DENSIFICATION OF BIOMASS USING A PILOT SCALE FLAT RING ROLLER PELLET MILL

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ABSTRACT

The production characteristics from a pilot scale flat ring die pellet mill were evaluated for four different biomass materials (miscanthus, corn stover, switchgrass, and wheat straw) to determine the effect of moisture preconditioning upon pelletization. The moisture content of the material entering the pellet mill was 10%, 15%, 20% and 25% for miscanthus, switchgrass, and wheat straw; while, only 15%, 20%, and 25% moisture content was evaluated for corn stover. For miscanthus, switchgrass, and wheat straw at the highest moisture content (25%), pellet formation was readily achieved with the percentage of pellets produced being 92%, 92%, and 96%, respectively. Corn stover preconditioned to a moisture content of 15% resulted in the highest rate of pellet formation, lowest specific energy requirement, and similar durability to other measured moisture contents. For the differing biomass materials, the specific energy requirements for the flat ring pellet mill was measured and varied between 101 to 324 kWh/Mg depending on the crop and moisture content. With energy consumption being one of the primary

costs of pelletization, the on-farm/localized pelletization of biomass using a flat ring die pellet mill may be impaired by the high specific energy requirements of pelletization relative to other pellet mill designs.

Keywords: crop residues, dedicated biomass crops, pelletization, specific energy, densification

1 INTRODUCTION

The volumetric energy content of lignocellulosic material used for biofuels is lower than traditional fossil fuel sources [1], and this low energy density is largely a result of the low bulk densities of biomass materials. Therefore, the densification of biomass is essential to improving the transport, storage, and handling capabilities of this lignocellulosic material. Pelletization is one of the technologies that has been proposed to mechanically increase the bulk density of biomass. The advantages of pelletization go beyond increases in bulk density, as the handling and storage of pelleted biofuel can be performed similar to free-flowing granular products, such as corn, soybeans, and wheat [2]. Biomass pellets have multiple end use applications which range from smaller scale combustion for residential heating to a more industrial scale where pellets could be co-fired with coal at power plants [3]. Worldwide, the total production of pellets increased 10 fold from 2000 to 2010 with the US being one of the leaders in pellet production [4]. The increased demand of pelleted fuel sources in Europe and North America could allow for more non-woody biomass resources such as dedicated biomass crops or crop residues to be used for pelletization.

Pelletization has been performed using either a flat ring die or a ring roller die [5]. Advantages and disadvantages exist with each type of mill. Ring roller dies are commonly used at commercial facilities due to their high throughput and pelletization properties have been assessed at many different moisture contents [6]. However, the flat ring die manifests more robustness with input biomass material and generally requires lower capital investment due to their lower capacity relative to a ring roller die [7]. The potential to use flat ring dies has yet to be fully assessed for the biomass industry. Flat ring die studies have been performed for poplar, vine shoots, industrial cork residue, pine sawdust, grape pomace, and pyrenean oak [8-10] along with high moisture (28% - 38%) corn stover [11] and pretreated corn stover [12]. Nonetheless, the influence of moisture content upon pelletization using a flat ring die has yet to be fully characterized for potential high tonnage biomass crop residues (corn stover and wheat straw) and dedicated biomass crops (miscanthus and switchgrass) [13].

One of the most important variables in pellet production is moisture content, as this property will ultimately determine the durability and density of pellets [6, 14]. The objective of this study was to characterize the sensitivity of the flat ring die to changes in the initial preconditioned moisture content for miscanthus, corn stover, switchgrass, and wheat straw. The moisture content of the material entering the pellet mill was varied from 10 - 25% moisture content (wet basis) for all the biomass materials except for corn stover. Ten percent moisture was the general baseline preconditioned moisture content as this moisture has been used for the pelletization of poplar, grape pomace, and pyrenean oak pellets with flat ring die pellet mill [8, 10]. Previous work by Tumuluru [11], showed corn stover pelletized at higher moisture contents; therefore the range of moisture contents investigated in this study went up to 25%. For the

various preconditioned moisture contents, the potential of a flat ring die to produce pellets from biomass crops was evaluated by measuring the percentage of pellets produced, bulk density, durability, production rate, and specific energy consumption.

2 MATERIALS AND METHODS

Alamo switchgrass (*Panicum virgatum L.*) and miscanthus (*Miscanthus x giganteus*) used in this study were harvested at the University of Kentucky's North Farm, Lexington, KY. The sample material was harvested in late winter 2013 using a disc mower and baled into small square bales (36 x 46 x 120 cm). Wheat straw and corn stover were raked and baled at the University of Kentucky C. Oran Little Research Center in the summer and fall 2013, respectively. The bales were stored in a barn prior to transportation to campus. The biomass was ground using a No. 20 Hammer mill (C.S. Bell Co., Tiffin, OH) and was collected using a cyclone (Cincinnati Fan and Ventilation Inc., Mason, OH). Round hole screen sizes of 3 mm, 5 mm, and 10 mm were used with the hammer mill.

2.1 Sample Conditioning

After grinding, samples were preconditioned in batches with 9 kg (20 lb) being rewetted within plastic storage containers. The moisture content of the ground material was approximately 8% after storage. Material was rewetted and mixed to 10%, 15%, 20%, and 25% moisture contents (wet basis) using a sprayer. Furthermore, challenges with plugging of the die limited the maximum moisture content used to 25%. The moisture contents were randomly tested throughout the conditioning process and analyzed using an Ohaus moisture analyzer (Ohaus Corporation, Parsippany, NJ) with a 1 gram sample dried at 130°C. The moisture measurements

with the Ohaus were equivalent to that of the convection air oven standard [15] with an $r^2 > 0.9$. Thus, the Ohaus was used since the determination of moisture content was conducted in minutes as opposed to days. The conditioned material was sealed inside the container and allowed to sit overnight. The material moisture content was retested the following morning and pelletized if the average was within 0.5% of the target value.

2.2 Pellet Mill

Material was fed into the pellet mill using a belt conveyor system with a paddle at the end to allow for uniform feeding. Pelletization was performed using a Model PM605 (Buskirk Engineering, Ossian, IN) pellet mill flat ring die with a 3.7 kW (5 horsepower) grease-packed gear motor that possessed the capacity to pelletize up to 90 kg/hour (200 lb/hour) according to manufacturer's specifications. The dimensions of the die used were 15.2 cm (6 in) in diameter and a 3.8 cm (1.5 in) thick machined die plate with approximately two hundred sixteen 6 mm diameter holes drilled in the die. Typical pellets formed were approximately 6 mm in diameter and 18 mm in length. Prior to conducting each test, the die was preheated to 90 °C as this temperature is generally considered the minimum threshold for pelletization [3]. Preheating of the die to 90 °C was conducted using dried distillers grain and was subsequently flushed with the lignocellulosic material that would follow. The die did not possess any form of heater, only the friction from the pellet formation controlled the die temperature. The die temperature was measured using a Fluke Hydra Series datalogger (Fluke Corporation, Everett, WA) with three type T thermocouples connected to the outer edge of the die as shown in Figure 1. The temperature was monitored during the test to ensure steady state operation, and the feed rate

varied to maintain the temperature. At the completion of each test, the ending temperature was recorded.

2.3 Power Consumption

The pellet mill operated on a 230V three phase electrical system. Current within each line was measured with an AcuAMP current transducer (AutomationDirect, Cumming, GA, part number ACT050-10-S) which possessed a 1% accuracy. The voltage output from the current transducers was calibrated using an Extech Power Analyzer 380803 (Nashua, NH) with various devices providing the amperage source for calibration points. The current transducers were placed on the output side of the variable frequency drive (VFD) (Lenze Americas Corporation, Uxbridge, MA, USA) that drove the pellet mill. Current was logged using a Measurement Computing USB 1408FS analog to digital board (Norton, MA), and a program was written using Visual Studio (Microsoft, Redmond, WA) to log the data onto a tablet. The software clock was used to achieve a sampling rate of 10 Hz. The voltage was measured on the output side of the VFD using a Fluke multimeter. The total power was calculated in terms of RMS magnitude for a balanced wye load as shown in Equation 1 [16].

$$P_T (kW) = \frac{\sqrt{3} \times V_L \times I_L \times Pf}{1000} \quad \text{Equation 1}$$

Where P_T was total power (kW); V_L was the line voltage (V); I_L was the line current (A); and Pf was the power factor (dimensionless). The power factor for the inductive cyclo drive motor was not directly measured. However, the motor specification stated a power factor of 0.817 under full load [17]. Power factor has been shown to change with load [18, 19], but for

cyclo drives, the power factor can remain constant over a range of speeds [20]. For the pellet mill used, all tests were performed at a constant speed of 1730 rpm for the cyclo drive motor. Furthermore, the feed rate of material into the pellet mill was manually controlled to keep the pellet mill's current draw to 10 A or greater, which would allow for the load amperage to remain above 75% of full load (motor name plate specification for full load amperage was 13.1 A). When operating at 75% of full-load and greater, the power factor remains relatively constant [19, 21, 22]. Thus, a constant power factor of 0.817 was assumed.

To determine the specific energy consumption per unit mass of pellets produced, the mass flow rate of the pellets was quantified by measuring pellet production during a 120 second time span with the pellet mill operating at steady state conditions. This was combined with the average total power consumption measured, P_{Tavg} , to determine the specific energy consumption (SEC) from Equation 2.

$$SEC = \frac{P_{Tavg} * \frac{120sec}{3600sec/h}}{M_p * \frac{1Mg}{1000kg}} \quad \text{Equation 2}$$

Where:

SEC = Specific energy consumption (kWh/Mg)

P_{Tavg} =Average total power consumption over the measurement window (kW)

M_p = Mass of pellets produced during the 120 second measurement window (kg)

2.4 Pellet Durability Index (PDI)

Once the pellets had cooled to ambient temperature, pellet durability was determined in accordance with the ASABE standard [23] to simulate the losses of pellets that would occur with handling, storage, and transport. The 6 mm diameter pellets were sieved on a 4.8 mm (12/64 in) round hole screen. A 500 gram sample of the sieved pellets were rotated in a 300 mm (12 in) by 300 mm by 50 mm deep (2 in) box with a 290 mm (9 in) long baffle of 50 mm angle iron for 10 minutes. The final pellet durability was determined using Equation 3:

$$Durability (\%) = \frac{\text{mass of pellets after tumbling}}{\text{mass of pellets before tumbling}} \times (100) \quad \text{Equation 3}$$

2.5 Bulk Density (as-is)

The bulk density was measured similar to the procedure performed by Mani, et al. [24], who measured the density using a 0.5 liter cup. For this study, cooled pellets were loaded into a funnel that was 50.8 mm (2 inches) above the top of a 1.1 liter (1 US dry quart) kettle. The bottom of the funnel was opened and pellets were allowed to free flow into the kettle. The excess pellets above the top rim of the kettle were removed by taking three strokes across the top of the kettle with a 4.76 mm (3/16 inch) rounded edge 305 mm by 44 mm by 10 mm (12 in by 1-3/4 in by 3/8 in) straight edge. With the tared kettle, the mass of pellets per volume were recorded with three replicates, and the bulk density (as-is) was calculated after the pellets had air cooled and dried at ambient conditions. The final moisture content of the cooled pelleted material for each biomass type was measured after being exposed to ambient laboratory conditions of approximately 25°C and 50% RH for two days.

2.6 Higher Heating Value (HHV)

The higher heating value (HHV), in MJ/kg, was determined for each of the four biomass materials used in this study. Samples of each biomass crop were further ground to pass through a #60 mesh. The ground biomass samples were processed by the University of Kentucky Center for Applied Energy Research to perform proximate analysis [25] and heating value assessment [26]. The higher heating value was measured using bomb calorimetry. The percent or fraction of energy used to make the pellets was measured according to Equation 4.

$$\% \text{ Energy} = \frac{P_{Tavg} \times 120 \text{ sec} \times \frac{1 \text{ MJ}}{1000 \text{ kJ}}}{(M_p) \times HHV \left(\frac{\text{MJ}}{\text{kg}}\right)} \quad \text{Equation 4}$$

Where:

$\% \text{ Energy}$ = Energy used during pelletization, relative to the energy content of the final product (%)

P_{Tavg} = Average power consumption over the 120 second measurement window (kW)

M_p = Mass of pellets produced during the 120 second measurement window (kg)

HHV = Higher Heating Value (MJ/kg)

2.7 Statistics

SAS (Statistical Analysis System, Cary, NC) v. 9.4 was used for the analysis. The Proc GLM procedure was used to perform the least significant differences (LSD) pairwise multiple comparison between the different moisture contents for each biomass crop.

3 RESULTS AND DISCUSSION

Particle size had a major impact on pellet quality and throughput. Initial testing demonstrated that material ground through the 10 mm screen pelletized poorly due to complications associated with material feeding into the die. Matting of the lignocellulosic material in front of the wheels in the pellet mill prevented the biomass from entering the die. Thus, the 10 mm material would not pelletize. The 3 mm material would pelletize; however, with material ground through this screen size, the majority of the biomass was captured in the cyclone filter bag during grinding, potentially skewing the sample composition. Thus, only material that was ground through a 5 mm screen was used for pelletization.

3.1 Trends in Pellet Formation

For miscanthus, switchgrass, and wheat straw at a moisture content of 10%, no pellets were produced and only fines passed through the die (Figure 2, Figure 3, and Figure 4). Similar results were observed at a moisture content of 15%, although 41% of the material was pelleted with miscanthus. The viable production of miscanthus, switchgrass, and wheat straw pellets took place at moisture contents above 20% with the greatest percentage of pellets being produced at a moisture content of 25%. The improved formation of pelleted biomass as the moisture increased for these biomass types was indicative of the improved binding among the particles. Corn stover exhibited a different trend than the other biomass materials (Figure 5). The percentage of pellets produced was equivalent at the 15%, 20%, and 25% moisture levels. Preliminary testing indicated that pellets were not being formed at 10%. Based on the lack of pellet formation for the other materials at 10% moisture content, corn stover was not fully evaluated.

Unlike ring roller dies, the flat ring die demonstrated a greater capability of making pellets at moisture contents greater than 15%. Groesbeck, et al. [27] showed that the pelletization of alfalfa with a ring roller die allowed for moisture contents of up to 9 - 12% to be utilized before plugging of the die occurred. The lower moisture required for alfalfa pelletization with a ring roller die was likely due to differences in the material composition and differences in operating conditions between the two types of pellet mills.

3.2 Effects of Moisture Content on Durability

Moisture content demonstrated a varied effect on pellet durability as well. For miscanthus, switchgrass, and wheat straw, the durability increased with increasing moisture content as shown in Figure 2, Figure 3, and Figure 4. At the 15% preconditioned moisture content, the PDI for miscanthus was 56% (Figure 2) - which is a very low durability when compared to pelleted feeds [28]. Mediocre PDI values were observed for switchgrass and wheat straw (80% and 66% respectively) at the 20% moisture level, which was the lowest moisture at which viable pellets were produced for these crops. Nonetheless, increasing the preconditioned moisture content from 20 to 25% significantly ($P \leq 0.05$) improved the pellet durability index by 23%, 17%, and 42% for miscanthus, switchgrass, and wheat straw, respectively. For corn stover pellets, the greatest durability was demonstrated at a 20% moisture content with the 15% and 25% moisture contents demonstrating equivalent, but slightly lower PDI (Figure 5). Furthermore for all of the biomass material utilized in this study, the 25% preconditioned moisture content resulted in PDI values that were over 90%. The PDI is generally assumed to be “good” if the pellet durability is above 80 -90% [28]. The increased durability of the pellets with increasing

moisture was due to the increased binding aspects of water during pelletization [14]. The pellets were allowed to cool in the laboratory for two days at approximately 25°C. The moisture content was measured prior to performing the PDI tests and was approximately 10% for all initial moisture contents and biomass types. After pelleting, the pellet temperature was likely around the die temperature of 90 °C, although the pellet temperature after formation was not measured. At the elevated temperature, some drying likely occurred during the cooling process, although this was not quantified. A considerable amount of water vapor was visible during the pelleting process for the elevated initial moisture contents, so some drying likely occurred during pelleting. Further investigation of the moisture content influence on pelleting and energy consumption warrants evaluation.

3.3 Pellet Mill Throughput

For miscanthus, switchgrass, and wheat straw, the increased preconditioned moisture content allowed for the improved formation of pellets and thereby increased the pellet throughput as shown in Figure 6. The numerically highest pellet production rate was observed at the highest preconditioned moisture content (25%) for these biomass materials. Moisture contents above 15% for miscanthus, switchgrass, and wheat straw allowed for more binding of material to form pellets and also acted as a lubricant with more pellets being produced as seen in previous studies [28]. For miscanthus, increasing preconditioned moisture content from 20 to 25% significantly increased ($P \leq 0.05$) the pellet production rate by 27%. This improved rate of pellet production with increased water content was consistent with results observed with livestock feed pelletization with a ring roller die where a 5% increase in moisture allowed for the

production rate to be increased by 31 to 50% [29]. Nonetheless for switchgrass, wheat straw, and corn stover increasing the precondition moisture content from 20 to 25% resulted in rates of production that were not significantly different. Alternatively for corn stover, increasing the moisture content from 15 to 20% significantly decreased ($P \leq 0.05$) the rate of production by 60%. For corn stover, the increased binding of the material at 20% and 25% moisture inhibited the rate of pellet formation. Tumuluru [11] pelletized corn stover with a flat ring die at even higher moistures (28 - 38%) than conducted in this study but did not report the production rate.

3.4 Bulk Density

The bulk density of uncompressed material ground through a 5 mm screen at 10% moisture was 86 ± 1.3 , 95 ± 1.9 , 77 ± 3.4 , and 91 ± 3.7 kg/m³ for miscanthus, switchgrass, wheat straw, and corn stover, respectively. The bulk density of miscanthus, pelletized at the 15% and 20% moisture level were comparable, yet the 25% moisture level resulted in a bulk density that was 38% and 27% higher than the 15% and 20% moisture content values, respectively (Figure 7). For switchgrass, the increase in moisture content from 20% to 25% elevated bulk density by 29%, but was not significant. For wheat straw, pellets formed at 25% preconditioned moisture resulted in a bulk density value that was 29% greater ($P \leq 0.05$) than that of pellets created at 20%. When compared to corn stover at the 15% preconditioned moisture content, increasing the moisture to 20% and 25% enhanced ($P \leq 0.05$) bulk density by 16% and 15% respectively. Bulk density of corn stover pellets with an initial 25% preconditioned moisture content in this study was 635 kg/m³ which was comparable to the 618 kg/m³ measured by Tumuluru [11] with a 60 hz

die speed, a die temperature of 110 °C, and a 28% moisture content using the ASTM standard [30].

3.5 Energy Consumption

The specific energy consumption (kWh/Mg pellets) was indicative of pellet production efficiency [27, 31]. The specific energy cost is one of the more important measures since the electrical consumption of the pellet mill long-term will outweigh the investment cost of the pellet mill [32]. Furthermore, the pelletization process uses the most electricity in a pellet production facility with grinding consuming the second most electricity [32]. For the differing biomass crops in this study, the flat ring die demonstrated a varied energy consumption with corn stover at 15% moisture content demonstrating the lowest specific energy of 101 kWh/Mg, and the highest average of 324 kWh/Mg was recorded with miscanthus at 15% (Figure 8). For miscanthus at 15% moisture content, increasing the moisture content to 25% significantly reduced ($P \leq 0.05$) the specific energy by 42%. Similar to the specific energy response of miscanthus, a 5% increase in moisture content in broiler diets pelletized with a ring roller die resulted in 16 - 19% reduction in specific energy [29].

Alternatively, corn stover exhibited the opposite trend, with statistically significant increases in specific energy requirements at each progressive moisture level. When compared to corn stover at 15%, increasing the moisture content to 20% or 25% elevated the specific energy consumption by 80% and 168%, respectively. It is not uncommon to find this increase in energy consumption as moisture content increases. For example, the pelletization of poultry by-product meal with a ring roller die showed that increased moisture content resulted in increased operating

costs due to higher specific energy requirements (30 – 80 kWh/Mg) [33]. When animal feedstuffs were typically processed, ring roller dies have exhibited production efficiencies of approximately 6 to 37.1 kWh/Mg [27, 34-36].

Pellet production efficiency of biomass was stated as varying from 16 to 74 kWh/Mg [5, 37]. In other studies, the flat ring die pelletization efficiency was stated to vary from 50 to 150 kWh/Mg for high moisture (28-38%) corn stover [38], 169 kWh/dry Mg for vine shoots [9], 121 kWh/dry Mg for industrial cork residue [9], and 166 kWh/dry Mg for pine sawdust [9]. The flat ring die energy consumption varied between 138 – 408 kWh/dry Mg for poplar [8]. Those authors also found that for poplar pelletization the addition of either lignosulfonate, corn starch, or both reduced the energy consumption to 95 – 123 kWh/dry Mg. The specific energy requirements from this study seemed to fit within the range that has been observed with other studies that had used flat ring die pellet mill, but also indicated that the flat ring die pellet mills may not be as efficient as ring roller dies. Stelte, et al. [5] stated that the production rate and energy use are strongly related which explained why the most desirable production efficiency was observed with the corn stover at 15% moisture content as this material possessed the highest pellet mass flow rate.

With ring roller die pellet mills, increases in the specific energy requirements increased pellet durability [31]. Fahrenholz [39] demonstrated that an uncertain relationship existed between the PDI and energy consumption as numerous variables could allow for direct or indirect relationships to exist. Factors such as the addition of lignosulfonate or steam conditioning increased both PDI and decreased energy consumption; while, adding oil or altering the composition resulted in a decrease in both. The inconsistent relationship between the PDI and

energy consumption previously reported [39] was also observed in this study. Bulk density and energy consumption have been surmised to be related. However, in this study, bulk density and specific energy were not related.

In relation to the final pelleted product, the fraction of energy that went into producing pellets was shown to be dependent upon the biomass type and preconditioned moisture content with the results being reflective of the specific energy requirement. The final energy in the pelletized product was determined using the higher heating value (HHV) per Mg dry matter (Table 1). The similarities among the HHV of the different biomass materials allowed for the specific energy to be the determining factor. Across the different biomass types, the percent of final pellet energy used to make pellets ranged between 2 to 8% which was generally higher than the 1-3% stated by Stelte, et al. [5] for ring roller dies. Again, the higher energy consumption could be an inherent property of the pilot scale flat ring die.

4 CONCLUSION

For a flat ring die, biomass moisture content was found to be influential in the formation and quality of pellets. For miscanthus, switchgrass, and wheat straw, preconditioned moisture contents less than 20% resulted in the poor (0 – 41%) formation of pellets. At moisture contents of 20% and 25%, the percentage of pellets formed increased to 73 - 96%, and the highest rate of pellet production was observed at the highest (25%) moisture content. Additionally, the durability of miscanthus, switchgrass, and wheat straw pellets responded positively to the increasing moisture content with durability of 92%, 92%, and 96% being observed for the 25% preconditioned moisture content. Corn stover demonstrated a different trend with the moisture

content as the percentage of pellets formed (92%, 96%, and 93%) were equivalent at the 15%, 20%, and 25% preconditioned moisture content, respectively. Nonetheless, the PDI value for corn stover was shown to be the greatest at the 20% preconditioned moisture content. Yet, the pellet production rate for corn stover decreased with increased moisture. When compared to 15% moisture content, corn stover pellet production rates for 20% and 25% moisture contents were reduced by 60% and 64%, respectively. For different biomass crops at the varied moisture contents, pellet production specific energy was found to range from 101 to 324 kWh/Mg for the flat ring die. The production efficiency of flat ring die formed pellets was surmised to be limited by the pellet production rate. When compared to the uncompressed material, pelleted material increased the bulk density by 4.8 - 6.6, 4.5 - 5.8, 4.9 - 6.2, and 6.0 – 7.0 times that of uncompressed material for miscanthus, switchgrass, wheat straw, and corn stover, respectively.

This study demonstrates that small scale production of pellets is possible for various types of biomass. Nonetheless, the higher specific energy requirements of the flat ring die pellet mills would potentially place them at a competitive disadvantage to ring roller die pellet mills. A larger flat ring die pellet mill could be more efficient in specific energy consumption, but this has yet to be shown. Future work with flat ring die pellet mill would need to analyze the impact that the size and scale of equipment can have on specific energy consumption. Furthermore, the pelletization characteristics of different woody biomass materials at various preconditioned moisture contents requires analysis as well.

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Figure 1 Pilot scale flat ring roller pellet mill with shielding removed showing rollers and location of thermocouples on die (circled)

Figure 2 Percentage of fines, pellets, and pellet durability index (PDI) for miscanthus at four moisture contents. ^{a,b,c,d} Means bearing differing superscripts within a group (Fines, Pellets, PDI) are significantly different ($p < 0.05$)

Figure 3 Percentage of fines, pellets, and pellet durability index (PDI) for switchgrass at four moisture contents. ^{a,b,c} Means bearing differing superscripts within a group (Fines, Pellets, PDI) are significantly different ($p < 0.05$)

Figure 4 Percentage of fines, pellets, and pellet durability index (PDI) for wheat straw at four moisture contents. ^{a,b,c} Means bearing differing superscripts within a group (Fines, Pellets, PDI) are significantly different ($p < 0.05$)

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378 Figure 5 Percentage of fines, pellets, and pellet durability index (PDI) for corn stover at four

379 moisture contents. ^{a,b} Means bearing differing superscripts within a group (Fines, Pellets, PDI)

380 are significantly different ($p < 0.05$)

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Figure 6 Production rate of pellets (g/min) at three moisture content levels for the four biomass feedstocks ^{a,b}. Means bearing differing superscripts within a feedstock are significantly different ($p < 0.05$)

Figure 7 Bulk density of four feedstocks at three moisture content levels. ^{a,b,c}, Means bearing differing superscripts within a feedstock are significantly different ($p < 0.05$)

Figure 8 Pellet production efficiency measured in the specific energy consumption of the mill per Mg of pellets produced ^{a,b,c}. Means bearing differing superscripts within a feedstock are significantly different ($p < 0.05$)

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Table 1 Higher heating value and proximate Analysis for Biomass Crops

Biomass Material	HHV (MJ/kg) (Dry)	Proximate Analysis (Dry Basis)		
		% Volatile Matter	% Ash	% Fixed Carbon
Miscanthus	18.09	82.98%	2.53%	14.49%
Corn stover	17.86	80.24%	3.93%	15.82%
Switchgrass	18.61	83.65%	2.99%	13.37%
Wheat straw	18.30	78.61%	5.49%	15.89%

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