Advances in Biomass Integrated Size Reduction and Separation

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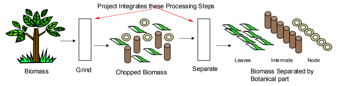
***Collaborative Project of:** The University of Tennessee, First American Scientific Company, Oak Ridge National Laboratory, University of British Columbia*



Executive Summary

Project objective is to address problems in biomass size reduction (chopping, grinding) and dry separation of plant components (sort by botanical/ chemical properties). First year priorities were to identify biomass ultimate failure stress/ energy/ physical properties and to better understand current equipment to identify grinder and separating actions for in-depth evaluation. Assessment tools were developed and include rapid imaging for sizing large, non-uniform particles, FT-NIR for rapid chemical analyses and wet chemical protocols to evaluate targets and separated biomass.

Biomass "models" were selected as follows: corn stover, switchgrass, rice straw, hickory wood, and bagasse. Performance targets identified for grinding energy from published literature were 40, 20, and 10 kW-h/ton for fine (~5 mm), medium (~10 mm), and coarse (~20 mm) grinds, respectively, for relatively dry (10% w.b.) fiber-rich biomass. A weakness of published literature was good documentation of pre- and post- grind particle spectra for comparisons. Most published data dealt with agronomic crop forage, not an array of biomass properties and conditions. Project original goal was 15% grinding savings, and is now projected to reduce typical grinding cost $3 to $4 per dry ton (about $^1/_4$ of current costs) based current understanding of pre- and post-grinding literature data. Multiple stage grinding may be most appropriate to maximize efficiency. Target particle size for bio-refinery was identified as ~6 mm based on input from industry experts. One U.S. Patent (5,677,154, *Production of ethanol from biomass*) verified nominal sizes of ~1 to 6 mm. These small sizes will likely require multiple stage grinding, and one question deals with identifying equipment and operations for each stage. Most literature report separation effectiveness between grain and lignocellulosic materials with separation efficiencies 95% or greater. Lower performance targets between for stalks and foliage material streams are expected because material properties are more similar than grain versus chaff.

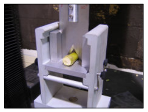
Size reduction technologies were identified for 2nd year instrumented testing as follows: hammer mill, knife mill, disk mill, and variable-spacing linear knife grid. Rationale for selection included maximizing more efficient shear failure with knife, shear bar, and pinch points. A Warner-Bratzler shearing device evaluated different knife bevel angles (30° and 45°) and found 18, 31, and 22 % less input energy for the 30° bevel angle for corn stover, hickory, and switchgrass, respectively. Direct measurement of grinder input power is being emphasized to evaluate grinders (not inferred as often published).

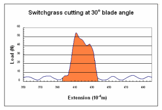
Sieve technologies were prioritized for separation. First, accurate evaluation of particle spectra from grinding studies is necessary to compare grinder energy results. Second, sieves are commercial-viable for biomass separation. Terminal velocity was identified as a separation action whereby aerodynamic and gravitational forces are equilibrated at a given air stream velocity. A 3.5-m tall vertical wind tunnel was developed for the project. Example terminal velocities of 12-mm long pieces of dry switchgrass were 5.6 m/s for internode, and 7.6 m/s for node – thereby indicating separation potential since the terminal velocities varied by more than 10% (published recommendation).

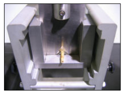
Micrographs of biomass cross sections were made to aid constituent identification (eg, silica). Image analysis techniques using a flat bed scanner were developed to measure irregular biomass on sieves. An FT-IR/NIR instrument operated in diffuse reflectance mode was applied to biomass compositional analysis. Standard wet chemistry techniques were initiated for monosaccharide units of cellulose and hemicellulose (HPLC), acid-insoluble lignin (oxidation, furnace), acid-soluble lignin (UV 205 nm), and ash (oxidation, furnace). New areas of improved chemistry include the use of ionic liquids to solubilize biomass for rapid wet chemistry and supercritical fluid chromatography (SFC) detection (SFC-UV 190 nm) with no solvent interference, linear calibration, and strong signal-to-noise ratio. SFC may be a desirable alternative, providing comparable resolution of chromatographic peaks at a shorter run time with less waste and costs.

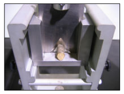
Impact of Activities

Individual Stem Properties were measured to better understand basic size reduction processes. Modified Warner-Bratzler device shown. Results indicate that the higher the biomass strength – the greater the response sensitivity magnitude and potential energy savings. Moisture and timing of grinding may be an important consideration to reduce energy for some biomass.









Biomass Property	Biomass and Blade Angle					
	Dry Corn Stover		Dry Hickory		Dry Switchgrass	
	30º	45º	30º	45º	30º	45º
Mean Shear Strength MPa (Std. Dev.)	1.8 (0.61)	2.1 (0.52)	16.8 (1.13)	24.9 (2.91)	12.0 (0.53)	12.5 (0.53)
Mean Cutting Energy kN/m (Std. Dev.)	27.9 (5.65)	34.2 (6.80)	122 (11.7)	160 (12.7)	78.0 (10.9)	95.2 (22.5)

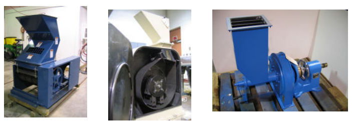
Biomass Property	Biomass and Blade Angle			
	Dry Hickory		Fresh Hickory	
	30º	45º	30º	45º
Mean Shear Strength MPa (Std. Dev.)	16.8 (1.13)	24.9 (2.91)	10.9 (1.06)	13.4 (1.13)
Mean Cutting Energy kN/m (Std. Dev.)	122 (11.7)	160 (12.7)	91.6 (9.42)	114 (19.1)

Instrumented Size Reduction of biomass using direct measures of torque and rpm of rotary grinders and input force-displacement of linear knife grid is underway to provide better, more objective comparisons of the grinding process using different types of equipment.

Four (4) Grinder Actions were identified as "test mules"
- Hammer Mill
- Knife Mill
- Disc Mill
- Linear Knife Grid

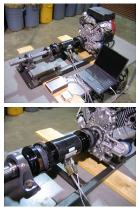
Design of Test Stands Began
- Direct Measurement of Mechanical Input Energy
- Identification of Side-by-Side Evaluation Prioritized

Decreasing Particle Size

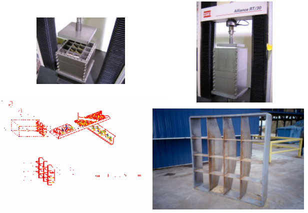


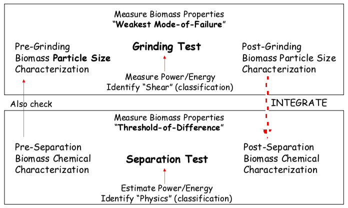
Knife mill, Hammer mill, and Disk Refiner Mill for side-by-side evaluations

Instrumentation to directly measure energy input



Linear Knife Grid Development





Measure Biomass Properties
"Weakest Mode-of-Failure"

Pre-Grinding
Biomass **Particle Size**
Characterization

Grinding Test

Measure Power/Energy
Identify "Shear" (classification)

Post-Grinding
Biomass Particle Size
Characterization

Also check

INTEGRATE

Measure Biomass Properties
"Threshold-of-Difference"

Pre-Separation
Biomass Chemical
Characterization

Separation Test

Estimate Power/Energy
Identify "Physics" (classification)

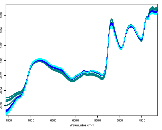
Post-Separation
Biomass Chemical
Characterization

Technical Approach & Targets

- Use shear failure for grinding, and particle property difference for separation
- Separation good for 10% or greater "threshold of difference" in property
- Adjust potential to improve size reduction/ separation performance based on instrumented results
- Target of 40, 20, and 10 kW-h/ton for fine (~5 mm), medium (~10 mm), and coarse (~20 mm) grinds, respectively, for relatively dry (10% w.b.) fiber-rich (tough) biomass
- Target grinding savings from ~$1/ton (stover) to $5/ton (switchgrass) (includes additional expense for providing separation by botanical component)

Rapid analyses of chemical constituents and traditional wet chemistry are underdevelopment to identify target plant constituents and to validate separations of plant anatomical components. The benefits of rapid chemical analysis are very apparent because Traditional wet chemistry is very tedious and time consuming. Additional photomicrographs aid identification of constituents.

FT-NIR Switchgrass



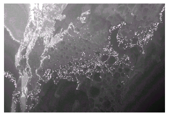
Wet Chemistry

Monosaccharide units of cellulose and hemicellulose (HPLC)
Acid-insoluble lignin (oxidation, furnace)
Acid-soluble lignin (UV 205 nm)
Ash (oxidation, furnace)
Possibly: Percent digestibility of cellulose-rich biomass (glucosidase and cellulase assay)
Possibly: protein (N elemental analysis)

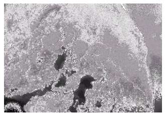
Looking for Innovations

Supercritical Fluid Chromatography

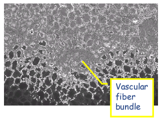
Substitution for HPLC saccharide analysis: SFC-UV 190 nm. detection (no solvent interference; linear calibration; strong signal-to-noise)
Use of UV-Vis, RP-HPLC and / or GPC (with multiple detectors) to characterize lignin and perhaps to quantify biomass types



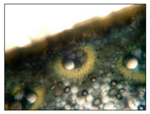
SEM x90: Cross-section of a switchgrass stalk (internode)



SEM x50: Cross-section of a switchgrass node

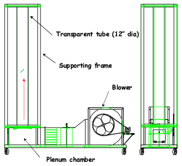


SEM x50: Corn stalk

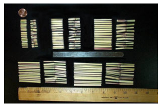


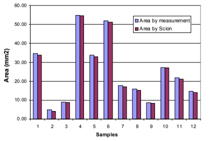
Optical micrograph of epidermal Structure of a section of corn stalk

Physical separation using aerodynamic properties and sieves are yielding results consistent with being able to grind and then separate anatomical feature.



Example: Nodes vs. Internodes
Short vs. Long





Terminal Velocity (examples: 12-mm biomass section length)

Biomass Property	Biomass					
	Dry Corn Stover		Dry Wheat Stover		Dry Switchgrass	
	Rind (internode)	Pith (internode)	Node	Internode	Node	Internode
Terminal Velocity (m/s)	7.06	2.87	4.93	3.42	7.72	5.71

Bottom Line: >10% difference in property for separation