

FARM-SCALE BIOMASS PELLETIZER PERFORMANCE FOR SWITCHGRASS PELLET PRODUCTION

D. Ciolkosz, R. Hilton, C. Swackhamer, H. Yi, V. M. Puri, D. Swomley, G. Roth

ABSTRACT. The impact of feedstock characteristics (moisture content, additive content) and operational parameters (die temperature, pelletizer speed) on pellet quality, plugging tendency, and pelletizer energy use was investigated for a small-scale pelletizer, suitable for on-farm use (~70 kg h⁻¹ rated output). Ground switchgrass (*Panicum virgatum*) was prepared in small (<1 kg) batches and run through a flat plate, rotating die pelletizer with 6 mm die holes and a die thickness of 25 mm. The resulting pellet quality and die flow (plugging tendency) were assessed using a subjective pellet quality scale. Results indicate that successful pelleting conditions were most consistently achieved by using a "premix" consisting of ground switchgrass and Distillers Dried Grains in a 3:7 ratio (mass basis) to condition the die, followed by the actual feedstock mixture. The highest quality pellets were obtained from switchgrass with a moisture content ranging from 12% to 18% (wet basis). Adding between 1% and 4% vegetable oil improved pellet appearance, while adding starch (1% to 5%) to the switchgrass feedstock did not yield quality improvements. Reducing the operating speed of the pelletizer resulted in improved quality of the pellets. Feedstock moisture content was positively correlated to pellet production rate and negatively correlated with pelletizer energy use.

Keywords. Biomass densification pellets.

Pelletizing is a process of creating a densified cylindrical compact by extruding granular material through a rigid die. Biomass pelletizing is typically achieved using rollers to press ground material through a die that is shaped either as a ring or a flat plate, with holes to allow for passage and densification of the ground biomass (fig. 1). While definitions vary, for the purposes of this article, the term "pellets" will refer to densified cylindrical biomass compacts 5 to 10 mm in diameter. Densified compacts greater than 25 mm in diameter will be referred to as "briquettes" (PFI, 2008; Ciolkosz, 2009).

Studies have investigated the pelleting of various types of biomass, including wood, compost, grasses, straw, crop residue, and torrefied material (Bergman and Kiel, 2005; Mani et al., 2006; Finney et al., 2009; Tumuluru et al., 2010; Stelte et al., 2011b). Typically, studies have focused on the impact of feedstock characteristics on fuel pellet

quality, often measured as the diametral compressive strength of the pellet and its resistance to crumbling when placed in a rotating test container (ASABE Standards, 2012). Variables of investigation have included:

- moisture content,
- steam addition,
- particle size distribution,
- feedstock age,
- process temperature,
- process pressure,
- feedstock additives,
- die Length-to-Diameter (L/D) ratio.

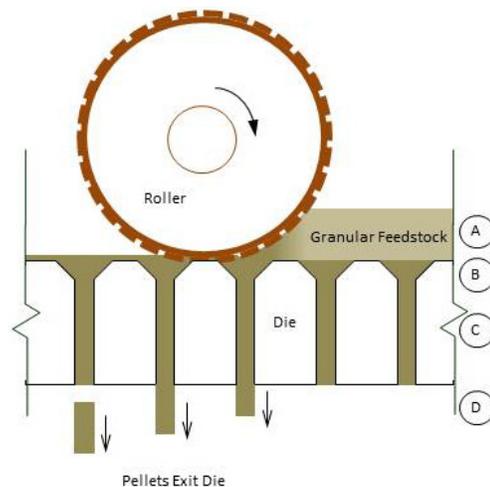


Figure 1. Schematic of key components and processes of a biomass pelletizer. A) axial compression of loose granular material, B) axial and transverse compression and movement, C) Axial compression and movement, and D) ejection and relaxation of pellets. (Not to scale)

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The variability of results from various studies suggests that the pelletizing process is highly sensitive to variations in procedure, and that the type of pelletizing equipment, as well as the manner in which it is used, may play an important role in the performance of the pelletizer.

Experimental manufacture of pellets is often carried out either using a slow, controlled densification process, or by using industrial scale pelleting equipment (i.e., Kaliyan and Morey, 2006; Arshadi et al., 2008). While the slower process is often more controlled and easier to characterize, the much faster process used in commercial pelleting equipment is likely to have different performance characteristics due to the different rates of compaction and different geometries of the dies.

Key mechanisms that are identified as being relevant to the biomass pelleting process include:

1. Moisture, which is shown to have a significant impact, by reducing the glass transition temperature of the lignin (Nielsen et al., 2009), and affecting the frictional characteristics of the material within the die, ultimately impacting pellet durability and density (Larsson et al., 2008). Steam is reported to be an especially effective means for achieving improved performance for biomass (Leaver, 1988),
2. Heating of lignin above its glass transition temperature, allowing for the (mobilized) lignin to form covalent bonds between adjacent particles as well as to experience plastic deformation forming mechanical “bridging” structures within the pellet (Kaliyan and Morey, 2009; Stelte et al., 2011a),
3. Longitudinal compression of the ground biomass within the die, resulting in increased density of the material. Resistive pressure is theorized to be a function of the pressure-friction characteristic of the compressed material within the die (Krizan et al., 2009), and
4. The Poisson ratio of the granular feedstock is suggested to be a key mechanism by which resisting pressure is built up in the die - impacting pellet quality, energy requirements, and tendency of the die to clog (Holm et al., 2006).

The pelleting of switchgrass using ring die pelletizer equipment has received some attention in the literature. Kaliyan et al. (2009) tested the impact of die aspect ratio when using a ring die pelletizer with 9.5 mm diameter die openings, finding that a greater Length to Diameter (L/D) ratio resulted in higher bulk density and durability of switchgrass pellets. They also found that preheating the feedstock was not necessary, concluding that friction between the particles and between the particles and the die was sufficient to heat the pellets to the point where natural binding agents were activated (i.e., the glass transition temperature of the binder, $\sim 75^{\circ}\text{C}$). They measured a specific energy consumption rate (excluding the power used to run the machine when empty) of 403 to 414 MJ t^{-1} .

Jannasch et al. (2004) pelletized switchgrass in a commercial-scale ring-die pelletizer. They found that reduced feedstock particle size results in increased pellet hardness, and reported a specific energy consumption rate of 268 MJ t^{-1} . In an earlier study, Samson et al. (2000)

measured a specific energy consumption rate of 300 MJ t^{-1} using the same equipment (Kaliyan et al., 2009). Specific energy consumption of the process is relevant as it gives a more precise indication of the energy used to densify the biomass (as opposed to total energy use of the device), and can in turn be used to determine the ratio of energy used in the process vs. the energy content of the feedstock.

Several mathematical/numerical models have been developed that attempt to characterize the biomass pelletizing process. Nielsen (2009) proposes a three-step model for biomass pelletization consisting of three distinct steps: compression of the granular material above the die, flow through the narrowing “inlet throat” of the die, and friction resistance as the material passes through the straight section of the die. Several studies have employed finite element models to simulate the process (Hu et al., 2010; Lu et al., 2012; Ye et al., 2013), yielding insight for die design. Axial pressure within the die is modeled to decrease exponentially as the biomass travels through the die (Krizan et al., 2009) dependent on feedstock characteristics. On the feedstock side, statistical models have been developed that characterize the density of the ground biomass as a function of pressure (Tumuluru et al., 2010), although their application to the pelletizing process has not been widely reported.

While the impact of variables on pellet quality is of significant importance, the impact on equipment performance has been less thoroughly studied. Problems such as die clogging, failure to form pellets (“wash through”), and excessive energy use can make the pelleting process quite challenging. For example, Holm et al. (2006) report that feedstock type, additive composition, and method of mixing can all impact the performance of the pelletizer. They also noted the beneficial impact of Brewers Spent Grains on the pelletizing process for wood pellet production, although the mechanism for this improvement was not identified.

The apparent mechanism of pellet formation and movement through the die involves resisting force developing within the feedstock matrix as pressure is applied from above. The maximum resisting force of a differential length of matrix is likely a function of the applied force from the roller, the properties of the feedstock matrix, and the “back pressure” applied from below. If the conditions experienced by the matrix are not sufficient to cause plastic deformation and agglomeration of the particles, “wash through” of feedstock occurs and pellets are not formed. If the maximum available downward force from the roller is greater than the resisting force of the matrix, the pellet material moves through the die. If not, clogging of the die occurs. However, higher quality pellets tend to be associated with higher compressive forces (Kaliyan and Morey, 2009).

One of the research opportunities in this area is to study and better understand the relationship between the applied compressive force, properties of the feedstock, design of and manner in which the equipment is used, and the resistive force provided by the feedstock. This will allow for better control of equipment design and operation so that the relatively small operational window of “good pellets”

can be achieved more reliably and less desirable outcomes can be avoided.

Small-scale pelletizing equipment is, in some respects, well suited for farm-scale production of biomass pellets. Its small size, portability, and affordability make it an attractive entry level device for small-scale pellet producers. They tend to be different from industrial scale devices in several respects. First, the infeed mechanism tends to be manual rather than metered. Second, the rollers tend to be of smaller diameter, which can impact the magnitude and direction of resulting compressive forces. Third, while industry recommendations for herbaceous biomass often specify a die hole length-to-diameter ratio of 8 to 12 (Leaver, 1988), the dies on small pelletizers can often be thinner (i.e., less deep), which can have critical impacts on the formation and properties of the pellets. Anecdotal discussions with operators of small pelletizers suggest that these devices are particularly prone to problems with producing consistent high quality pellets, and that the mechanisms controlling their performance are only vaguely understood (i.e. Shang et al., 2014).

Because of these unique differences and the lack of a more rigorous understanding of the pelletizing process, there is a need for continued work for assessing the performance of small-scale pelletizer devices under different feedstock and operating conditions. This study seeks to help address this issue by examining the impact of moisture content, use of additives, and equipment speed on equipment performance and pellet quality when making switchgrass pellets.

METHODOLOGY

Table 1 lists the selected experimental treatments for the study to investigate the impact of five operational variables on pelletizer performance.

The rationale for selecting these variables and corresponding ranges is based on the operational capabilities of the pelleting equipment and the common operating conditions reported in other biomass densification studies. Switchgrass (*Panicum virgatum* cv. “Cave in Rock”) was obtained from a local farmer in baled form, and was then ground in a Munson Knife Mill (Model SCC-10-S, Utica, N.Y.) with a 6.3 mm size screen. Moisture content of the ground material was measured based on mass loss in a sample when placed in a drying oven at 105°C for 24 h. Approximately 500 g of ground switchgrass were then prepared for testing. Moisture content was adjusted by manually adding liquid water to the sample using a spray bottle and mixing by hand until the material appeared

completely uniform. The sample was not subjected to a waiting/hold period at this point, but was immediately used for pelleting. DDG, starch, and oil were likewise added and mixed manually (if called for). Cornstarch, when used, was always mixed before the addition of water, as this facilitated even mixing. Cornstarch and canola oil were never used in the same testing mix; they were always used separately.

As a follow-up experiment, six additional tests were run at six moisture contents ranging from 15% to 29%, during which pellets were collected on a 15 s time interval and evaluated separately for each time period. This allowed for evaluation of the variation in pellet quality and energy use over the course of the pelleting operation. Power use by the pelletizer was measured using a three-phase power transducer (Ohio Semitronics Model W-061C, Hilliard, Ohio), and voltage and current were also measured (Veris Hawkeye Model 922, Tualatin Ore., and CR Magnetics Model CR4550-250, St Louis, Mo.). Readings were taken on a 1 s interval and stored in a datalogger (Campbell Scientific Model CR1000, Logan, Utah) for later analysis. Correlation analysis was used to identify relationships between energy use, pellet throughput (mass produced during the 15 s period), and pellet quality.

The pelletizer used for this study is a Pellet Pros (Model PP220, Dubuque, Iowa) consisting of a 75 mm diameter roller and a 150 mm diameter flat plate die, 25 mm thick with 6 mm diameter die holes. The inlet taper is 5 mm deep with an angle of 22°, and the exit taper is 1 mm deep. Pelletizer speed was controlled using a variable frequency drive (Automation Direct Model GS2-25PO, Cumming Ga.).

Prior to each experimental run, the die and housing were brushed clean and the die holes were unplugged using a hammer and punch. It should be noted that the innermost ring of holes on the die were left plugged because the roller does not fully pass over them during operation. The hopper was then fixed to the feed mouth to finish prepping the machine for the pelletizing of switchgrass mixtures.

An earlier study indicated that it is very difficult for the switchgrass to pelletize properly in the machine, although once the machine started to make pellets, it tended to operate more effectively (Rooney et al., 2012). One important operational detail that was discovered was that slow addition of the feedstock to the device was not effective - probably due to heating and drying of the feedstock material prior to its being pressed into the die. Instead, adding the material all at once yielded better results. More importantly, however, it was found that a mixture of switchgrass and DDG, when added to the

Table 1. Experimental variables for study of forming pellets using switchgrass.

Test Variable	Moisture Content (wet basis)	DDG Content (% by mass)	Corn Starch Content (% by mass)	Oil Content (% by mass)	Die Temp at Start	Pelletizer Speed (Hz)
Moisture Content	5% - 30%	0%	0%	0%	20°C	5.7
Added DDG ^[a]	10%, 20%	0, 10, 20, 30, 40%	0%	0%	20°C	5.7
Added corn starch	14%-17%	0%	0, 1, 2, 4, 6, 10%	0%	20°C	5.7
Added oil	14%	0%	0%	0, 1, 2, 3, 4, 5, 6%	20°C	5.7
Pelletizer speed	14%	0%	0, 1, 2, 4, 6%	0, 1, 2, 3, 4, 5, 6%	20°C	11.3 or 5.7

^[a] DDG=Distillers Dried Grains.

pelletizer at the start of the experimental run, caused the subsequent test sample to pelletize much more reliably. As a result, this approach (use of a “premix” followed by the sample treatment) was used for all experimental treatments reported here. Preliminary tests (data not shown, see Hilton and Swomley, 2012) indicated that the pre-mix was most effective when a high percentage of DDG was used, and a mixture of 70% DDG and 30% switchgrass (mass basis) was selected for use.

Evaluation of the resulting pellets was carried out using two subjective pellet evaluation scales: one for pellet quality and one for the “die flow” of the process (table 2). A score ranging from 0 to 10 was given to the results of each experimental treatment, providing an evaluation of the quality of the final product and the likelihood of the die to clog with material and cease functioning. Descriptions of ratings of 1, 5, and 10 were developed, and operators were asked to use their judgment to assign a whole number score based on those descriptions. Typically, 200 to 300 g of pellets were produced by a single treatment for subsequent evaluation. Comparison of subjective ratings of pellet quality to durability measured by the standard “tumbling box” test (*ASABE Standards*, 2012) has indicated a positive correlation between the two measures, with greater sensitivity from the subjective ratings (i.e. a 60% variation in subjective rating corresponded to a 40% variation in durability rating – Vendetti and Crawford, 2013). Also, multiple individuals using the scale gave evaluations in good agreement with one another, further indicating the robustness of the measure.

Table 2. Subjective rating scale descriptions.

Score:	0	5	10
Pellet quality rating	No pellets made	Small pellet formed; brittle and not tightly packed	Large, strong, tightly packed pellet equal in quality to commercial grade wood pellets
Die flow rating	Die clogged immediately (< 20 pellets formed)	Die clogged within 1 min of starting to run (<50 pellets formed)	Virtually no clogging; all material ran through die

Statistical analysis of the impact of moisture content, starch, and oil on pellet quality and die flow included correlation and regression analysis. Analysis of the impact of pelletizer speed was carried out using a paired t-test between the two speeds tested. Analysis of energy use and pellet quality utilized correlation analysis-calculating correlation between energy use, production rate, and pellet quality and by regressing production rate and energy use versus moisture content.

RESULTS

IMPACT OF MOISTURE CONTENT

The correlation coefficient between moisture content and pellet quality is only 0.119-suggesting a very weak relationship. However, examining the data (fig. 2) shows that varying the moisture content of the feedstock actually has a noticeable impact on the pelletizing process. Die temperature was measured during these tests using an infra-red sensor, with die temperatures in the 80°C to 90°C range, and no apparent correlation to feedstock moisture content.

Pellet quality had higher ratings when moisture content of the test mixture ranged between approximately 12% and 25%. Outside this range, pellet quality was lower. Tests below 12% moisture generally failed to form pellets, resulting in “washthrough” of the die. Tests at high moisture contents either failed to form pellets or else clogged the die. Die flow ratings tended to decrease as moisture content increased, according to the following regression equation:

$$F_D = -0.3043 * M + 11.647 \quad (1)$$

where

F_D = die flow rating,

M = moisture content (% , wet basis),

R^2 = 0.5829.

Based on pellet quality and die flow, the optimum moisture content appears to be between 12% and 18% for small-scale pelletizers.

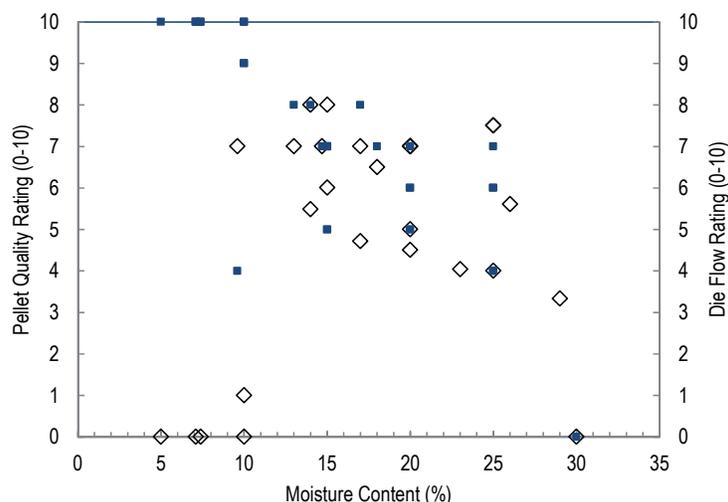


Figure 2. Impact of feedstock moisture (percent, w.b.) on pellet quality (diamonds) and die flow (squares).

IMPACT OF ADDING DISTILLERS DRIED GRAINS (DDG)

Adding DDG to switchgrass at 20% moisture content resulted in creation of pellets that were not very strong, whereas mixtures with DDG and 10% moisture were more successful. Increasing the fraction of DDG in the mix is associated with a slight reduction in pellet quality, but this trend is not statistically significant ($p=0.12$).

IMPACT OF ADDING STARCH

Adding corn starch to the test mixture did not have a noticeable impact on either pellet quality or die flow. The correlation between starch content and pellet quality, and between starch content and die flow, are 0.154 and 0.183, respectively. Small granules of hardened starch were observed in the pellets, which may indicate that the starch was not uniformly distributed in the test material. The pellets that formed tended to exhibit many minor transverse cracks, suggestive of longitudinal expansion of the pellet after it left the die. The mean pellet quality and die flow ratings for starch addition were 6.75 and 7.75, respectively.

IMPACT OF ADDING CANOLA OIL

Results of the testing of canola oil's impact on pelletizer performance are summarized below.

The use of canola oil as an additive did not noticeably improve pellet quality or die flow—in fact, a slight downward trend may be noticed in figure 3 (p value for linear regression = 0.087). Unlike pellets with added starch, pellets using oil in the feedstock did not exhibit longitudinal cracks but instead had a shiny appearance. The pellets received mean ratings of 6.4 and 7.4 for pellet quality and die flow, respectively. The best results were observed when a test mixture was used with a moisture content of 14% mixed with 1% canola oil. Pellets that were produced using this mixture attained a higher quality than tests run using no additives.

Table 3. Impact of DDG on pelletizer performance.

% DDG	10% Moisture		20% Moisture	
	Pellet Quality	Die Flow	Pellet Quality	Die Flow
0%	7	8	5	7
10%	6	7	4.5	7
20%	6.5	7	5	7
30%	6.5	8	5	7
40%	6.5	8	4.5	7

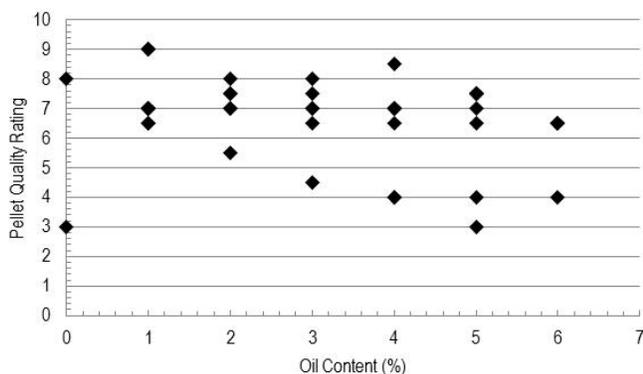


Figure 3. Impact of canola oil on pelletizer performance.

IMPACT OF PELLETIZER SPEED

Several experimental runs were conducted with the die rotating at full speed (11.3 Hz), then repeated but with the die at half speed (5.7 Hz), in order to investigate the impact of equipment speed on pelletizer performance (fig. 4). Our results showed that none of the full speed tests produced pellets with a greater quality than tests run at half speed. The mean pellet quality for tests run at half speed is 7.36, and is 5.64 for the tests run at full speed, while the p -value for the paired t -test is <0.001 . However, the die flow rating tended to be higher for tests run at full speed, with a mean die flow of 7.21 at half speed and 8.21 at full speed (again, $p<0.001$).

It was found that, when tests were run at half speed the material fed into the hopper had to be manually agitated to achieve good performance. Otherwise, the pelletizer stopped producing pellets and the testing mixture would “wash through” the die without forming pellets. This may be due to formation of pockets of steam at the surface of the die that disrupted the flow of feedstock into the die.

When tests were run at full speed, vibration of the machine caused the feedstock in the hopper to be more vigorously agitated by the motion of the pelletizer, presumably preventing steam pockets from developing.

TIME INTERVAL ANALYSIS

Pellet quality, mass of pellets produced and energy use varied a great deal over the course of each experimental run. Figure 5 shows an example of this variation, in this instance for the 20% moisture treatment.

Summarized results from the time interval runs are shown in table 4. The “Weighted Pellet Quality” data are weighted according to the mass of pellets produced during each time interval, as follows:

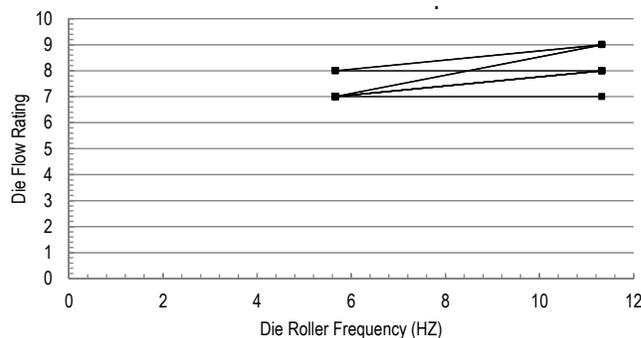
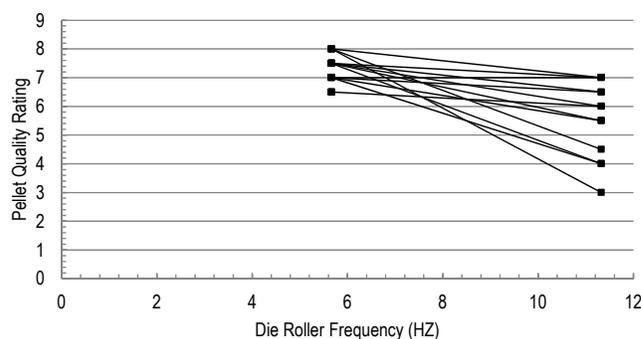


Figure 4. Impact of die speed on pelletizer performance.

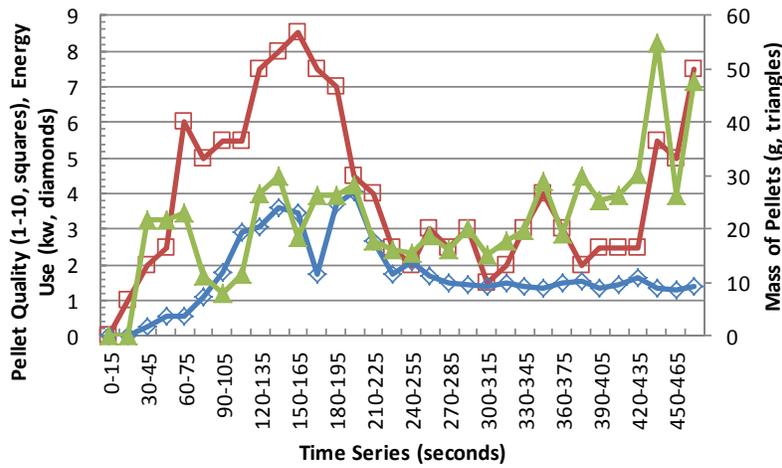


Figure 5. Time series data for 20% moisture feedstock.

Table 4. Performance of time interval runs.

Moisture Content (%)	Weighted Pellet Quality (0-10)	Elapsed Time (s)	Mass of Feedstock Processed (g)	Mass of Pellets Produced (g)	Energy Used (kwh)
14	5.5	315	1088.2	369.9	0.132
17	4.7	450	1156.5	314.1	0.172
20	4.5	480	1123.8	701.0	0.230
23	4.0	465	1289.6	1024.7	0.214
26	5.6	390	1148.2	875.9	0.255
29	3.3	555	1098.2	984.0	0.197

$$Q_w = (\sum M_i * Q_i) / \sum M_i \quad (2)$$

where

Q_w = weighted pellet quality (1-10),

M_i = mass of pellets produced during “ith” time interval (g),

Q_i = pellet quality of “ith” time interval (1-10).

Analysis of average energy and throughput for the six time interval runs indicates that as moisture content of the feedstock increases, the rate of pellet production increases, and the specific energy use (kwh per kg) decreases (fig. 6). Best fit equations for these trends are as follows:

$$R_p = -0.4447 + 0.2873 * M \quad (3)$$

where

R_p = pelletizer production rate ($kg\ h^{-1}$),

M = moisture content (%),

$R^2 = 0.5496$,

$$E = 0.6632 - 0.0159 * M \quad (4)$$

where

E = pelletizer energy use ($kwh\ kg^{-1}$),

M = moisture content (%),

$R^2 = 0.4961$.

This suggests that moisture may be acting as a lubricant, reducing friction either between particles or between the matrix and the die wall. In addition, moisture is known to reduce the glass transition temperature of the natural occurring binders and plasticize compounds that are acting as lubricants (Kaliyan and Morey, 2009).

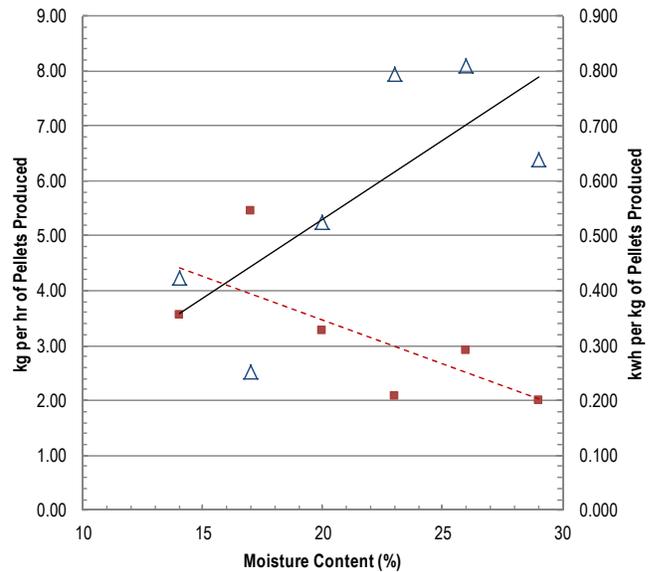


Figure 6. Pellet production rate (triangles) and energy use (squares) vs. moisture content, with best fit line for pellet production rate (solid) and energy use (dashed).

When assessing 15 s interval data from these runs, The strongest correlation is between energy use and pellet quality, especially at the lower moisture contents tested (<20% m.c.), where the correlation coefficient is 0.898. The same trend is evident for correlation between pellet quality and mass of pellets produced, with a strong correlation (0.863) when the moisture content is below 20%, but lower for wetter samples. This suggests that energy use for high moisture feedstocks may be dictated by factors other than resistance to flow within the die.

DISCUSSION

These results suggest several interesting things about the pelleting process. Using a “premix” of switchgrass and DDG followed by the test mixture, was successful at achieving repeatable performance from the device. This result bears resemblance to the findings of Holm et al. (2006), who noted improved pellet durability when brewers

spent grains were added to the feedstock. However, DDG did not appear to improve pellet quality in this study. The working hypothesis regarding DDG and ground switchgrass that developed over the course of these experiments was that the DDG/Switchgrass mix is more readily able to form a “dynamic plug” -a matrix of material within the die that resists flow enough to allow back pressure to be developed, but does not resist flow so much that the device clogs. The mechanism by which this occurs is not clear, but does not appear to be linked to starch or oil content in the DDG. Instead, this phenomenon may involve the shape of the DDG causing the switchgrass fibers to be oriented more randomly, thus increasing their tendency to lock together and form bridging structures within the die. The photos in figure 7 show un-densified chopped switchgrass, DDG, and a mixture of the two materials.

The finding that pellet quality improved when the pelletizer was run at half speed was interesting. The likely mechanism for this effect is that the pellets spent a longer residence time in the die, perhaps allowing the particles to relax stress in their densified position and reduce the amount of springback that occurred when the pellets left the die. Alternately, additional time in the die could have allowed the lignin in the biomass to more fully heat and better adhere to adjacent particles. This explanation is consistent with the findings of Kaliyan et al. (2009), in which a thicker die (i.e. longer residence time) was found to increase pellet bulk density and durability. Some models of the pelleting process (Tumurulu et al., 2010) do not include a time component, but it appears that such an inclusion may be in order. This finding raises the interesting possibility of using a thinner die at a slower throughput rate, which may have system or energetic benefits.

Moisture content has often been reported as a key parameter impacting switchgrass pellet quality (Tumurulu et al., 2010), and results from this study suggest the same. Pellet quality and die flow were best with moisture content in the range of 12% to 18%. The die tended to clog at very high moisture content, and pellet quality at extremes of moisture content was also very poor.

Oil and starch were both investigated as possible additives-oil did improve switchgrass pellet appearance-reducing cracking of the pellet, but did not impact overall quality appreciably. Starch addition did not have a discernable positive impact on pellet quality or die flow. This is surprising, since gelatinized starch is a well-known

binder in pellets (Thomas et al., 1998). Perhaps the added starch was not appropriately mixed or else not in high enough quantity to impact pellet quality. Effectiveness of starch as a binder depends on uniform coverage of the biomass particles with a film of starch, as well as “gelatinization” or rupturing of the starch granule, which may not have occurred during the tests.

The subjective pellet quality and die flow ratings developed in this study proved themselves to be rapid and practical methods to assess the results of the experiments. While subjective assessments are not always considered ideal for scientific work, in this case they provide a necessary and useful method to obtain information not otherwise available. Methods have been established for measuring some physical properties of biomass pellets, but these methods are either slow and costly (i.e. compressive strength testing) or are not successful for weak pellets (i.e. tumbling box durability tester). Furthermore, the “quality” of a pellet is a subjective term in and of itself, and experienced personal evaluation is probably the best single approach for obtaining a full assessment of the pellet-especially for small-scale operations or production for personal use, where a quick, inexpensive assessment is needed. “Die Flow” is another characteristic that can be evaluated subjectively, but does not subject itself readily to a physical-reductionist approach. Development of improved testing methods that evaluate pellets more completely and in a cost-effective manner would be useful, but in the meantime, subjective analysis appears to be an appropriate and valuable method for quick and easy assessment.

Power consumption was recorded for a limited portion of the tests carried out in this study, so this study does not provide a complete picture of power consumption characteristics for the different mixtures. However, higher moisture content feedstocks tended to result in lower energy use and higher rates of production, suggesting in turn that moisture may have a lubricant effect on the pellets and/or by lowering the glass transition temperature of natural binders to enable stronger inter-particle binding as they pass through the die. Energy use and pellet quality are positively correlated, which suggests, reasonably, that greater energy use is translating into more effective densification. However, the correlation between pellet quality and mass of pellets produced is a somewhat surprising, but welcome result, indicating that high quality



Figure 7. Close-up photos of (L to R) chopped switchgrass, distillers dried grains (DDG), and a mix of switchgrass and DDG. A mm scale is shown in the leftmost photo.

and high rates of production may not be mutually exclusive.

The results and experience obtained in this study suggest that the pelleting process is highly dependent on a feedback mechanism, in which the “back pressure” resisting forward movement of the pellet in the die is dependent on the quality of the pellet that is being formed, and the quality of the pellet that is being formed is dependent in part on the back pressure that is resisting forward movement of the pellet in the die. Achieving a stable operating point for small-scale pelletizers gives every indication of being a challenging task. Maintaining that stable operating point via long duration runs may be challenging as well. The existence of a feedback mechanism in the system suggests the possibility of developing control methods that can more effectively stabilize and even optimize the operation of small-scale pelletizers, but this will require greater insight into the controlling mechanisms within the process. A Markov-chain model (Grinstead and Snell, 1997) may lend itself to characterizing this process, due to the cyclical nature of the applied force from the roller to the granular feedstock.

CONCLUSIONS

Switchgrass pellet quality and pelletizer performance were found to be linked to feedstock and operational characteristics of small pelletizers. Conclusions from this study include:

- A two-step process was successful at creating switchgrass pellets, in which a premix of DDG and switchgrass is followed by the test mixture.
- Moisture content had a noticeable effect on pellet quality and die flow, with best results occurring in the range between 12% and 18% (wet basis).
- Using cornstarch as an additive to our testing mixture did not improve the quality of switchgrass pellets.
- Using canola oil as an additive to our testing mixture did not improve the quality of switchgrass pellets.
- Increased feedstock moisture content increased machine throughput and reduced energy use.
- Switchgrass pellet quality is positively correlated with energy use as well as machine throughput.

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