

Value of Distributed Preprocessing of Biomass Feedstocks to a Bioenergy Industry

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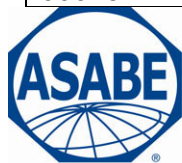
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Abstract. *Biomass preprocessing is one of the primary operations in the feedstock assembly system and the front-end of a biorefinery. Its purpose is to chop, grind, or otherwise format the biomass into a suitable feedstock for conversion to ethanol and other bioproducts. Many variables such as equipment cost and efficiency, and feedstock moisture content, particle size, bulk density, compressibility, and flowability affect the location and implementation of this unit operation. Previous conceptual designs show this operation to be located at the front-end of the biorefinery. However, data are presented that show distributed preprocessing at the field-side or in a fixed preprocessing facility can provide significant cost benefits by producing a higher value feedstock with improved handling, transporting, and merchandising potential. In addition, data supporting the preferential deconstruction of feedstock materials due to their bio-composite structure identifies the potential for significant improvements in equipment efficiencies and compositional quality upgrades. Theses data are collected from full-scale low and high capacity hammermill grinders with various screen sizes. Multiple feedstock varieties with a range of moisture values were used in the preprocessing tests.*

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The comparative values of the different grinding configurations, feedstock varieties, and moisture levels are assessed through post-grinding analysis of the different particle fractions separated with a medium-scale forage particle separator and a Rototap separator. The results show that distributed preprocessing produces a material that has bulk flowable properties and fractionation benefits that can improve the ease of transporting, handling and conveying the material to the biorefinery and improve the biochemical and thermochemical conversion processes.

Keywords. Biomass Feedstock, Preprocessing, Feedstock Assembly, Grinding, Densification

Introduction

Mechanical preprocessing is one of the primary operations in the feedstock assembly system and front-end operations of a biorefinery. Its importance to the overall bioindustry is its influence on critical cost and quality barriers associated with bulk handling, transportation, and biomass variability, quality, and constancy. There are many variables associated with each preprocessing unit operation and the form of the resulting biomass (i.e., operational cost and efficiency, moisture content, particle size, bulk density, compressibility, and flowability) that directly impact the ability to address and overcome these barriers. Ultimately, trade-offs between equipment costs and efficiencies, feedstock quality and consistency, and transportation distances will determine where and how preprocessing is implemented in the assembly system.

Generally, preprocessing unit operations can be centralized (at the biorefinery prior to pretreatment), distributed (at the field during harvest and collection), or anywhere in between (at a preprocessing facility or depot). Regardless of where it occurs, mechanical preprocessing is necessary prior to pretreatment for conversion to ethanol in order to alter particle size and density and produce a material that has bulk properties and flowable characteristics for improved ease of handling and conveying throughout the biorefinery (Hamalinck et. al, 2005). These preprocessing steps also increase biomass surface area for improved pretreatment efficiencies (Walker and Wilson, 1991; Mansfield et. al, 1999) uniformity during blending, and quality by separating or sorting fractions with different compositions. In corn wet and dry milling operations, preprocessing, or grinding, of the grain occurs just prior to the grain flowing into the conversion processes. Biomass biorefinery facilities, as well as biomass combustion facilities, have considered similar designs, in which bales of straw are delivered to the facility and then ground to meet certain processing specifications (Aden et. al, 2002). In contrast, grinding preprocessing could be used earlier in the feedstock assembly system to reduce the size of the biomass prior to delivery to the biorefinery. This will allow the feedstock to be handled with conventional bulk solids handling and transport equipment, enabling the implementation of non-bale harvesting and collection systems. Furthermore, the biomass fractions produced by grinding preprocessing provide for a potentially higher quality feedstock delivered to the biorefinery.

Experimental Design

Distributed Grinding

Distributed field-side grinding has certain transportation, plant handling, and quality enhancement advantages over centralize grinding at the biorefinery. These advantages are assessed through two full-scale field-side grinding tests. Each test used baled biomass as the feedstock because it is currently the standard collection format and is relatively difficult to preprocess compared to loose collection formats.

The field-side tests used Diamond Z 1352B and 1350L mobile grinders equipped with proprietary forage hammers and standard conveyer loading systems (Figures 1 and 2). One-year stored straw bales at approximately 9 – 12% moisture were used in each test. Grinding parameters such as test time, fuel consumption, and engine loading were recorded in order to determine capacity, throughput, efficiency, and formatting metrics for a given grinder screen configuration.



Figure 1. Diamond Z 1352B Tub Grinder with CAT 3412E – 860 hp Engine, 60-inch hammer mill, and Diamond Z fixed forage hammers.



Figure 2. Diamond Z 1350L Tub Grinder with CAT 3412E – 1000 hp Engine, 50-inch hammer mill, Diamond Z fixed forage hammers, and Self-Loader.

The first set of field-side tests (Diamond Z 1352B) was designed to assess operational cost and biomass quality resulting from multiple grinder screen sizes. These tests ground approximately 1000 lb. 4'X4'X8' bales of barley straw (variety Harrington; Rupert, Idaho) through six different interchangeable screen size configurations. Each test consumed approximately one-half a bale and conveyed the ground material into a 37.6 ft³ super sack for post-test analysis. At least two tests were conducted for each screen size. Table 1 shows the grinder configuration and test condition for each test case. The bales used in the tests were loaded into the grinder tub at ambient conditions (measured with a thermometer and moisture probe)

Table 1. Straw preprocessing (grinding) test matrix.

Equipment	Biomass Format into Grinder	Biomass Material	Grinder Configuration Screen size (inches) & Shape	Total Biomass Ground for Test (wet lbs)
Diamond Z 1352B Tub Grinder with fixed forage hammers	Baled, 4'X4'X8' 1000 lbs, 6-string poly-twine, not removed	Barley Straw – Harrington	0.25 X 0.1875 Round	551
				491
			0.50 X 0.1875, Round	594
				506
			0.75 X 0.1875, Round	538
				443
			1.00 X 0.1875, Round	560
				260
Diamond Z 1350L Tub Grinder with fixed forage hammers	Baled, 4'X4'X8' 1000 lbs, 6-string poly-twine, not removed	Wheat Straw – West Bred 936	1.50 X 1.00, Round	640
				841
			5 X 7 X 1, Square	169
				415
			0.25 X 0.1875 Round	21,080
			0.25 X 0.1875 Round	20,620

The second set of field-side tests (Diamond Z 1350L) was designed to assess loading efficiencies and truck capacity (compressed bulk density) for 1/4" minus material. Approximately 1000 lb. 4'X4'X8' one-year stored bales of wheat straw (variety West Bred 936; Rupert, Idaho) and barley straw (variety Harrington; Rupert, Idaho) were ground to produce enough material to fill two 10 ton trucks. The grinder configuration and test conditions for each of these test cases are shown in Table 1. The Diamond Z 1350L was equipped with a self loading system and conveyer belt to allow for continuous feeding of the baled feedstock and loading of the trucks. Figure 2 shows the Diamond Z 1350L grinder with the Self-Loader and belt conveyer.

Compositional Quality

The compositional quality tests were designed to use the same feedstock fractions produced in the full-scale grinding tests. This data connects mechanical preprocessing and transportation costs to the quality and consistency of the resulting feedstock fractions providing a foundation to multilaterally optimize feedstock unit operations and directly connect the feedstock assembly system to the biorefinery conversion process.

Triplicate samples of the 0.25, 0.50, and 5X7 inch grind fractions were prepped to be analyzed according to the procedures for traditional wet chemistry (Sluiter et. al, 2004) to produce the percentage of composition compounds found in the material. A standard reference material was also chosen to validate the final results. The ultimate purpose of the compositional quality tests was to correlate the composition of these fractions with the operational costs associated with producing each fraction and the conversion processes of pretreatment and simultaneous saccharification and fermentation (SSF).

Experimental Results and Discussion

Distributed Grinding

The first grinding test was designed to demonstrate performance targets of 30 tons/hour capacity, 0.25" minus particle size, and 8 ft³ bulk density or greater for typical moisture levels (8-13%). All performance targets were assessed using the grinder screen size configuration shown in Table 1. The logistical data used to measure the performance of the first distributed grind test (Diamond Z 1352B) is shown in Table 2. Grinding configurations with bold, italicized data met or exceeded the performance targets indicated.

Table 2. Grinder configuration tests for straw at moisture levels of 8.5-13%.

Screen Sizes (inches)	Screen hole shape	Moisture (%)	Capacity (ton/hr)	Energy (gallon diesel/ton)	Energy ¹ (kWh)	Supersack Bulk Density (lbs/ft ³)	Mean particle size (in)	Particle size standard deviation	Test Name
0.25 X 0.19	Round	10.29	8.21	2.92	111.3	9.72	0.0457	0.103	G1
0.50 X 0.19	Round	11.04	14.26	1.68	64.00	8.46	0.0728	0.114	G2
0.75 X 0.19	Round	12.09	17.26	1.39	52.96	7.71	0.0862	0.119	G3
1.0 X 0.19	Round	10.12	25.66	0.94	35.81	7.36	0.0843	0.120	G4
1.5 X 1.0	Round	8.47	25.91	0.93	35.43	8.08	0.0685	0.119	G5
5 X 7 X 1	Square	12.87	25.38	0.95	36.19	5.45	0.139	0.135	G13
1. Cummins Diesel, 2005 Straw was barley, variety Harrington All values based on typical "dry" moisture levels of (8-13%) Grinder configuration was a tub feed with a Diamond Z forage hammer and various screen sizes.									

As indicated in Table 2, the difference between the highest (0.25" screen) and lowest (5"X7" screen) bulk density is 4.27 lbs/ft³. Table 2 also shows that the higher bulk density (0.25" screen) came at a capacity cost of 17.2 ton/hr and energy cost of 75.1 kWh. While the set of screen sizes are designed to reduce the nominal particle size in a range from 7.0" to 0.25", 78.4% of the straw passing through the 5"X7" screen was nominally at or below the 0.25" minus particle size target (Figure 3). Similarly, a majority of the particle sizes produced from each grinder screen were about one order of magnitude smaller than the nominal screen size. This suggests that a majority of the material easily fractionates in the grinding process, while the remainder of the material requires a longer grind, and thus more energy to reach the design size. In the case of the 0.25" screen, compared to the 5"X7" screen, an additional 75.1 kWh of energy was required to reduce the remaining 21.6% of straw material to the 0.25" minus target.

The overall best configuration in terms of the established performance targets was the 1.5" screen. It had the highest production rate for the smaller screen size configurations and produced a better particle size distribution and bulk density than the 1.0" and 0.75" screens. The key to the better performance of this screen size is its larger hole, allowing the 0.25" minus particles to escape more easily, and the greater screen thickness, reducing spearing of the larger particles. The combination of these two parameters allowed the remaining larger particles to be reduced in size with a much lower burden from those particles that were at or below the target size. Thus, the 1.5" screen configuration came closest to simultaneously achieving all three production targets. At 25.9 ton/hr, it was 86% of the capacity target, at 8.08 lbs/ft³, it was 100% of the bulk density target, and at a 0.0685 inch geometric mean particle size and 0.119 inch geometric standard deviation, 97.7% of the particles were 0.25 inch minus.

A key result of the grinding test is the relationship between nominal grinding size and the resulting particle size distribution. In all cases, the material preferentially deconstructed into smaller particle sizes than was expected regardless of the nominal screen sizes used on the grinders. For example, the material passing through the 5"X7" screen was expected to have particles on the order of 5 to 7 inches long. However, post-grinding analysis using a forage particle separator (ANSI/ASAE, 2001a) shows that 78.4% of the material is less than 0.25 inches. Similarly, 63% of the material ground through the 0.25" screen was less than 0.08 inches. Figure 3 highlights this result, which is consistent across all grinding tests performed. This result emphasizes the composite nature of the material and underlines the potential to exploit its biomechanical behavior to optimize size reduction with respect to machine capacity, power input, and configuration.

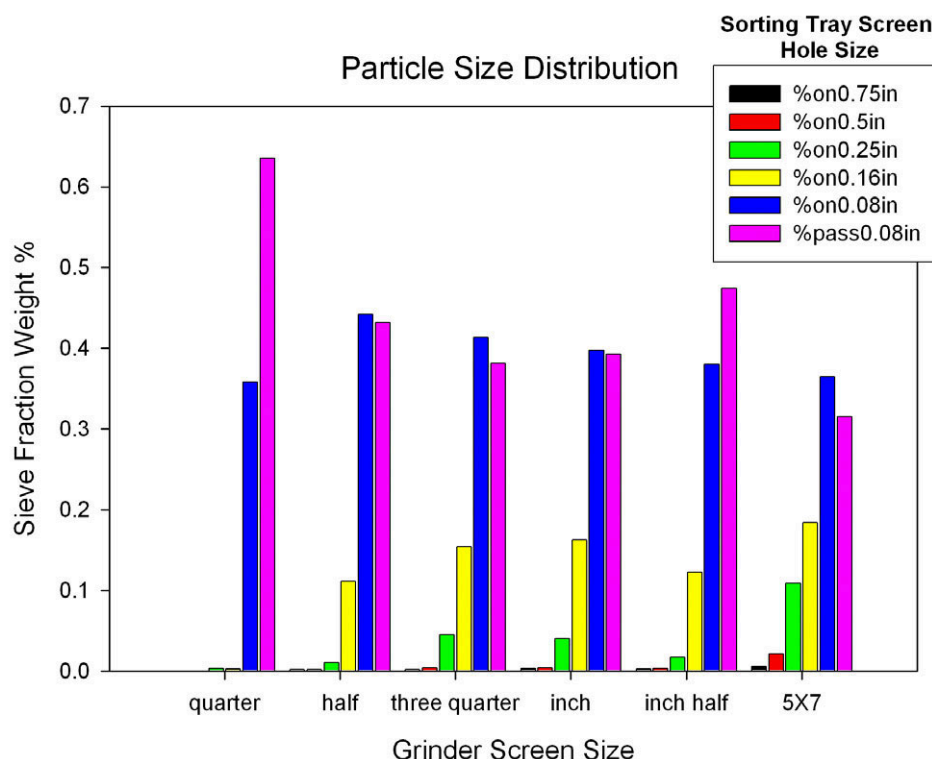


Figure 3. Particle size distributions by weight percent from the different Diamond Z grinder screen sizes (x-axis) and the forage particle separator (bar colors).

Compositional Quality

Selections of the grinding fractions produced with the different Diamond Z screen sizes were analyzed using traditional wet chemistry procedures (Sluiter, et al., 2004) for composition. These fractions came from the forage particle separator (ANSI/ASAE, 2001a) for the 0.25", 0.50", and 5.0"X7.0" screen size tests. These analyses are used to compare the relative value of the different grind sizes and particle separations in terms of theoretical ethanol yield (EERE, 2005). Table 3 shows the results from these analyses where the compositional values are reported as the percentage of the given compound and the theoretic ethanol yield is reported in gallons per tons of feedstock. The key result of these analyses is the measurable difference in fractional composition and the resulting ethanol yield for the different fractions produced by

preprocessing. In particular, the smaller particle fractions (i.e., Pan) consistently yield less ethanol than the larger particle fractions (i.e., Tray 4 or Tray 5).

Table 3. Mass fractions and compositional data from the 0.25", 0.50", and 5"X7" grinds.

Test Name & Size (inches)	Separation Size (inches)	% Mass on Separation Trays	Glucan	Xylan	Galactan	Arabinan	Mannan	% Lignin	Theoretical Ethanol Yield gal/dry ton
G1-0.25	Tray 6: 0.08	35.8%	43.5%	19.3%	0.04%	2.80%	0.06%	20.0%	114.60
	Pan: 0.08 –	63.6%	37.9%	20.4%	0.24%	2.85%	0.00%	22.6%	106.90
G2-0.50	Tray 5: 0.16	11.1%	37.2%	21.3%	0.29%	4.80%	0.23%	18.7%	111.30
	Tray 6: 0.08	44.2%	41.2%	20.4%	0.22%	2.97%	0.00%	21.0%	112.90
	Pan: 0.08 –	43.2%	34.6%	21.0%	0.27%	3.05%	0.05%	25.0%	102.90
G13-5X7	Tray 4: 0.25	15.9%	39.4%	22.2%	0.50%	3.49%	0.00%	19.0%	114.40
	Tray 5: 0.16	19.0%	38.8%	21.1%	0.52%	3.57%	0.00%	18.2%	111.50
	Tray 6: 0.08	32.6%	40.9%	21.4%	1.01%	2.82%	0.00%	18.9%	115.10
	Pan: 0.08 –	26.8%	31.7%	22.0%	0.28%	3.12%	0.00%	24.4%	99.70

Just as important as compositional differences between the fractions is the mass percentage of each fraction collected on the separation trays. This percentage, shown in column 3 of Table 3, in conjunction with the ethanol yield data (last column) helps identifies those fractions that might be more valuable in terms of ethanol yield and biomass available. For example, if separations occurred between Tray 6 and the Pan, then the 0.25" fractions would produce 41.0 and 67.9 gal/dry ton of ethanol for Tray 6 and Pan, respectively. However, with the 5"X7" fractions, Trays 4-6 would produce 76.9 gal/dry ton of ethanol while the pan would produce 26.7 gal/dry ton. If the separation between Tray 6 and the Pan were maintained then the 5"X7" grind would produce 46.6% more ethanol per dry ton of feedstock than the 0.25" grind. Furthermore, as discussed previously, material from the 5"X7" grind is produced 3.1 times faster than the 0.25" material. In general, these results show a significant potential to increase the feedstock quality through fractionation and separation.

Conclusion

The results from the preprocessing (grinding) tests performed in this section help assess the feasibility and value of performing distributed grinding upstream of the biorefinery in order to address critical collection, handling, and transportation barriers that significantly impact the cost of the feedstock assembly system and the quality of the delivered feedstock. Based on the preprocessing data, the feasibility of performing upstream grinding and densification has been established. These preprocessing tests have shown a significant potential for improved efficiencies based on the range of data produced with each of the different grinder screen sizes. At the core of these results is the fundamental behavior of the feedstock biomass when loaded with forces designed to produce a flowable, higher density feedstock. Further understanding of the fundamental characteristics of biomass feedstock will enable the appropriate models and relationships to be developed that will allow for a truly integrated design and optimization.

Based on the composite structure and preferential deconstruction of the biomass feedstock, the grinding operation for all types of feedstocks tested resulted in a smaller particle size distribution compared to the nominal size of the grinder screen. As a result, changes in bulk density from different grinder screen sizes are far outweighed by increases in capacity and decreases in

operational costs. The size of the screen opening and the thickness of the screen plate are critical parameters that contribute to the resulting capacity and operational cost improvements. The grinding results presented in this section illustrate that an optimum screen size can be determined. In this limited case, the 1.5" round by 1.0" thick screen performed the best with respect to the capacity, particle size, and bulk density performance targets.

The particle sizes of the material produced in these tests and the conveying equipment use during testing establishes the potential of preprocessed material to be formatted such that it becomes a bulk, flowable material capable of improving the handling systems throughout the feedstock assembly system and the biorefinery. In addition, compared to bales, this unit operation has the potential to increase biomass surface area for improved pretreatment efficiencies, increase uniformity during mixing for improved plant efficiencies, and increase feedstock quality for improved conversion efficiencies. The versatility in locating this unit operation at the field-side or in a preprocessing facility (depot) will allow it to be optimized for regional diversity in feedstocks and varying agronomic practices. Ultimately, trade-offs between equipment costs and efficiencies, feedstock quality and consistency, and transportation distances will determine where and how the grinding unit operation is implemented in the assembly system.

Using the field data from this study, the cost of field-side grinding and transporting biomass was calculated (Table 4). The values in Table 4 show the bulk density in both a supersack and fully loaded semi tractor-trailer, the capacity of a fully grossed truck by weight, the transportation and grinding costs for each grinder fraction, and the total transportation and grinding costs. Consistent with its performance based on pre-testing targets, the 1.5"x1.0" grinder fraction resulted in the minimum cost of \$12.87/dry ton.

Table 4. Bulk density relationships and their affect on transportation cost.

Screen Sizes (inches)	Supersack Bulk Density (dry lbs/ft ³)	Truck Bulk Density ¹ (dry lbs/ft ³)	Feedstock Truck Capacity ² (dry ton)	Transport ³ (\$/dry ton)	Grinding ⁴ (\$/dry ton)	Total Cost (\$/dry ton)
0.25 X 0.19	8.72	11.29	19.81	7.57	14.65	22.22
0.50 X 0.19	7.53	10.02	17.58	8.53	8.51	17.04
0.75 X 0.19	6.78	9.69	17.00	8.82	7.12	15.94
1.00 X 0.19	6.62	9.74	17.09	8.78	4.68	13.46
1.5 X 1.0	7.4	10.27	18.03	8.32	4.55	12.87
5.0 X 7.0 X 1.0	4.75	7.72	13.54	11.08	4.88	15.96
1. based on 3510 ft ³ volume capacity 2. at the given truck bulk density (column 4) 3. based on a 40 mile haul with \$2.25/gal fuel 4. based on operational costs summarized in Table 9.8						

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