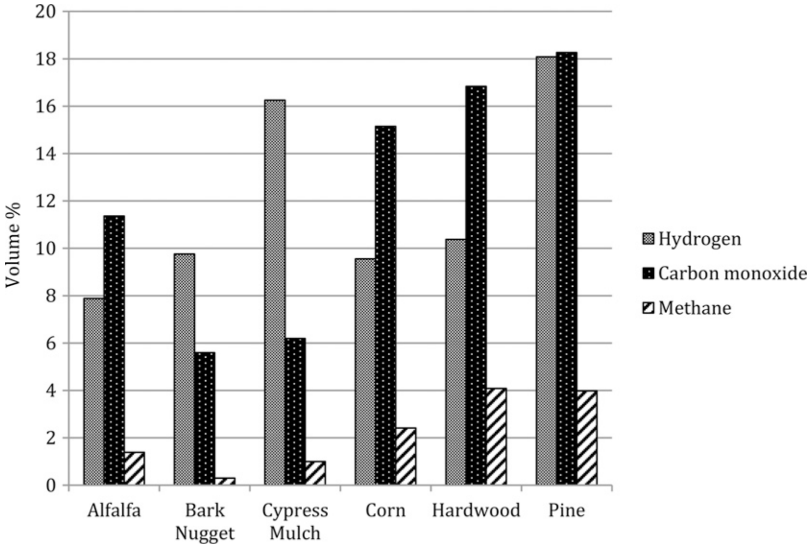

Figure 7. Gas composition resulting from the gasification of different biomass feedstocks.

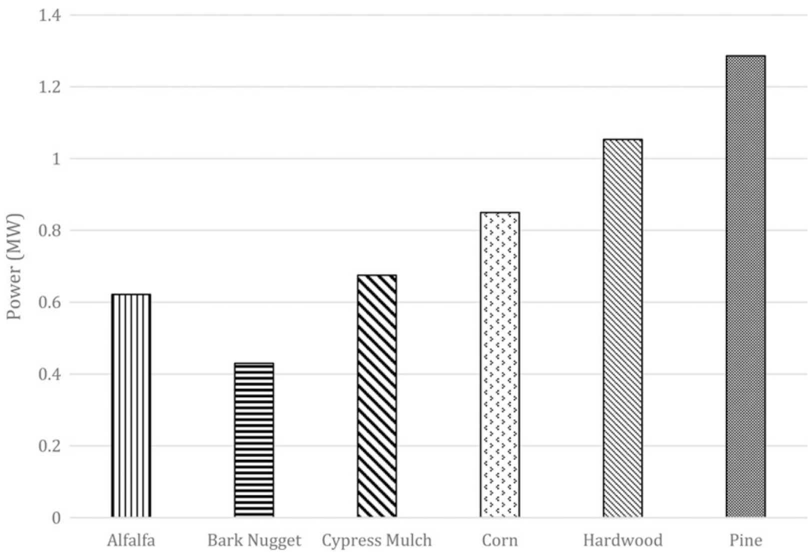

Figure 8. Power generated from combustion of gasification products from different biomass feedstocks.

mixture. The HHV of methane (38 MJ/m^3) is more than three times as large as hydrogen (12.1 MJ/m^3) and carbon monoxide (12.0 MJ/m^3); therefore, even a small difference in producer gas methane composition can have a large effect on the overall HHV of the gas mixture. High feedstock carbon content is a critical chemical feedstock characteristic in generating an energy-rich producer gas. The pine and hardwood feedstocks had relatively high carbon content, while simultaneously having low moisture and high density. When considering mass balance of the gasification system, a high feedstock carbon content translates directly into the ability to form more carbon monoxide and methane, resulting in a product rich with combustible gas. Conversely, elevated ash quantities in a feedstock sample, as in the case of poultry litter and dairy manure, would not yield high-quality producer gas. The presence of inorganic compounds in a sample that make up ash limit the amount of combustible gas that can be ultimately generated from a given feedstock mass.

Additionally, it is also important to have a significantly dense sample to increase the volumetric efficiency of biomass conversion during gasification. This is apparent in observing properties of the woody biomass samples analyzed. Higher density feedstocks provide more mass available for conversion during gasification per unit volume. While all four samples (pine, hardwood, cypress mulch, and bark nugget) had very comparable low ash quantities, cypress mulch and bark nugget had much lower densities. When comparing the energy produced through combustion of producer gas from these feedstocks, cypress mulch and bark nugget resulted in a much lower energy output. Finally, low MC is also found to be critical for successful feedstock gasification. If the MC of the feedstock is too high, it was observed during gasifier testing that biomass inside the gasification unit tended to gel and bridge, physically limiting the flow through the unit. This had the practical effect of necessitating shut down of the gasification system to clear any blockages, resulting in an effectively unsuccessful gasification run.

CONCLUSIONS

Physical and chemical properties of several different biomass samples were analyzed to assess their viability for use in biomass gasification. It was found that pine had the greatest feedstock HHV among those studied with the lowest HHV belonging to corn and poultry litter. Animal wastes showed the highest density, whereas cypress mulch and bark nuggets showed the lowest densities. The low densities of cypress and bark are attributed to density measurement taking place on the sample in its natural form, rather than measuring a pelletized sample. Corn showed the highest moisture percentage, with pine, hardwood, and cypress mulch having the lowest moisture. Ultimately, it was shown in this research that among the studied feedstocks, pine and hardwood performed most effectively in biomass gasification. This is evidenced by the high amount of combustible gases generated from these two samples and subsequent high energy output following combustion of these gases. Analysis of the physical and chemical properties of biomass, as presented in this study, shows the potential to be an affordable and promising method by which to identify or estimate which feedstocks could be most effective in biomass gasification. Low moisture, low ash content, high carbon content, and high density are concluded to be of critical importance for gasification feedstock selection.

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REFERENCES

American Society for Testing and Materials (ASTM) (1996) Standard test method for gross calorific value of solid fuel by the adiabatic bomb calorimeter. D2015. ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) (2007a) Standard test method for ash in wood. D1102-84. ASTM, West Conshohocken, PA.

American Society for Testing and Materials (ASTM) (2007b) Standard test methods for direct moisture content measurement of wood and wood-base materials. D4442-07. ASTM, West Conshohocken, PA.

Arshanitsa A, Barmina I, Telysheva G, Dizhbite T, Andersone A, Zake M, Grants I (2009) The composition and fuel characteristics of non-hydrolyzed residues from wheat straw ethanol production. Eng for Rural Dev 28:105-111.

Babu SP, Whaley TP (1992) IEA biomass thermal gasification project. Biomass Bioenerg 2(1-6):299-306.

Boateng AA, Jung HG, Adler PR (2006) Pyrolysis of energy crops including alfalfa stems, reed canarygrass, and eastern gamagrass. Fuel 85(17-18):2450-2457.

Delong MM, Onischak M, Schmid M, Wiant B, Oelke E (1995) Alfalfa stem feedstock for IGCC power system fuel. Preprints of Papers, ACS Division of Fuel Chemistry 40(3): 699-703.

Demirbas A (1997) Calculation of higher heating values of biomass fuels. Fuel 76(5):431-434.

Engler C, Capereda S, Muktar S (2010) Assembly and testing of an on-farm manure to energy conversion BMP for animal waste pollution control. Texas Water Resources Institute Technical Report No. 366: 1-21.

Environmetal Protection Agency (EPA) (1997) Determination of carbon and nitrogen in sediments and particulates of estuarine/coastal waters using elemental analysis. Method 440.0. US EPA, Cincinnati, OH.

Environmetal Protection Agency (EPA) (2000) Inductively coupled plasma-atomic emission spectrometry. Method 6010C. US EPA, Cincinnati, OH.

Erlich C, Öhman M, Björnbom E, Fransson TH (2005) Thermochemical characteristics of sugar cane bagasse pellets. Fuel 84(5):569-575.

Erol M, Haykiri-Acma H, Kucukbayrak S (2010) Calorific value estimation of biomass from their proximate analyses data. Renew Energy 35(1):170-173.

Fantozzi F, Buratti C (2009) Biogas production from different substrates in an experimental continuously stirred tank reactor anaerobic digester. Biores Technol 100(23):5783-5789.

Friedl A, Padouvas E, Rotter H, Varmuza K (2005) Prediction of heating values of biomass fuel from elemental composition. Anal Chimica Acta 544(1-2):191-198.

Garcia-Perez M, Adams TT, Goodrum JW, Geller D, Das KC (2007) Production and fuel properties of pine chip bio-oil/biodiesel blends. Energy Fuels 21(4):2363-2372.

Geyer WA, Walawender WP (1999) Biomass and gasification properties of young catalpa trees. Wood Fiber Sci 31(1):95-100.

Gil MV, Oulego P, Casal MD, Pevida C, Pis JJ, Rubiera F (2010) Mechanical durability and combustion characteristics of pellets from biomass blends. Biores Technol 101(22):8859-8867.

Igathinathane C, Davis JD, Purswell JL, Columbus EP (2010) Application of 3D scanned imaging methodology for volume, surface area, and envelope density evaluation of densified biomass. Biores Technol 101(11):4220-4227.

Kirubakaran V, Sivaramakrishnan V, Nalini R, Sekar T, Premalatha M, Subramanian P (2009) A review on gasification of biomass. Renew Sustain Energy Rev 13(1):179-186.

Mani S, Tabil LG, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenerg 30(7):648-654.

McKendry P (2002) Energy production from biomass (part 1): Overview of biomass. Biores Technol 83:37-46.

Mukhtar S, Capareda S (2012) Manure to energy: Understanding processes, principles and jargon. Agricultural Communications, Texas A&M University. http://tammi.tamu.edu/ManurtoEnrgyE428.pdf (26 August 2015).

Obernberger I, Thek G (2004) Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass Bioenerg 27(6):653-669.

Raveendran K, Ganesh A (1996) Heating value of biomass and biomass pyrolysis products. Fuel 75(15):1715-1720.

Raveendran K, Ganesh A, Khilar KC (1995) Influence of mineral matter on biomass pyrolysis characteristics. Fuel 74(12):1812-1822.

Sensoz S (2003) Slow pyrolysis of wood barks from *Pinus brutia* Ten. and product compositions. Biores Technol 89(3):307-311.

Sheng C, Azevedo JLT (2005) Estimating the higher heating value of biomass fuels from basic analysis data. Biomass Bioenerg 28(5):499-507.

Tabil LG Jr, Sokhansanj S (1997) Bulk properties of alfalfa grind in relation to its compaction characteristics. Food & Process Engineering Inst. of ASAE 13(4):499-506.

Tavasoli A, Ahangari MG, Soni C, Dalai AK (2009) Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed-bed micro reactor. Fuel Process Technol 90(4):472-482.

Telmo C, Lousada J (2011) Heating values of wood pellets from different species. Biomass Bioenerg 35(7):2634-2639.

Young L, Pian CCP (2003) High-temperature, air-blown gasification of dairy-farm wastes for energy production. Energy 28(7):655-672.