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U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) 2017 Project Peer Review

1.2.1.2 Biomass Engineering: Size reduction, drying and densification of high moisture biomass

Technology Area Session: Feedstock Supply & Logistics

March 7th, 2017

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Goal Statement

The goal of this project is to develop and demonstrate biomass preprocessing technologies that are adaptable to a wide range of biomass moisture content, with a focus on technology development to reduce costs of preprocessing high-moisture (25-30%) biomass.

Major outcome:

In support of the DOE feedstock cost of $84/dry ton, demonstrate a 50% reduction of preprocessing cost of high-moisture (25-30%, w.b.) biomass by 2017 compared to 2013 state of technology (SOT), while producing pellets that meet quality standards of density >560 kg/m^3 and durability >97.5%.

Relevance:

a) High-moisture biomass, which includes >50% of the total available biomass in the U.S. today, is not considered for use by biorefineries due to high preprocessing cost.

b) Variable moisture content and particle size, and elastic and cohesive properties of the biomass is currently limiting the ability of biorefineries to operate at capacity. This project will convert biomass into a dense, uniform feedstock with consistent moisture and particle size that exhibits much better flow characteristics than raw milled biomass.

Quad Chart Overview

Timeline

- Project Start Date: 10/01/14
- Project End Date: 09/30/17
- Percent complete 83%
- On-going

Budget

	FY 15 Costs	FY 16 Costs	Total Planned Funding (FY 17-Project End Date)
DOE Funded	$1.38M	$1.56M	$1.23M

Barriers

- Barriers addressed:
- Ft-K Biomass Physical State Alteration
- Ft-L Biomass Material Handling and Transportation
- Ft-M Overall Integration and Scale-Up

Partners

Industry collaborations

- Size reduction: Vermeer Corporation
- Separations: BHS LLC, Rotex LLC
- High-moisture pelleting: Primo Farms, Idaho Falls (animal feed)
- Dynamic mechanical analysis: Virginia Tech.
- Pellet drying: Forest Concepts, LLC


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2- Approach (Management)

- DOE, Merit Review in 2014
- Participate in BETO, Feedstock Supply & Logistics (FSL) weekly call and update the technology manager regarding progress of the project
- Major milestones, and Go/No-Go decision points
- Work with INL analysis team to update the state of technology costs based on the results obtained in this project.
- Validate the processes developed in this project by peer review publication

Critical success factors

- Scale up of lab-scale high-moisture pelleting process (HMPP) to pilot- and commercial-scale pellet mill and meet the quality and cost targets (go/no-go milestone).
- Integrated demonstration of preprocessing technologies (fractional milling, high-moisture pelleting and low-temperature drying) and reduce the preprocessing cost by 50% by 2017 compared to 2013 state of technology (SOT).

2- Approach (Technical)

Aim: Reduce grinding and drying energy to make biomass into a dense flowable product

Fractional milling: Increase screen size of stage-1 grinder and insert separator between stage-1 & 2 grinding operations to bypass fraction which meets stage-2 grinder specs

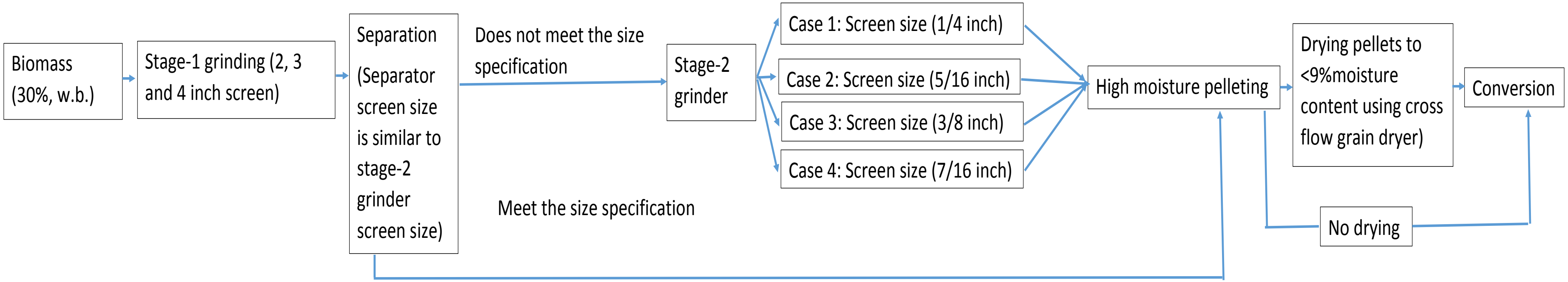
- Avoids redundant preprocessing and saves energy.
- Tighter particle size distribution with reduced fines.

High-moisture pelleting: Biomass is pelleted at moistures 18-30% (w.b.).

- Biomass loses moisture (5-10%, w.b.) due to preheating & frictional heat in the die
- Drying is optional (pellets can be dried only when highly durable and aerobically stable pellets are needed).

Low-temperature drying: High-moisture pellets can be dried using grain and belt dryers

- Less energy and capital intensive
- Eliminates the volatile organic emissions during drying



Biomass (30%, w.b.)

Stage-1 grinding (2, 3 and 4 inch screen)

Separation (Separator screen size is similar to stage-2 grinder screen size)

Does not meet the size specification

Stage-2 grinder

Case 1: Screen size (1/4 inch)

Case 2: Screen size (5/16 inch)

Case 3: Screen size (3/8 inch)

Case 4: Screen size (7/16 inch)

Meet the size specification

High moisture pelleting

Drying pellets to <9%moisture content using cross flow grain dryer)

No drying

Conversion

Preprocessing	Total energy (kWh/ton)
Conventional	566
Advanced (FM+HMPP+LTD)	210 (goal) (62% reduction compared to conventional)

3 - Technical Accomplishments (High Moisture Pelleting)

One critical success factor for this project is scaling up high-moisture pelleting process to ring die pellet mill (go/no-go milestone)

In FY-15 we demonstrated high-moisture pelleting on a lab scale flat die pellet mill (40 lb/hr) (Tumuluru, 2014, 2015, 2016, Tumuluru et al., 2016).

Challenge: Scale up of high moisture pelleting process to a ring die pellet mill (1 ton/hr) (50-fold scale factor)

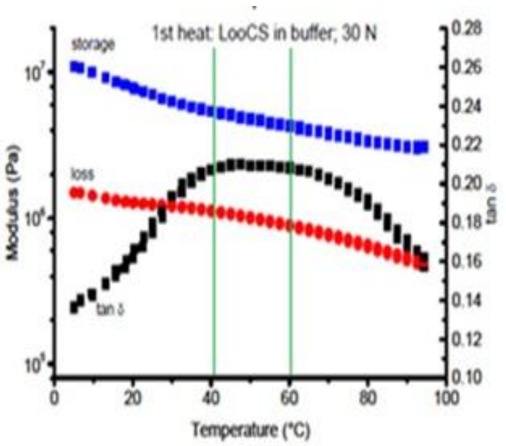
Four criteria used for scale-up of high-moisture pelleting process to pilot scale pellet mill (1 ton/hr)

1) Identify fundamental mechanisms of high-moisture pelleting process
2) Test the technical feasibility of high-moisture pelleting process in lab scale flat die pellet mill (40 lb/hr) and develop scale up methodology
3) Test high-moisture pelleting process on ring die pellet mill (1 ton/hr capacity)
4) Compare quality of the high-moisture pellets produced in a ring pellet mill with 2016 quality targets (bulk density: >480 kg/m^3 and durability: >95%).

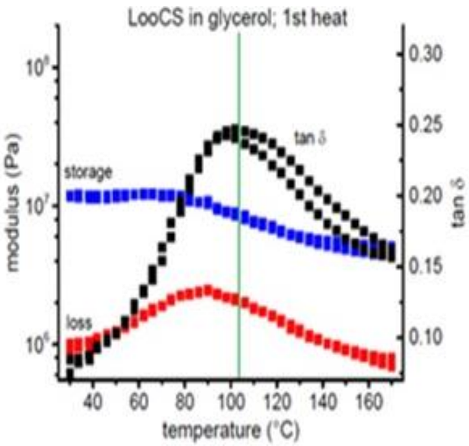
3 - Technical Accomplishments (High-moisture pelleting)

Criteria 1: Identify fundamental mechanisms of high-moisture pelleting process

Dynamic Mechanical Analysis



High moisture



Low moisture

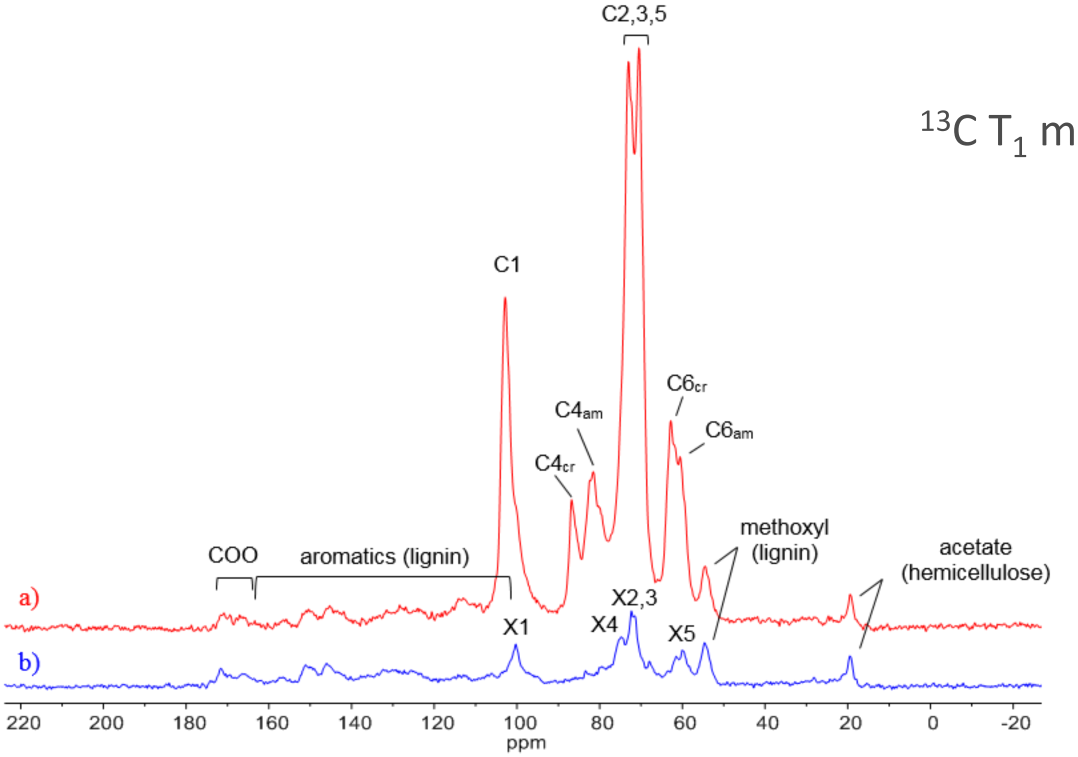
Compression-torsion DMA of ground corn stover immersed in aqueous buffer (pH 7, and in glycerol (right)). Thermal transitions are defined by peaks in the tan δ curve (tan δ = loss modulus ÷ storage modulus)

Dynamic mechanical analysis: Based on the thermal transitions defined by peaks in the tan δ curve, it can be concluded that low preheating temperature (~40-60° C) can help activate biomass components such as lignin and others that can aid the densification process in high-moisture biomass.

3 - Technical Accomplishments (High-moisture pelleting)

Solid State NMR

NMR provides information on molecular mobility of specific biomass components



a) Solid state NMR spectrum of wet corn stover
b) Spectrum with dipolar dephasing

^{13}C T_1 mobile component relaxation rate constants

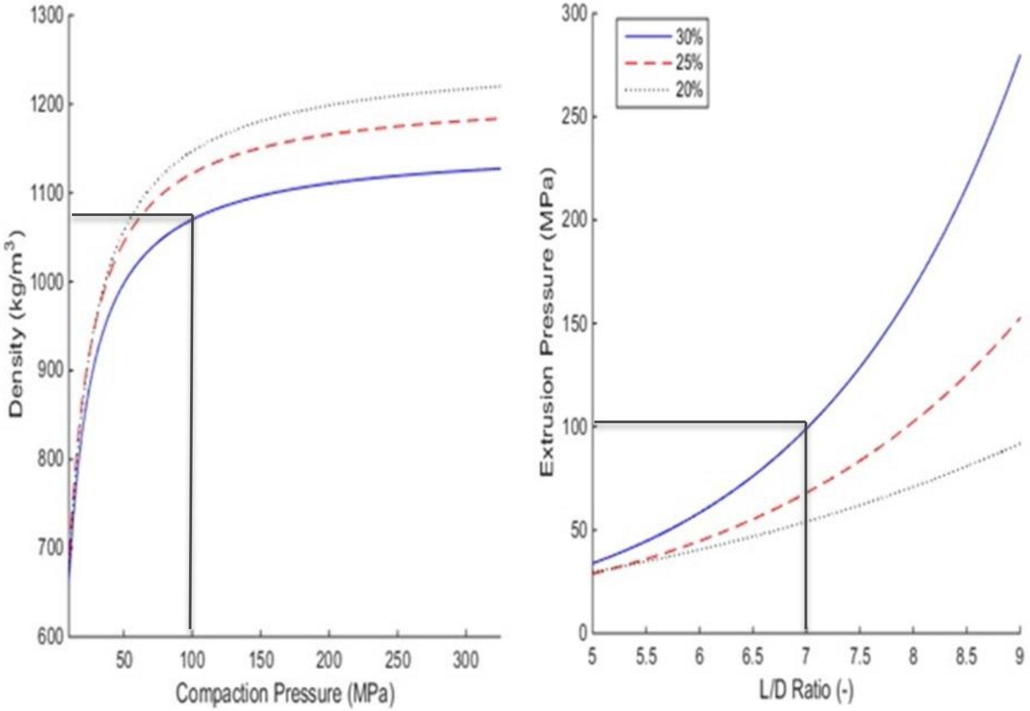
	Chemical shift (ppm)				
	72.7 (HC)	70.4 (HC)	62.8 (HC)	53.6 (LI)	19 (HC)
Dry Corn Stover	12 s	12 s	4.2 s	3.0 s	10 s
Wet Corn Stover	4.5 s	4.6 s	1.6 s	2.3 s	6.5 s

- Dipolar dephased spectrum of wet biomass shows xylans and lignin as the mobile components
- ^{13}C spin-lattice relaxation rate constants show hemicellulose mobility is increased more than lignin in presence of water

3 - Technical Accomplishments (High-moisture pelleting)

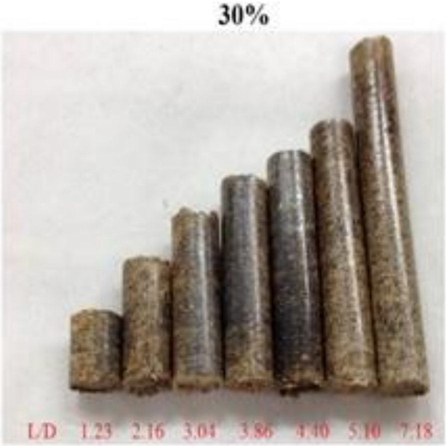
Criteria 2: HMPP scale-up methodology

- Holm model expresses the relationship between L/D ratio of the pellet mill die to extrusion pressure and Kawakita-Ludde relates compression pressure to unit density.
- To fit Holm and Kawakita-Ludde models, experiments were conducted for the process conditions such as preheating temperature (70-110°C), moisture content (20-30%, w.b.), length to diameter ratio (1-9), and compaction pressure (10-250 MPa).



Family of curves for corn stover at 110° C for different L/D ratio, compression pressure and feedstock moisture content based on Holm and Kawakita-Ludde model

Corn stover pellets made at different L/D ratio and 110°C preheating temperature



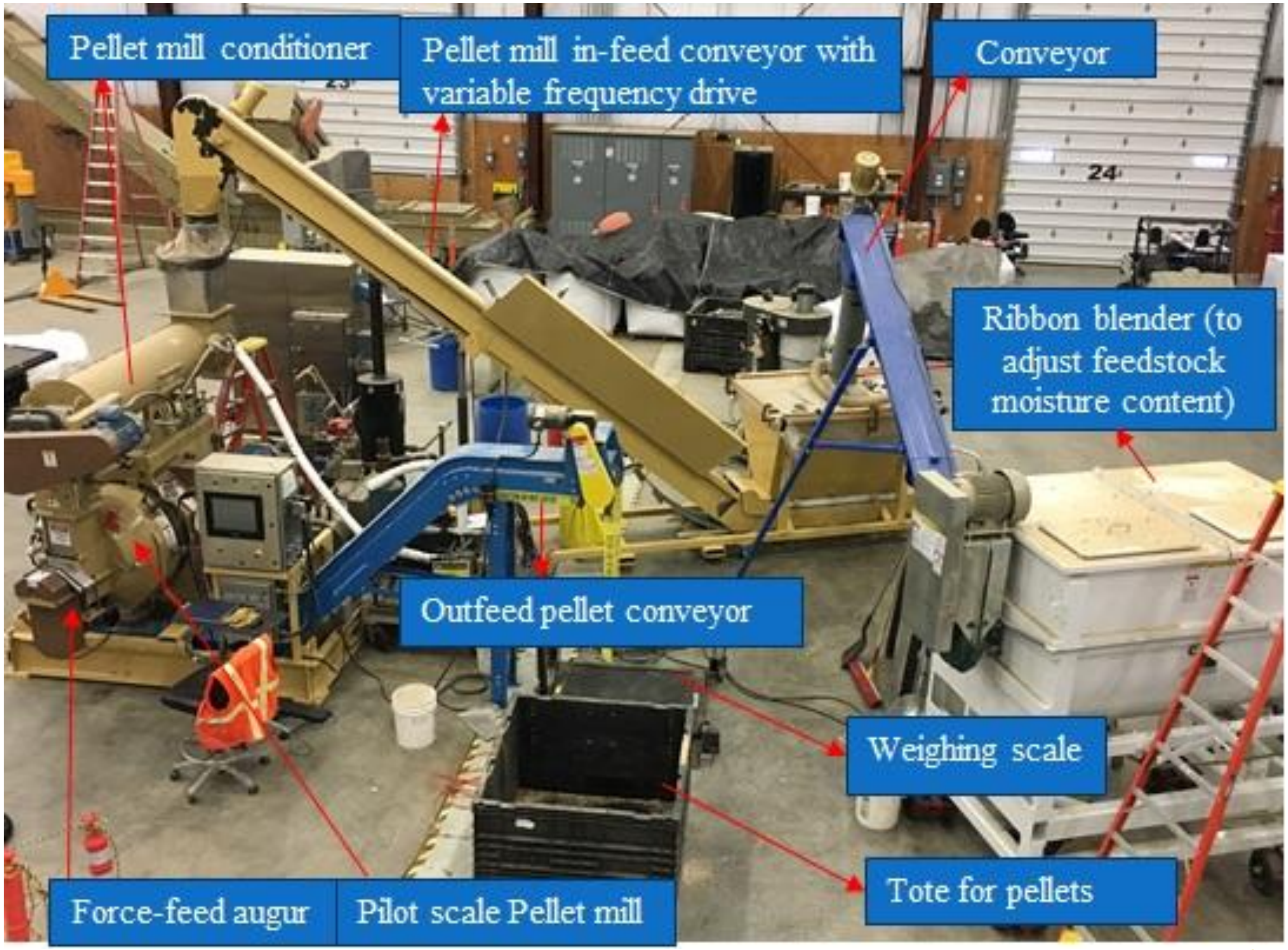
These models helped to identify the L/D ratio of the pellet die necessary to produce pellet with desired density at high moisture content.

At 30% moisture content, L/D ratio of 7 was found to produce pellets with the desired unit density

3-Technical Accomplishments (High-moisture pelleting)

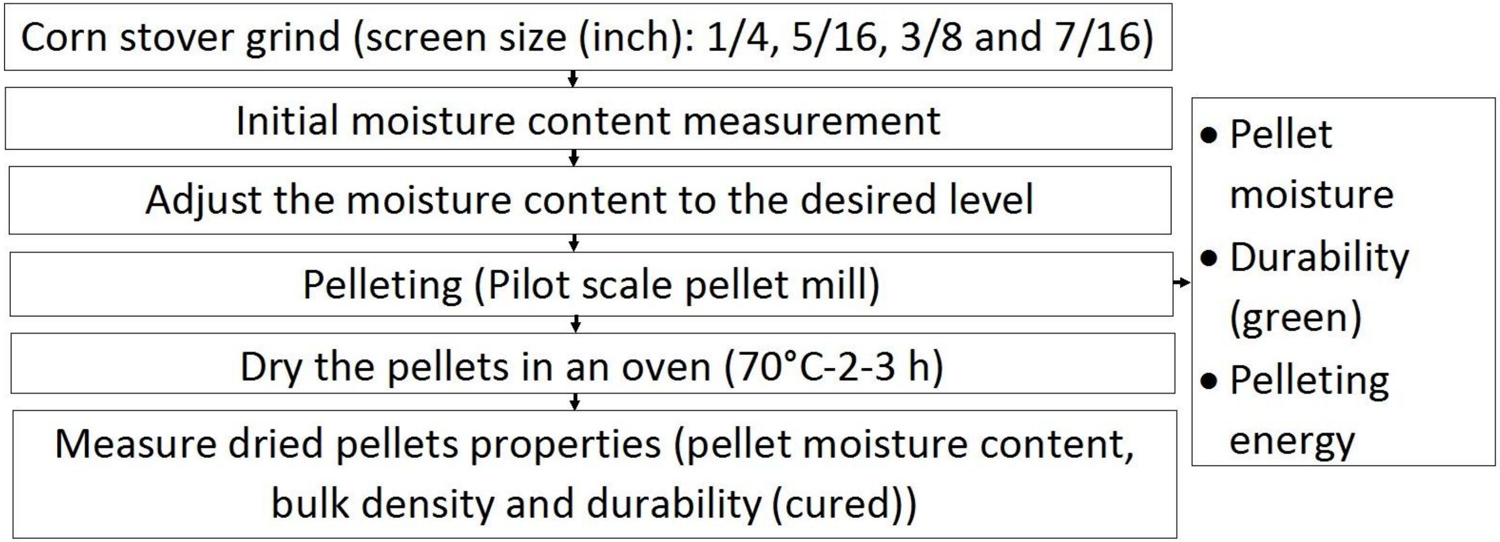
Criteria 3: Pilot-scale demonstration of high-moisture pelleting process

Designed and developed 1 ton/hour pelleting process using a commercial ring die pellet mill at Idaho National Laboratory.



3-Technical Accomplishments (High-moisture pelleting)

Process flow diagram for high moisture pelleting process (Tumuluru 2014, 2016)



Corn stover grind (screen size (inch): 1/4, 5/16, 3/8 and 7/16)

Initial moisture content measurement

Adjust the moisture content to the desired level

Pelleting (Pilot scale pellet mill)

Dry the pellets in an oven (70°C-2-3 h)

Measure dried pellets properties (pellet moisture content, bulk density and durability (cured))

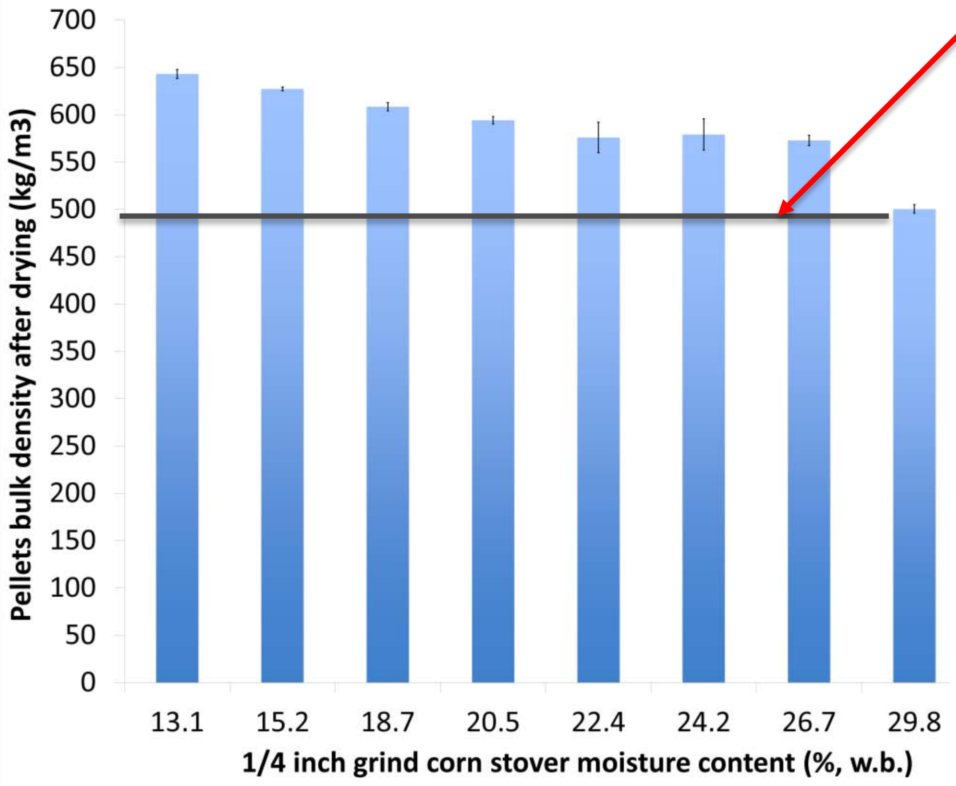
- Pellet moisture
- Durability (green)
- Pelleting energy

Pelleting test conditions for low- and high-moisture corn stover grind

Process variables			
Corn stover grind moisture content (%, w.b.)	**L/D ratio**	**Stage-2 grinder screen size (inch)**	**Pellet properties**
13.1, 15.2, 18.7, 20.5, 22.4, 24.2, 26.7, 29.8	7	1/4, 5/16, 3/8, and 7/16	• Pellet moisture content (%, w.b.) (after pelleting and after drying) • Bulk density (kg/m3)(after drying) • Durability (%) (green & cured) • Pelleting energy

3- Technical Accomplishments (High-moisture pelleting)

1/4 inch grind corn stover pelleting results

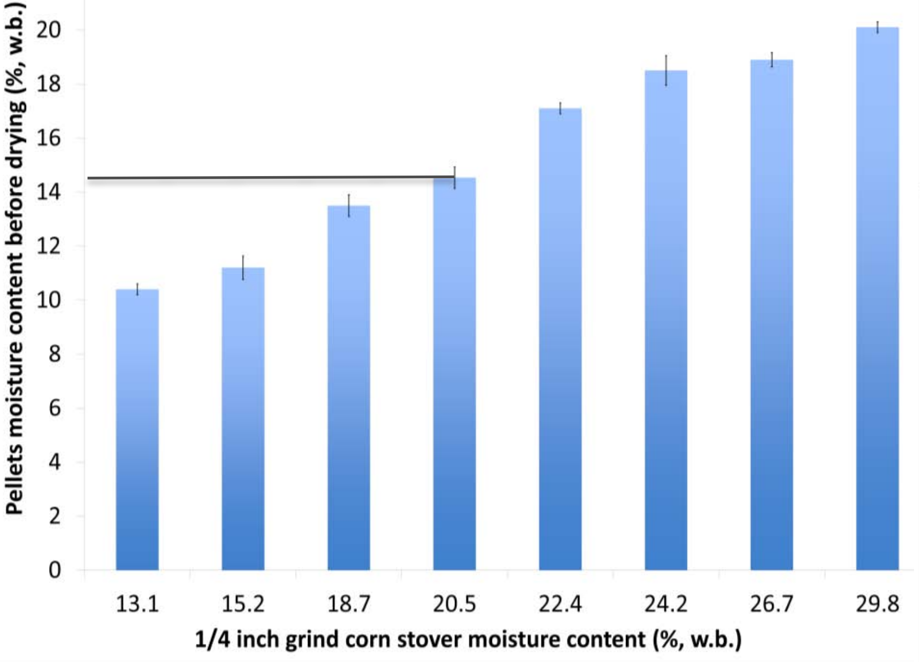


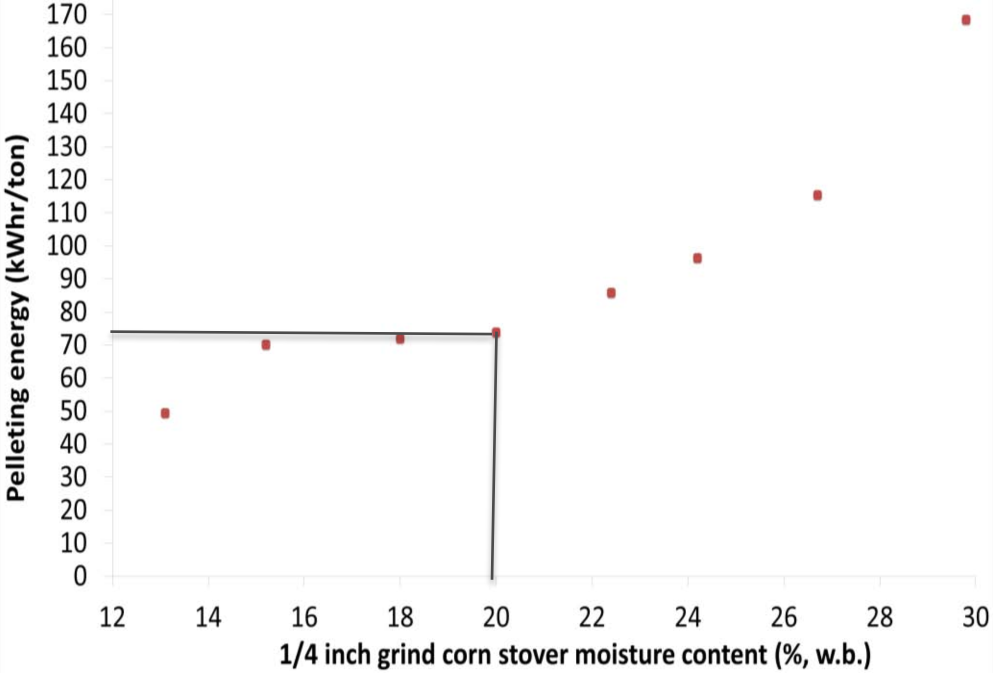
Pellet bulk density target >480 kg/m^3.

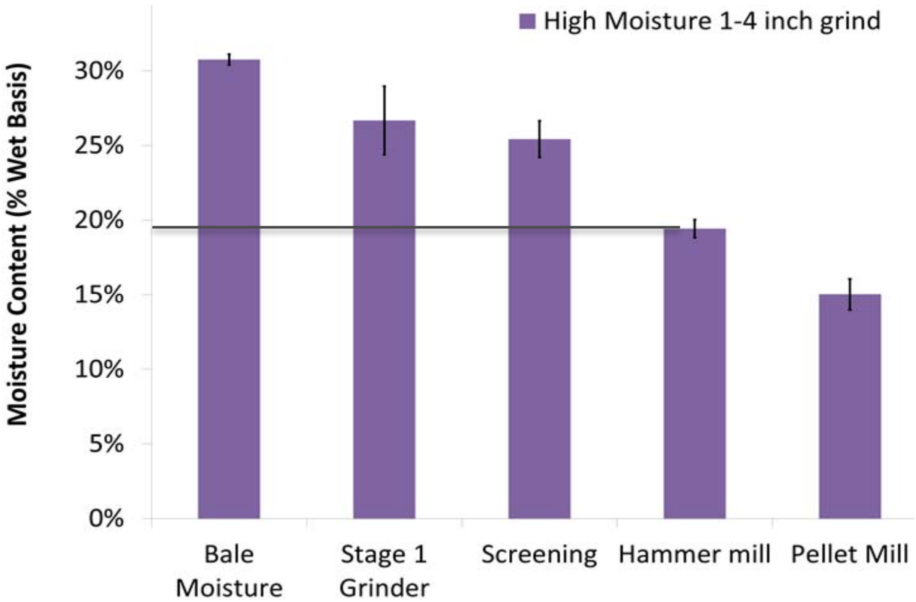
Pellet bulk density and durability decreased with increase in corn stover grind moisture content.

Pellet durability target > 95%

3- Technical Accomplishments (High-moisture pelleting)







Pelleting energy increased steeply when the moisture content is >22% (w.b).

Moisture loss was significant during fractional milling and high-moisture pelleting (about 15%, w.b. from initial moisture content of 30%, w.b.)

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3-Technical Accomplishments (High-moisture pelleting)

Criteria-4: Comparison of the pellet quality with 2016 design targets

2016 Design targets:
- Bulk density (kg/m³): >480
- Durability (%): >95

Goal met: Pelleting tests on 1/4 inch corn stover grind at high moisture resulted in **pellets with bulk density of >480 kg/m³ and durability values >95 %.**

The cost target achieved using a 1/4 inch screen in stage-2 grinder was $29.09/dry ton which is above the established cost target of $25.67/dry ton for FY-16

Feedstock moisture content: 18.7 %
Pellet moisture content: 13.5%
Cured durability: 99.0%
Bulk density: 608 kg/m3

Feedstock moisture content: 22.1 %
Pellet moisture content: 17.2%
Cured durability: 98.04%
Bulk density: 578.2 kg/m3

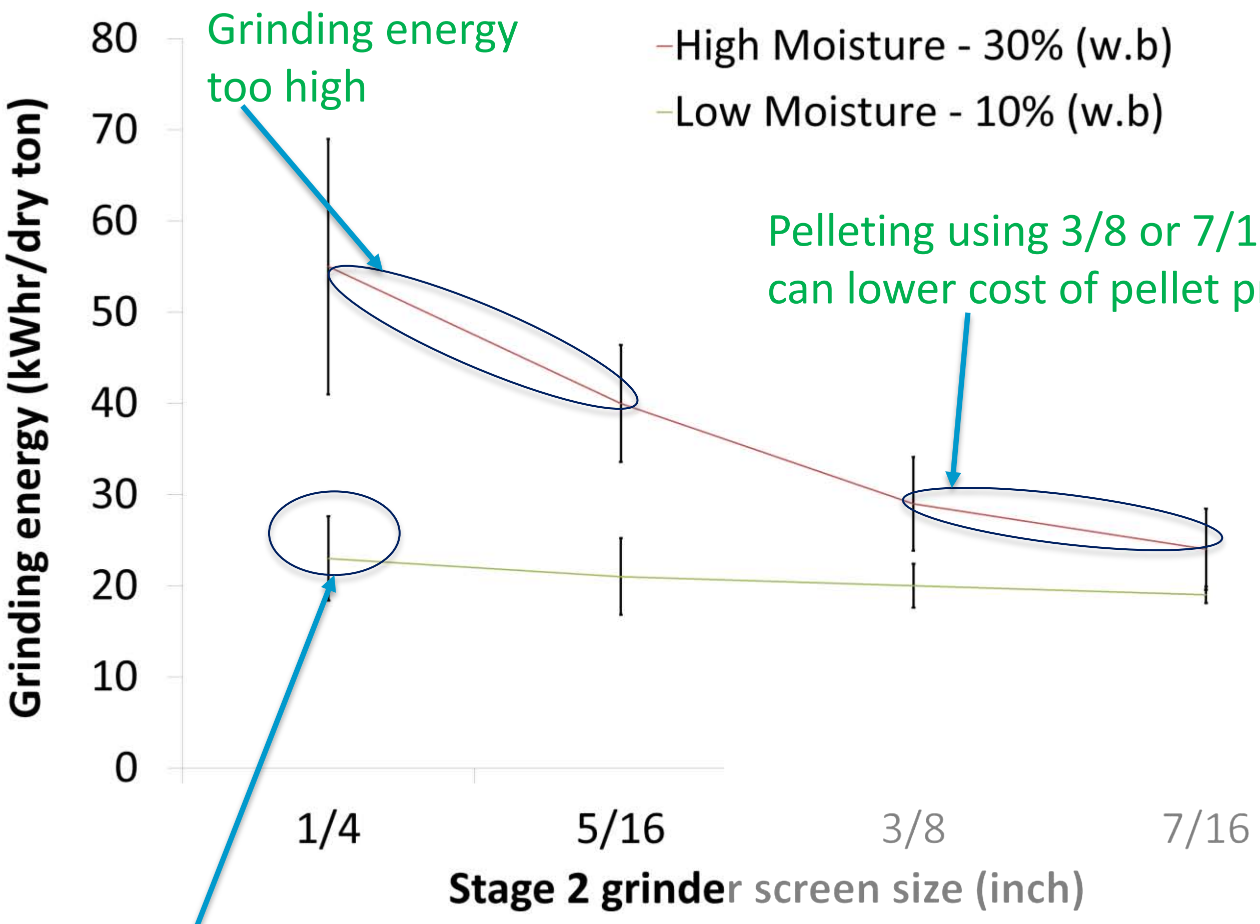
Feedstock moisture content: 26.7 %
Pellet moisture content: 18.5%
Cured durability: 97.1%
Bulk density: 522.5 kg/m3

Feedstock moisture content: 29.8 %
Pellet moisture content: 20.2%
Cured durability: 95.3%
Bulk density: 500.3 kg/m3

Photograph of corn stover pellets produced at high moisture contents

Our approach to reduce the overall preprocessing cost is by increasing the screen size (>1/4 inch) in the stage-2 grinder.

3 - Technical Accomplishments (Fractional milling)



Grinding energy too high

Pelleting using 3/8 or 7/16 screen size can lower cost of pellet production.

Grinding energy is inversely related to screen size and directly related to biomass moisture content.

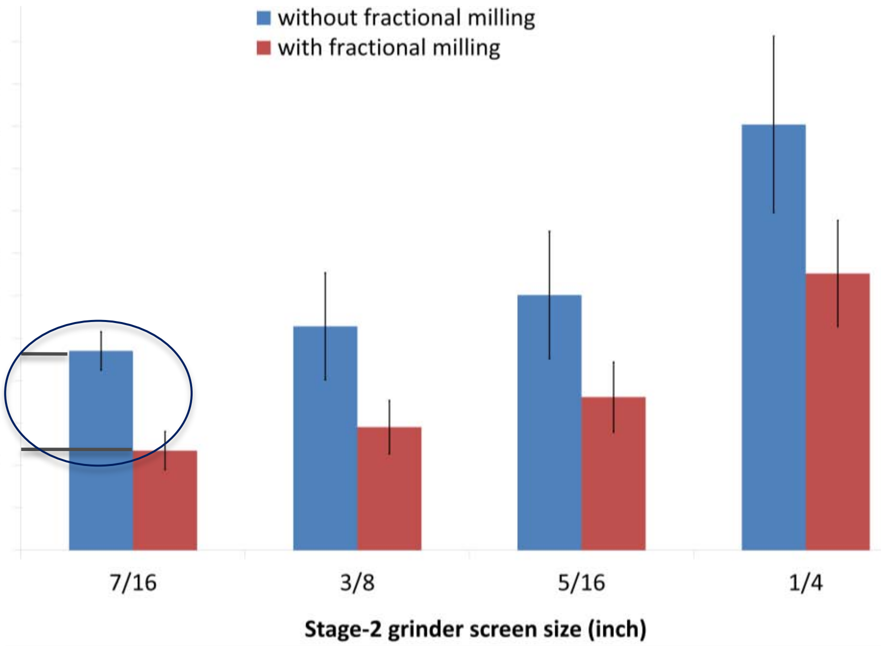
Industry pelleting standard of 1/4 inch works well for low moisture content (10%, w.b.) as the grinding energy does not change significantly with the screen size. At high moisture, smaller screen size increases the grinding energy exponentially.

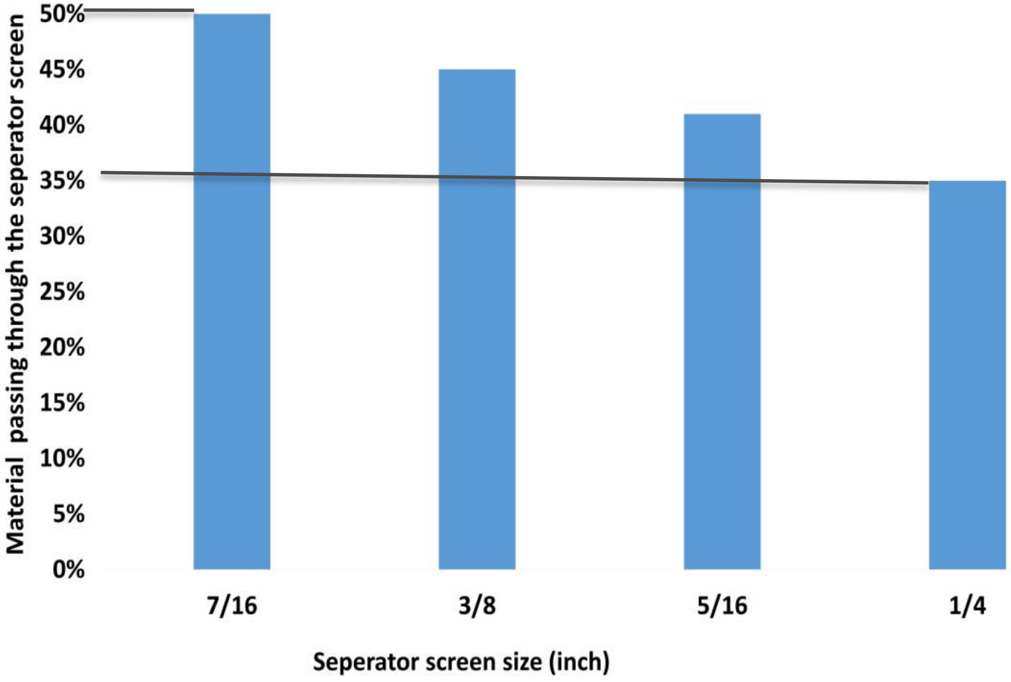
Increasing stage-2 grinder screen size from 1/4" to 7/16" reduced grinding energy by ~56%.

3 - Technical Accomplishments (Fractional milling)

Fractional milling can reduce impact of screen size and moisture content on grinding energy

- For 1/4 inch the separation efficiency is about 35%, whereas for 7/16 it is about 50%.
- There is about 65% decrease in grinding energy using 7/16 inch screen compared to 1/4 inch screen with fractional milling.





Effect of grinder screen size on mean particle size

Grinder screen size (inch)	Mean particle size (mm)
7/16	1.13
3/8	1.12
5/16	1.00
1/4	0.90

3-Technical Accomplishments (High-moisture pelleting)

High-moisture pelleting tests were conducted using different screen size material

- Increasing the particle of stage-2 grinder decreased the bulk density whereas durability values were >97.5%.
- The decrease in bulk density using bigger screen size (7/16 inch) material is due to increase in mean particle size of the grind (0.9 to 1.13 mm).
- Pelleting energy increase (14%) is less significant than the grinding energy decrease (65%) using a 7/16 inch screen size in stage-2 grinder

Process variables			**Pellet properties**				
Stage-2 grinder screen size (inch)	Corn stover grind moisture content (%, w.b.)	Length to diameter ratio of pellet die	Pellet moisture content (%, .w.b)	Bulk density (after drying) (kg/m3)	Green durability (before drying) (%)	Cured durability (after drying)(%)	Pelleting (kWhr/ton)
1/4	20	7	13.5	608.4	97.6	97.9	73.78
5/16			15.3	585.5	98.3	98.8	74.97
3/8			15.8	573.6	98.4	98.6	75.73
7/16			15.5	545.5	98.4	98.6	84.34

We met the quality target (bulk density: >480 kg/m^3; durability >95%) even using a 7/16 inch screen size in stage-2 grinder.

3-Technical Accomplishments (Low-temperature drying)

Lab-scale grain dryer at Idaho National Laboratory

FY-15 pellet drying model was developed

- Model inputs
  - Material properties
  - Dryer geometry
  - Air flow rates
- Outputs
  - Temperature (air & pellets)
  - Moisture content (air & pellets)
- In FY-16, laboratory-scale grain drying system was developed at INL to conduct drying tests on high moisture pellets

FY-17:

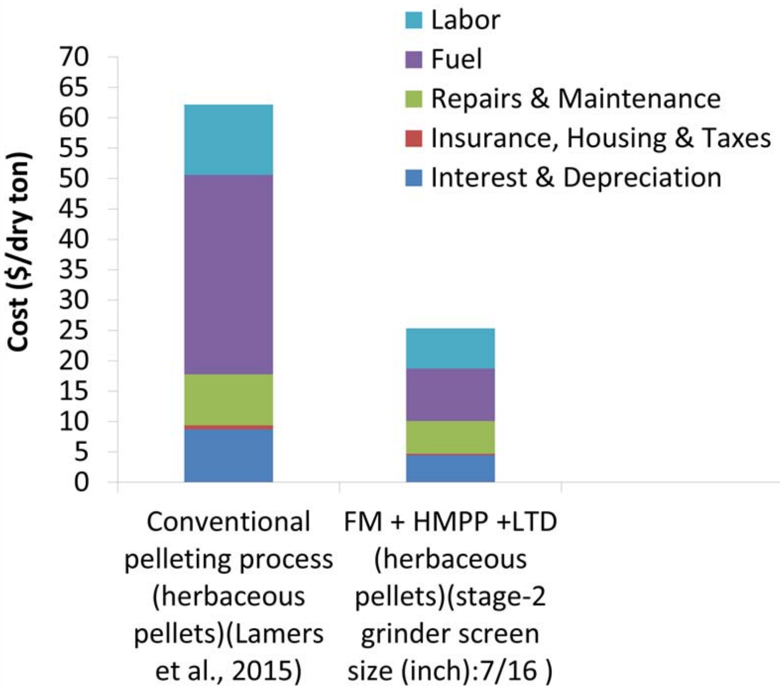
- Conduct drying tests on high-moisture pellets in grain dryer.
- Collaborate with Forest Concepts, LLC on drying of high-moisture pellets using their downdraft dryer.

3-Technical Accomplishments (Techno-economic analysis)

Fractional milling, high-moisture pelleting and low-temperature drying reduced pelleting cost of high moisture corn stover by about 62% compared to Current State of Technology (2013 SOT).

Cost targets established for preprocessing corn stover bales at 30% moisture content

FY	2013 (SOT)	2016	2017
Design Target: Preprocessing cost targets for high moisture corn stover bales (30%, w.b.) biomass ($/dry ton)-1 inch grind (Kenney et al., 2013)	43.60	25.67	21.90
Cost to produce corn stover pellets using FM+HMPP+LTD (stage-2 grinder fitted with 7/16 inch screen)		25.35	21.90



Preprocessing cost target of $25.67/dry ton for 2016 was for 1” grind. We made pellets at $25.35/dry ton using fractional milling, high-moisture pelleting and low-temperature drying

Techno-economic analysis of corn stover bales at high moisture content (30%, w.b.)

4 - Relevance

Impact

- Demonstrating preprocessing technologies capable of supporting the DOE feedstock cost target of $84/dry ton
- Helps achieve DOE vision of commoditized biomass at lower cost for biofuels applications
- Helps overcome current biorefinery challenges like feeding and handling.

Output

- Preprocessing process models developed in this project can be used by the industry for commercial-scale implementation to reduce their preprocessing cost.
- The preprocessing technologies developed in this project can be used by biomass processors and designers of preprocessing systems for producing biofuels, chemicals, and bioproducts from biomass feedstocks.

Lab-corps study revealed:

- Profit margins of pellet producers are razor thin.
- Mobile pelleting industry is interested in high-moisture pelleting as it eliminates the rotary dryer.

5-Summary

Accomplishments

- Scale-up of high-moisture pelleting process from lab scale (40 lb./h) to ring die pellet mill (1 ton/h).
- Reduced herbaceous biomass pellet production cost by about 62% compared to 2013 SOT using fractional milling, high-moisture densification and low-temperature drying.
- The cost target ($25.67/dry ton) set for 2016 was for 1 inch screen size. Using fractional milling, high-moisture pelleting and low-temperature drying, we could met the cost target for 1/4 inch pellet ($25.35/dry ton).

Lessons learned

- Efficient moisture management during preprocessing is critical for reducing the cost.
- Moisture loss during preprocessing is significant and should be considered in integrated preprocessing design.
- Biomass drying is optional, only used when high durability and aerobically stable pellets are needed for long-term storage and long-distance transportation.
- Industry standards for pelleting at low moisture dictated a grind size of 1/4 inch prior to pelleting. In high-moisture pelleting, grinding using a 7/16 inch screen is much more efficient in terms grinder throughput, energy consumption and improves separation efficiency during fractional milling.

6-Future work

– **Future work in FY-17**

  Integrated demonstration of fractional milling, high-moisture pelleting and low-temperature drying at a commercial scale using Biomass National User Facility at Idaho National Laboratory.

— **Follow on work**

- Test grinding of high-moisture biomass (>30%, w.b.) using rotary shear and other milling technologies to reduce the grinding energy.
- Identify and test alternative bale deconstruction modules compared to current stage-1 grinder to reduce the stage-1 grinding energy (which we believe it is still high).
- Test and optimize the process models developed for fractional milling, high-moisture pelleting and low-temperature drying for other feedstocks (woody, herbaceous, municipal solid waste and their blends).
- Test the other densification technologies and commercial and natural binders on high-moisture biomass (>30%, w.b.) in order to reduce the pelleting energy and improve the quality attributes.
- Measure the attrition of the particle size due to densification, which can have negative impact on the biochemical conversion.
- Scale up the pellet drying process to pilot- and commercial-scale low-temperature drying systems (grain or belt dryer).

Abbreviations and References used in this presentation

Nomenclature

HMPP: High moisture pelleting process; FM: Fractional milling; DMA: Dynamic mechanical analysis; L/D ratio: Length to diameter ratio; LTD; Low temperature drying; TEA: Techno-economic analysis; w.b.: wet basis; HC: Hemicellulose; LI: Lignin
SOT: State of technology

References

Kenney, K.L, et al. Feedstock Supply System Design and Economics for Conversion of Sugars to Hydrocarbons. 2013. INL/EXT-13-30342.

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Tumuluru, J. S. 2016. Specific energy consumption and quality of wood pellets produced using high-moisture lodgepole pine grind in a flat die pellet mill. Chemical Engineering Research and Design. 110: 82-97.

Tumuluru, J. S., Conner, C. C., Hoover, A. N. Method to Produce Durable Pellets at Lower Energy Consumption Using High Moisture Corn Stover and a Corn Starch Binder in a Flat Die Pellet Mill. J. Vis. Exp. (112), e54092, doi:10.3791/54092 (2016) (Video link for the High moisture pelleting process published: https://www.jove.com/video/54092).

Additional slides

Responses to Previous Reviewers' Comments

Comment: Did not understand the focus on densification and how that was justified as a key cost saving step. There was a methodical and systematic approach developed but I am not sure the resulting effort moved the needle. Where did we end up? IS the $10.40 in savings really a success? Do the improvements get us close enough? I don't think so.

Reply: In general most of woody biomass and 50% of herbaceous biomass are available at moisture >30% (w.b.). INL and ORNL workshop on depot preprocessing of biomass conducted in 2015 indicated that one of the major limitations to use high moisture biomass feedstocks is the costs associated with preprocessing. Our TEA analysis using the process development unit (INL biomass national User Facility) data has indicated that efficient moisture management is critical to reduce the preprocessing cost of high moisture biomass. Energy analysis of the various unit operations in preprocessing of high moisture biomass indicated that drying takes about 65% energy; stage-1 grinding consumes about 17% of the energy whereas stage-2 and pelleting takes 8% of energy. Addressing the costs associated with drying is critical to make high moisture biomass available for biofuels applications. The cost of preprocessing of high moisture (30%, w.b.) biomass to meet particle size specification of ¼ inch screen is $43.60/ dry ton (Kevin et al., 2013). This cost has to be reduced by 50% by 2017 to meet the DOE feedstock cost target $80.0 /dry ton. This can be achieved by reducing the drying cost or by effectively managing the moisture in the biomass.

To effectively manage the moisture in the biomass we have introduced fractional milling and high moisture pelleting. In high moisture pelleting the biomass is pelleted at high moisture of about 30% (w.b.) (Tumuluru 2014). High-moisture pelleting differs from the current or conventional pelleting process by replacing the energy intensive drying step (typically using a rotary dryer) after second-stage milling with a low-temperature (approximately 110°C), and a short duration (typically several minutes) preheating step prior to pelleting. The combination of preheating, frictional heat generated in the pellet die, and further cooling partially dries the biomass, removing 5 to 10 points of moisture (e.g., from 30% down to 20-25%) (Tumuluru 2014). The pellets produced which still have high moistures can be further dried if necessary to stable moistures of <9% (w.b.) using more energy efficient dryers such as grain dryers (Tumuluru 2014). The main advantage of this method is that it provides an economical alternate to biomass drying (replacing energy intensive rotary dryer in the front end with a grain dryer at the back end of the pelleting process). Further, by moving drying to the end of the process, drying becomes more flexible and is used only when high durability, stability and density are required (such as long distance transportation). An additional advantage is that we believe pelleting of high moisture biomass (even without drying) will provide a viable solution for feedstock handling and feeding problems, particularly when dealing with high- or variable-moisture feedstocks. Projection of preprocessing cost for high moisture biomass (30%, w.b.) by 2017 based on TEA analysis are given in table 1 (Kenney et al., 2013).

The ultimate outcome of this project is the demonstration of integrated biomass preprocessing (fractional milling and high moisture pelleting) system capable of reducing the preprocessing costs by 50% compared to the 2013 SOT to support the DOE feedstock cost of $80/dry ton. In FY-14 the fractional milling studies has helped to reduce the preprocessing cost by $10.40/dry ton. Our TEA analysis indicated that fractional milling combined with high moisture densification will reduce the preprocessing cost of high moisture feedstock by 50% by 2017 (Kenney et al., 2013; Jacobson et al., 2014).

This project interface with biochem and thermochem interface tasks to test the products developed for their conversion performance. Also this task interfaces with the other tasks like storage and handling through our analysis task (WBS 1.2.1.3).

FY	2013 (SOT)	2014	2015	2016	2017
Preprocessing costs ($/dry ton)	43.60	34.80	33.20	25.67	21.90

Responses to Previous Reviewers' Comments

Comment: Not clear how this work will result in additional feedstock available for conversion, primarily because demonstrated need has not been clearly shown.

Reply: Most of woody biomass and 50% of herbaceous biomass available has moisture >30% (w.b.). INL and ORNL workshop on depot preprocessing of biomass conducted in 2015 indicated that one of the major limitations to use high moisture biomass feedstocks by the biorefineries is the costs associated with preprocessing. Lowering the preprocessing cost for high moisture biomass will encourage the biorefineries to utilize these materials. So developing cost and energy efficient preprocessing technologies which can efficiently manage moisture in the biomass is critical to lower the preprocessing cost and in turn the biomass feedstock cost. This makes more biomass available for biofuel application. In this project we are developing cost and energy efficient preprocessing technologies (fractional milling and high moisture densification). Both the fractional milling and high moisture pelleting has been tested for their feasibility and we have published articles in peer review journals. This project is very well positioned to address issues like energy and cost of associates with high moisture woody and herbaceous biomass.

Publications, Patents, Presentations, Awards, and Commercialization

Peer Reviewed Publications

2016

1. (INVITED). Jaya Shankar Tumuluru. 2016. Specific energy consumption and quality of wood pellets made from high moisture lodgepole pine biomass. Chemical Engineering Research and Design, 110, 82-97
2. (INVITED- Feature Article) Jaya Shankar Tumuluru. 2016. Effect of Deep Drying and Torrefaction Temperature on Proximate, Ultimate Composition, and Heating Value of 2-mm Lodgepole Pine (Pinus contorta) Grind. Bioengineering, 3, 16; doi:10.3390/bioengineering 3020016
3. (INVITED). Jaya Shankar Tumuluru, Craig C Conner, Amber Hoover. 2016. A method to produce high quality pellets at lower specific energy consumption using high moisture corn stove and a starch binder. Journal of Visualized Experiments, 112, e54092, doi:10.3791/54092.
4. Cannayen, I., Tumuluru, J.S., Keshawni, D., Schmer,M., Archer, D., Liebig, Mark., Halvorson, J., Hendrickson, J., Kronberg. S. 2016. Biomass bale stack and field outlet locations assessment for efficient infield logistics. Biomass and Bioenergy, 91, 217-226.
5. Ian Bonner, David Thompson, Mitchell Plummer, Matthew Dee, Jaya Shankar Tumuluru, David Pace, Farzaneh Teymouri, and Timothy Campbell. 2016. Impact of Ammonia Fiber Expansion (AFEX) Pretreatment on Energy Consumption during Drying, Grinding, and Pelletization of Corn Stover. Drying Technology, 34 (11), 1319-1329.
6. Williams, C. L., Westover, T., Emerson, R., Jaya Shankar Tumuluru., Li, C. 2016. Sources of biomass feedstock variability and the potential impact on the biofuels production. Bioenergy Research, 9(1), 1-14.
7. Tumuluru, J.S.; McCulloch, R. Application of Hybrid Genetic Algorithm Routine in Optimizing Food and Bioengineering Processes. *Foods* **2016**, *5*, 76.

2015

9. Jaya Shankar Tumuluru. 2015. Comparison of chemical composition and energy properties of torrefied switchgrass and corn stover. Frontiers in Energy Research, 3:46. doi: 10.3389/fenrg.2015.00046.
10. Jaya Shankar Tumuluru, Shahab Sokhansanj, C. Jim Lim, Tony Bi, Xingya Kuang, Staffan Melin, Fahimeh Yazdanpanah. 2015. Analysis on Storage off-gas emissions from woody, herbaceous, and torrefied biomass. Energies, 8(3), 1745-1759.

Publications, Patents, Presentations, Awards, and Commercialization

11. Ian J. Bonner, David N. Thompson, Farzaneh Teymouri, Timothy Campbell, Bryan Bals, Jaya Shankar Tumuluru. 2015. Impact of Sequential Ammonia Fiber Expansion (AFEX) Pretreatment and Pelletization on the Moisture Sorption Properties of Corn Stover. Drying Technology, 33(14), 1768-1778.
12. Jaya Shankar Tumuluru. 2015. Pelletization of high moisture corn stover using a flat die pellet mill with 6 mm die: physical properties and specific energy consumption, Energy Science and Engineering, 3(4), 327-341.
13. Jaya Shankar Tumuluru and Richard J. Hess. 2015. New market potential: torrefaction of woody biomass. Materials World. June/2015
14. Jaya Shankar Tumuluru, L. G. Tabil, Y. Song, K. L. Iroba, and V. Meda. 2015. Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. Bioenergy Research, 8(1), 388-401.
15. Lamers, P., Roni, M. S., Tumuluru, J. S., Jacobson, J. J., Cafferty, K. G., Hansen, J. K., Kenney, K., Teymouri, F., & Bals, B. 2015. Techno-economic analysis of decentralized biomass processing depots. Bioresource Technol. 194, 205-213.

Book chapters

1. Tumuluru, J.S., Searcy E., Kenney, K.L., Smith, W.A., Gresham, G.L. & Yancey, N. A. 2016. Impact of Feedstock Supply Systems unit operations on feedstock cost and quality for bioenergy applications. Edited by R. Kumar, S. Singh, & V. Balan, (Eds.), Biomass pretreatment and conversion processes, Nova Publishing Science Publishers.
2. Md. S. Roni, Kara G. Cafferty, J. Richard Hess, Jacob J. Jacobson, Kevin L. Kenney, Erin Searcy, Jaya Shankar Tumuluru. 2016. Lignocellulosic Crop Supply Chains (e.g. miscanthus, switchgrass, reed canary grass, rye, giant reed etc., Edited by: Jens Holm-Nielsen and Ehiaze Augustine Ehimen ISBN: 978-1-78242-366-9, 271-291, Woodhead Publishing Series.
3. Luke Williams, Rachel Emerson, Jaya Shankar Tumuluru. 2016. Biomass compositional analysis for conversion to renewable fuels and chemicals. Edited by Jaya Shankar Tumuluru, Biomass Volume Estimation and Valorization for Energy, INTECH Publisher (In press).
4. Tumuluru J.S. 2015. Snack Foods: Role in Diet. In: Caballero, B., Finglas, P., and Toldrá, F. (eds.) The Encyclopedia of Food and Health vol. 5, pp. 6-12. Oxford: Academic Press.

Publications, Patents, Presentations, Awards, and Commercialization

Conference Presentations Submitted and Accepted Conference proceedings

1. Jaya Shankar Tumuluru and Richard McCulloch. 2015. A new hybrid genetic algorithm for optimizing the single and multivariate objective functions. ASABE Annual Meeting, Paper Number 152188606, 2015 New Orleans, Louisiana, July 26-29, 2015. @2015 (Proceeding paper)
2. Pordesimo, L. O. and J. S. Tumuluru. 2015. Challenges and Strategies on Fibrous Feedstuffs Densification and Its Interaction with Liquid Ingredients. Presented at the XVII Congresso Bienal AMENA (ASOCIACION MEXICANA DE ESPECIALISTAS EN NUTRICION ANIMAL, A. C.), Puerto Vallarta, Jalisco, Mexico, October 20-23. (invited) (Proceeding paper).

Conference presentations

2017

1. Jaya Shankar Tumuluru, John Aston, Dave Thompson. 2017. Impact of moisture content on grinding and pelleting characteristics of alkali pretreated corn stover. 8th International granulation workshop in Shefiled, UK, June, 2017 (accepted for presentation)
2. Jaya Shankar Tumuluru, and Neal Yancey. 2017. Effect of moisture content and screen size on size reduction and densification characteristics of municipal solid waste. 2017 International BIOMASS Conference & Expo conference, April, 2017 (accepted for presentation).
3. Jaya Shankar Tumuluru, Neal A. Yancey, Craig C. Conner, and Matt Dee. 2017. Impact of moisture content on the density and durability of alfalfa pellets. American Society of Agricultural and Biological Engineers Annual Meeting, July, 2017 (Submitted).
4. Jaya Shankar Tumuluru, Craig C Conner, and Ty Dansie. 2017.Impact on moisture content, particle size on the physical properties and energy consumption of corn stover, switchgrass and lodgepole pine blend briquettes. American Society of Agricultural and Biological Engineers Annual Meeting, July, 2017 (Submitted).
5. Neal. A. Yancey; Matthew O. Anderson, Craig C. Conner; Jaya Shankar Tumuluru. 2017. Controlling Particle Size in 2 Stage Grinding Processes. American Society of Agricultural and Biological Engineers Annual Meeting, July, 2017 (Submitted).

Publications, Patents, Presentations, Awards, and Commercialization

2016

6. Tumuluru, J. S, Yancey, N., Conner, C., & Dee, M. 2016. Grinding and briquetting characteristics of municipal solid waste for biofuels applications. American Society of Agricultural and Biological Engineering Annual Meeting, Jul 17-20, 2016, Orlando, Florida.
7. Tumuluru, J. S, & Richard McCulloch. 2016. Comparison of performance of various regular and hybrid evolutionary algorithms in solving single and multivariable optimization problems. American Society of Agricultural and Biological Engineering Annual Meeting, Jul 17-20, 2016, Orlando, Florida (oral).
8. Yancey, N., Tumuluru, J. S, and Conner, C. 2016. Impact of grinding and pelleting on the particle size distribution of biomass. American Society of Agricultural and Biological Engineering Annual Meeting, Jul 17-20, 2016, Orlando, Florida (oral).
9. Yancey, N., Tumuluru, J. S, and Conner, C. 2016. Comparing RoTap particle size distribution data with digital imaging. American Society of Agricultural and Biological Engineering Annual Meeting, Jul 17-20, 2016, Orlando, Florida (oral).
10. Tumuluru, J. S. 2015. Thermal and mechanical preprocessing of biomass to improve physical, chemical, energy and storage properties. Session Keynote Speaker for 14th International Symposium on Bioplastics, Biocomposites, and Biorefining (ISBBB 2016), Guelph, Canada.
11. Tumuluru, J. S. and Kenney, K. L. 2016. Briquetting characteristics of woody, and herbaceous biomass blends Biomass Conference & Expo. Charlotte, North Carolina, April 11-14, 2016.
12. Nagle, N. J., Wolfrum, E. J., Templeton, D. W., Ray, A. E., Yancey, N., Tumuluru, J. S. and Crawford, N. 2016. Impact of preprocessing on bioconversion yields from densified and blended feedstocks. 38th Symposium on Biotechnology for Fuels and Chemicals. Baltimore, MD, April-25-28, 2016 (oral).
13. Garold L. Gresham, Amber Hoover, Rachel Emerson, Jaya Shankar Tumuluru, Erin Searcy, Kevin L. Kenney, William A. Smith, David Thompson, and Neal A. Yancey. 2016. Mobilization of Biomass: Feedstock quality, Umeå Renewable Energy Meeting 2016, Umea University, Feb, 21-28, 2016.
14. C. Igathinathane, Jaya Shankar Tumuluru, Keshwani D, Marty Schmer, David W. Archer, Liebig M, Halvolson J, J.R. Hendrickson, Scott Kronberg. 2016. Efficient infield biomass bale logistics through bale stack and field outlet locations. Bio Industry Summit, At North Dakota State University, Fargo, ND, Volume: May 12, 2016

Publications, Patents, Presentations, Awards, and Commercialization

15. Art Baker and Jaya Shankar Tumuluru. High moisture pelleting. DOE-NYSERD Laboratory Investor Knowledge Seminar, June, 16th, 2016.

2015

16. Jaya Shankar Tumuluru and Richard McCulloch. 2015. A new hybrid genetic algorithm for optimizing the single and multivariate objective functions. American Society of Agricultural and Biological Engineers Annual International Meeting, New Orleans Marriott, New Orleans, LA, USA, July 2015.
17. Jaya Shankar Tumuluru, Cannayen Igathinathane, Archer David and Richard McCulloch. 2015. Energy analysis and break-even distance for transportation for biofuels in comparison to fossil fuels. American Society of Agricultural and Biological Engineers Annual International Meeting, New Orleans Marriott, New Orleans, LA, USA, July 2015.
18. Jaya Shankar Tumuluru, Ty Dansie, Isaac E Johnson and Craig C Conner 2015 Specific Energy consumption and quality of briquettes produced using wood and herbaceous biomass. American Society of Agricultural and Biological Engineers Annual International Meeting, New Orleans Marriott, New Orleans, LA, USA, July 2015.
19. John E Aston, Jaya Shankar Tumuluru, Lacey, J. A, Thompson, D.N, Thompson, V.S, and Fox, S. 2015. Alkaline deacetylation of corn stover: Effects on feedstock quality. 2015, AICHE Annual Meeting, November, 8-13, Paper 516b
20. Yancey, Neal A, Tumuluru, Jaya Shankar, Conner, Craig C. 2015. Economic and Process Benefits of Fractional Milling Herbaceous Feedstocks Prior to Biochemical or Thermochemical Conversion (ASABE Annual Meeting, July 2015).
21. Jaya Shankar Tumuluru. 2015. Feedstock logistics: Biomass size reduction, drying and densification. 2015. DOE Bioenergy Technologies Office (BETO), Project Peer Review. March 23-27, 2015, Washington DC.
22. High moisture pelleting process. Researcher Presentation to DOE-ID. 8th, April, 2015.
23. Jaya Shankar Tumuluru, Ty Dansie, and Craig. C. Conner. 2015. Briquetting characteristics of woody and herbaceous biomass mixed feedstocks. AICHE Annual meeting, Salt Lake City, November 8-13, 2015.
24. Jaya Shankar Tumuluru and Craig C Conner. 2015. Specific energy consumption and quality of wood pellets produced using high moisture lodgepole pine. 7th International Granulation Conference, University of Sheffield, UK, July, 1st-3rd, 2015.

Awards

1. Received “Outstanding Reviewer Award” for Food and Process Engineering Division, American Society of Agricultural and Biological Engineers, Orlando, Florida, Jul, 17-20, 2016

Publications, Patents, Presentations, Awards, and Commercialization

Editor

1. Guest Editor-Bioengineering Journal- Special issue on Advances in Biomass size reduction, densification and torrefaction (Invited).
2. Guest Editor-Energies Journal – Special issue on Woody Biomass for bioenergy production (Invited).
3. Editor for book titled "Biomass Preprocessing for biofuels production: Mechanical, chemical and thermal methods" to be published CRC press in 2017 (Invited).
4. Editor for book titled "Biomass" to be published by INTECH publisher in 2016 (Invited).

Reviewer, Moderator, technical co-chair and invited presentation

1. Keynote presentation in 14th International Symposium on Bioplastics, Biocomposites, and Biorefining, Guelph, Ontario, Canada (Invited), May31st-June 3rd, 2016.
2. Technical Co-Chair for 14th International Symposium on Bioplastics, Biocomposites, and Biorefining, Guelph, Ontario, Canada (Invited), May31st-June 3rd, 2016.
3. Session moderator "Advances in biomass preprocessing and pretreatment-part-1 & 2, American society of Agricultural and Biological Engineer Annual Meeting, Orlando, Florida, Jul, 17-20, 2016
4. High moisture pelleting process was selected for Lab-Corps training, sponsored by U.S. Department of Energy
5. Grant reviewer for Alberta Foundation (Invited)
6. Reviewed a proposal for Mitacs Accelerate research proposal, Canada.
7. Invited to present high moisture pelleting process in DOE-NYSERD laboratory investor knowledge seminar, June, 16th, 2016
8. Invited to present high moisture pelleting process at NREL Innovation Showcase, October, 6-7th, 2016. This is hosted by NREL's Innovation and Entrepreneurship Center
9. Moderated three sessions in American society of Agricultural and Biological Engineer annual meeting, New Orleans, Louisiana: Session title: "Advances in biomass preprocessing and pretreatment (part-1), Advances in biomass preprocessing and pretreatment (part-2) and Feedstock logistics".
10. Outstanding Contribution in Reviewing, Biomass and Bioenergy Journal
11. Grant reviewer for Natural Sciences and Engineering Research Council of Canada (Discovery Grant)

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12. Grant reviewer for Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) (University of Guelph).
13. Reviewed a proposal for U.S. Dept. of Agriculture Small Business Innovation Research (SBIR) program, National Institute of Food and Agriculture Small Business Innovation Research Program Forests and Related Resources, United States Department of Agriculture
14. Grant proposal reviewer for Alberta Innovates
15. ISO-TC-293-US TAG member for Feed Machinery Terminology
16. Technical committee member ES-255 US TAG ISO TC255 Biogas