U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

1.2.1.2 Biomass Engineering: Size reduction, drying and densification

Technology Review Area: Feedstock Supply and Logistics

March 25th, 2015

This presentation does not contain any proprietary, confidential, or otherwise restricted information

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Goal Statement

Develop and demonstrate preprocessing technologies to

- Reduce the preprocessing cost by 50% by 2017 to support the DOE feedstock cost of $80/dry ton
- Develop innovative and cost effective solutions for preprocessing high and low moisture biomass
- Collaborate with biomass preprocessing industries to advance Current State of Technology (SOT).

Table 1: Biomass feedstock total cost & preprocessing cost

	2013 SOT	2017 Projection
Feedstock	Corn Stover	Blend
Total Delivered Cost ($/dry ton)	139.70	80.00
Preprocessing Cost($/dry ton)	43.60	21.90

Kevin et al. (2013). Biological Conversion of Sugars to Hydrocarbons "The 2017 Design Case", Idaho National Laboratory, Bioenergy Program Idaho Falls, Idaho

Quad Chart Overview

Timeline

- Project start date FY-14
- Project end date FY-17
- Percent complete 35%

Budget

	Total Costs FY 10 – FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$0	$0	$737,916	$4,662,084
Project Cost Share (Comp.) *				

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 and Forest Concepts, LLC
  - Separations: Rotex LLC
  - Drying: Forest Concepts, LLC
  - University of Nebraska Lincoln: Extrusion Technology

1 - Project Overview

History

- FY: 07-12 studies were on conventional systems for pioneer biorefineries. The focus was on preprocessing technologies for dry biomass.
- TEA analysis identified high preprocessing costs is a major barrier to utilize high moisture biomass.
  - Dry feedstock (10%, w.b.): $12/dry ton (stage-1 &2 grinding)
  - High moisture feedstock (30%, w. b) is $43.60/dry ton (stage-1 & 2 grinding and drying).
  - Pelleting: $8.00/dry ton
- Efficient moisture management is critical to reduce the feedstock cost.
- FY13 studies on high moisture (>28%) pelleting of corn stover indicated that costs associated with drying can be significantly reduced.

Present research

- Develop and demonstrate cost effective preprocessing technologies (size reduction, drying and densification) adaptable to a wide range of biomass moisture contents, with a focus on high moisture (>20%, w.b.) biomass feedstocks.

High level objective

Improve the preprocessing process efficiencies to reduce the cost by 50% (based on 2013 SOT) by 2017 to meet the DOE feedstock cost of $80/dry ton .

2- Approach (Technical)

Fractional milling

Increase the screen size of stage-1 grinder and inse separator between stage-1 & 2 grinding operations, bypass fraction which meets specs

- Avoids redundant processing.
- Decouples stage-1 &2 grinding and saves energy.
- Better or tighter particle size distribution with reduced fines.

High moisture pelleting

Biomass is pelleted at moistures >28% (w.b.).

- Biomass lose some moisture (5-8%, w.b.) due to preheating and frictional heat developed in the die
- Drying is optional (i.e. can be used only when high durability and stable pellets are needed
- Energy efficient dryers (grain or belt dryers) can be used for drying high moisture pellets

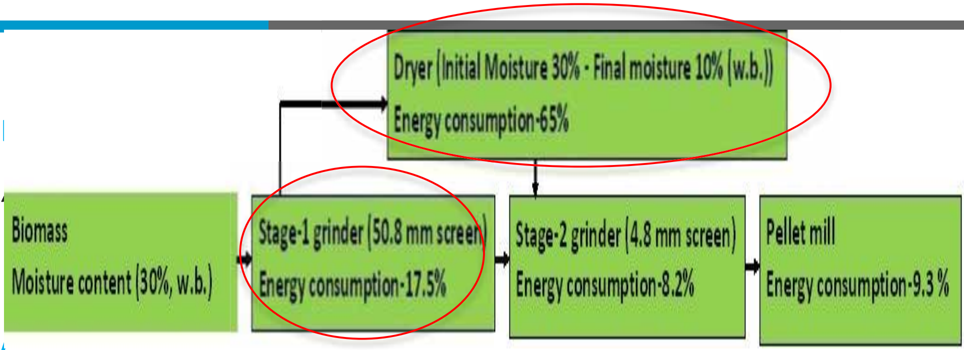


Fig. 1 Flow diagram for conventional pelleting process (Yancey et al, 2013)

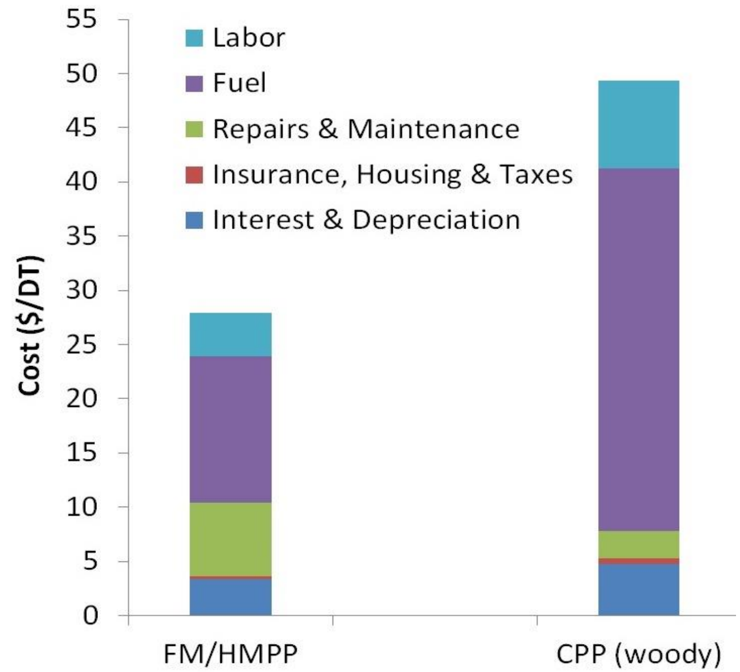


Fig. 3 TEA analysis of conventional and high moisture pelleting process (Patrick et al., 2014).

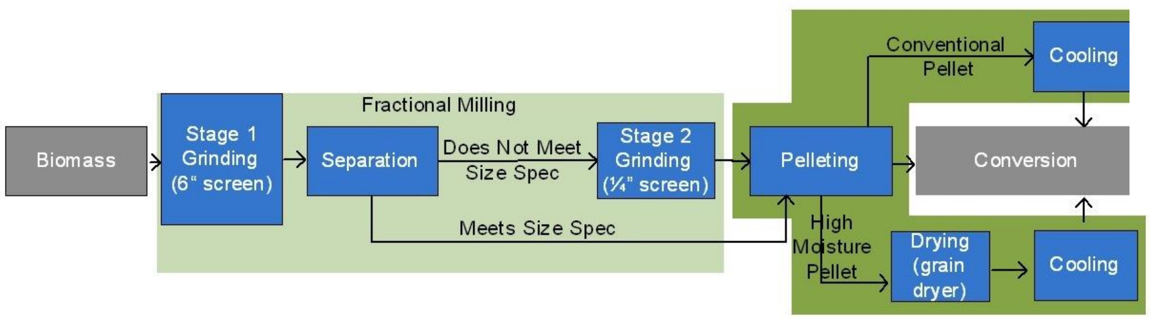


Fig. 2 Flow diagram for FM/HMPP

2- Approach (Management)

- This project has gone through DOE, AOP, Merit Review in 2014. Major milestones, tracking millstones and go-no go decision points are identified for the next three years (FY-15-17).
- Communicate with DOE regularly the technical and cost outcomes.
- 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 publications.
- Engage industry partners through user facility agreements.

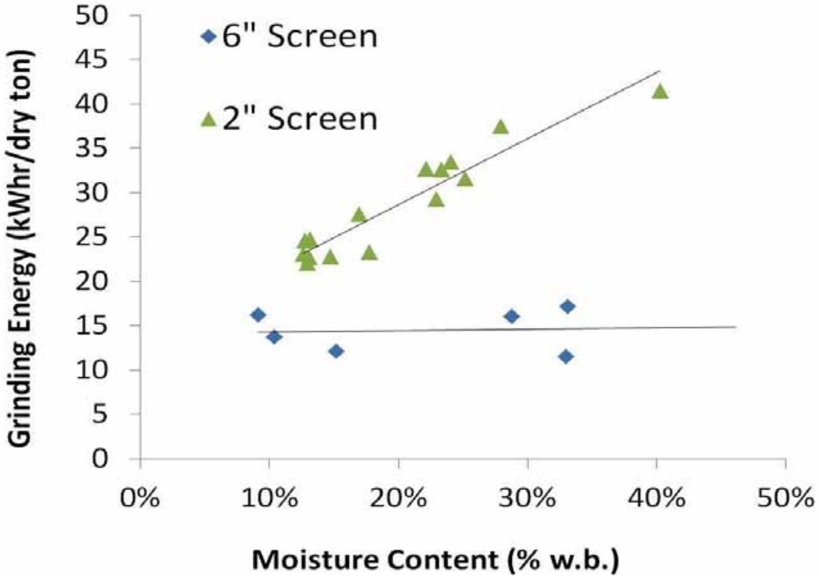
Table 2: Timeline of the project

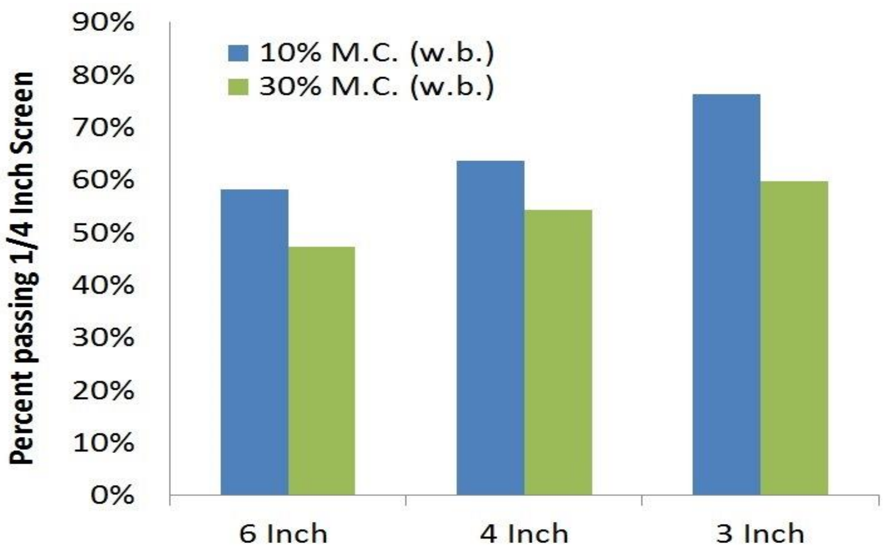
FY13	FY14	FY15	FY16	FY17
Completed TEA, established technical and cost targets for fractional milling and high moisture pelletization	Preliminary process model for lab-scale high moisture pelletization developed Stage-1 fractional milling studies conducted.	Conduct experiments and develop process model for stage-1 and stage-2 grinding Conduct experiment and complete lab-scale high moisture pelletization process model.	Develop process model for separator and integrated with stage-1 & 2 grinding process models developed in FY-15. Scale up of high moisture pelletization process from flat die (50lb/hr) to ring die (1 ton/hr) pellet mill. Validate the pellet drying process model by experimental data	Integrated process model (fractional milling, high moisture pelletization, and drying) completed PDU scale demonstration of the integrated process

Critical success factors

- Scale-up of the lab scale processes and meet cost targets.
- Integrated demonstration of fractional milling, high moisture pelletization and drying and meet cost targets.
- Collaborate with preprocessing industries to advance the state of technology.

3 – Technical Accomplishments/ Fractional milling





Figs. 4 & 5 Fractional milling studies on corn stover

- Going to bigger screen from 2 to 6 inch size in stage- 1 grinder reduced the grinding energy from 39 kWhr/ton-16 kWhr / dry ton.
- 40-60 % of ground biomass based on the initial moisture content meet the spec of stage-2 and can be bypassed.
- 2014 Fractional milling results has reduced the preprocessing cost by $10.40/dry ton compared to 2013 SOT
- Cost saving are mainly due to
  - reducing the grinding energy
  - bypassing the spec material
  - increasing the throughput of stage-1 grinder

3-Technical Accomplishments-Densification

Lodgepole pine pelletization studies

Process variables

Moisture content: 33-39% (w.b.); Die speed (40-60 Hz); Preheating temperature: 30-90 C; Screen size: 4.8 mm

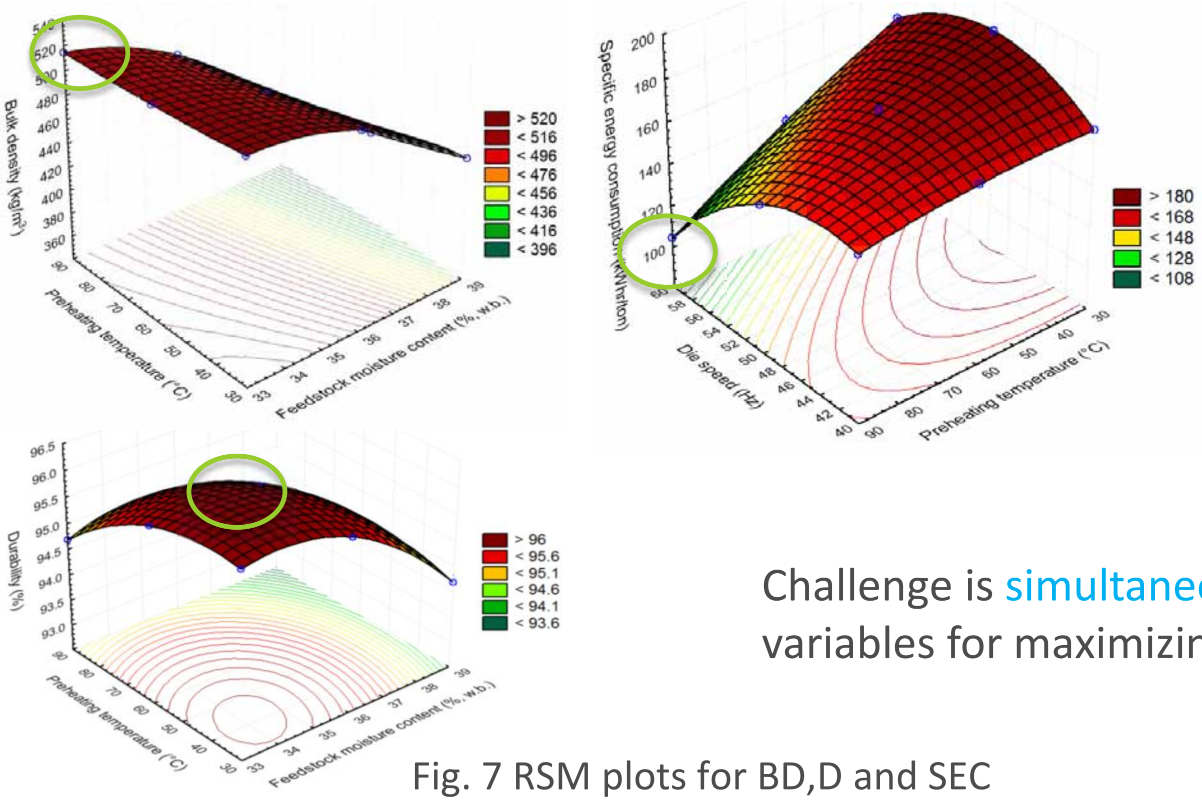
Pellet properties

- Bulk density (BD)(kg/m^3), Durability (D) (%), and specific energy consumption (SEC)(kWhr/ton)

Fig. 6 Lodgepole pine pellets at different process conditions

High density and durability pellets are produced using high moisture lodgepole pine samples

Response surface models were developed for BD, D and SEC



Challenge is simultaneous optimization of process variables for maximizing BD and D and minimizing SEC

Fig. 7 RSM plots for BD,D and SEC

3-Technical Accomplishments-Densification

A new multiobjective optimization tool was developed to optimize BD, D and SEC response surface models

Equation used to find common optimum process conditions:
BD+D-SEC = maximize

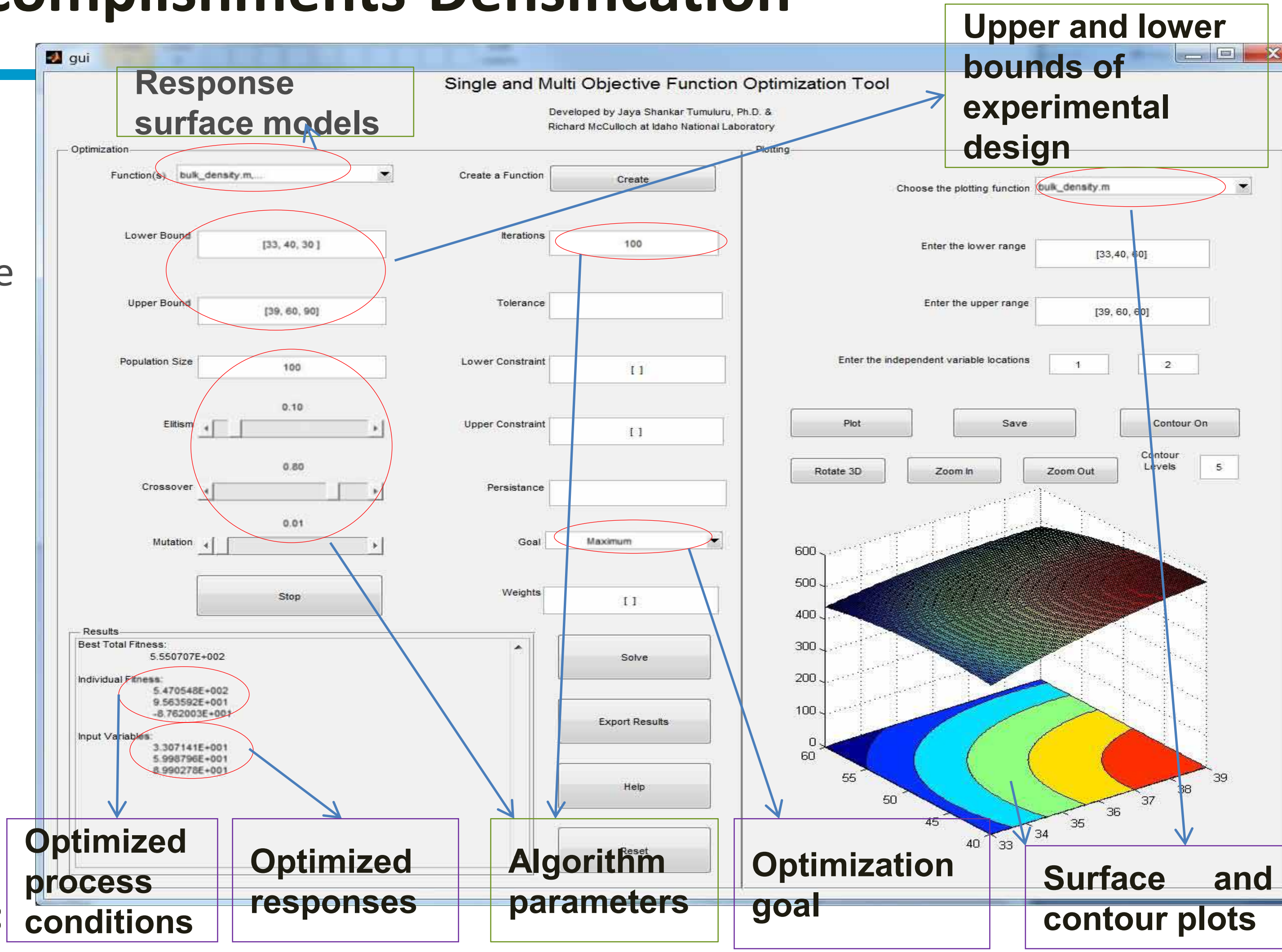


Fig. 8 Single and multiobjective optimization tool developed using hybrid genetic algorithm

Optimized conditions:

– Feedstock moisture content & die speed: 33% (w.b.) & 60 Hz for both corn stover and lodgepole pine

– Preheating temperature: 30 C for corn stover and 90 C for lodgepole pine

– Predicted maximum BD & D: >30lb/ft3 >95% and minimum SEC <100kWhr/ton.

3-Technical accomplishments-Densification

SEM studies indicated that lignin glass transition at high moisture and the pelleting temperature is one of primary reason for binding of biomass.

Moisture flash-off as the pellet comes out of the narrow constricted die hole resulted in diametrical expansion of the pellets and reduced the density.

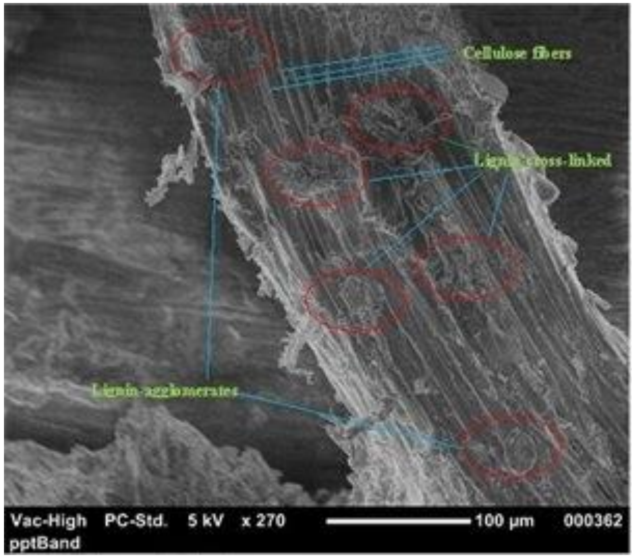


Fig. 9 SEM image of corn stover pellet

J.S. Tumuluru. 2014. Biosystems Engineering, 199, 44-57.

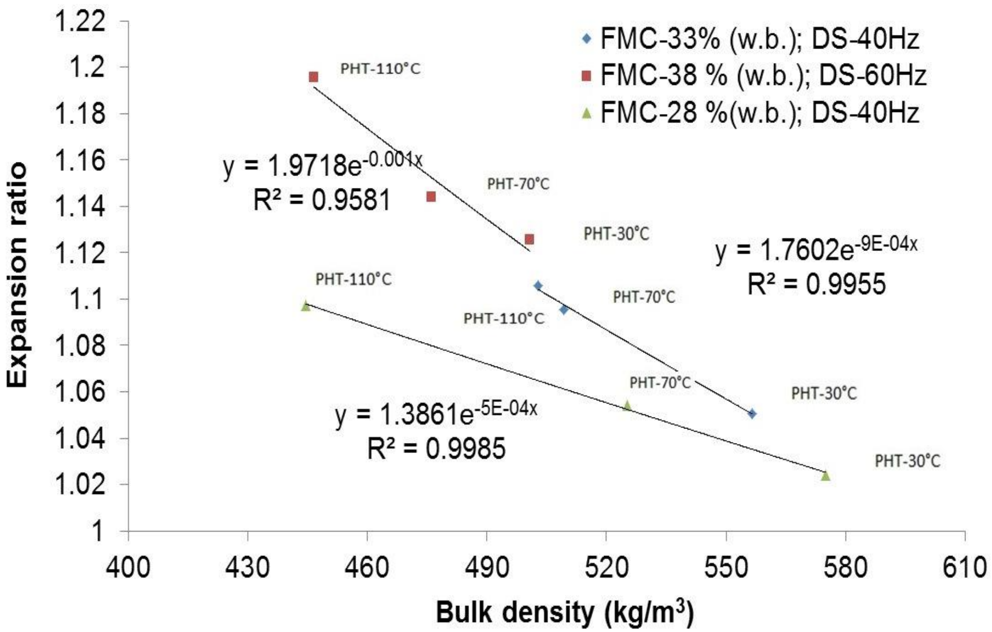


Fig. 10 Expansion ratio of moisture high corn stover pellets

J.S. Tumuluru. 2015. Energy Science and Engineering (under review)

Reducing the expansion ratio increases the density of the pellets.
This is possible by a) optimizing the die geometry, b) adding binders and c) steam conditioning.

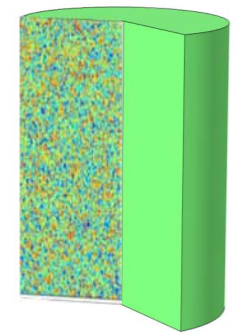
3-Technical Accomplishments-Drying

Developed 3-D numerical model for pellet drying

- Inputs
  - Material properties (Absorption isotherm, pellet geometry)
  - Dryer geometry
  - Air flow rates
- Outputs
  - Temperature (air & pellets)
  - Moisture content (air & pellets)
- Provides optimization tool for dryer design & control parameters
- Preliminary results yield good match to published models on grain drying (Aregba & Nadeau 2007)
- Developed a grain dryer at INL to conduct drying tests on high moisture pellets.
- Model is ready for validation against experimental data

Physical Model

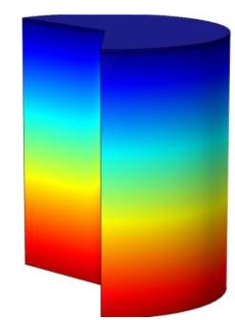
Numerical Model Domain



Material properties

PDEs

Output distribution



Temperature

4 – Relevance

- Demonstrating preprocessing technologies capable of achieving the DOE feedstock cost target of $80/ dry ton

Table-3 Waterfall chart developed preprocessing cost based on TEA

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

- Addresses feedstock barriers like Ft-K: Physical State Alteration, Ft-L: Material Handling, and Ft-M: Integration and Scale-Up.
- Develop technologies to economically preprocess high moisture biomass resources to utilize Billion Ton resources available in USA for bioenergy production .
- Provide commercial feasibility to increase utilization of high moisture biomass for biofuels applications
- Commoditization (DOE vision)of biomass for biofuels applications

5 – Future Work

- Optimize integrated fractional milling system (stage-1& 2 and separator)
- Scale-up of the lab scale flat die process (50 lb/hr) to ring die process (1 ton/hr) and further to commercial pellet mill (5 ton/hr)
- Integrated demonstration of fractional milling, high moisture pelletization and drying by 2017 and achieve the cost targets.

Key milestones (FY-15-17)

- Develop process models for stage-1 & 2 grinders and separator and optimize the integrated fractional milling process.
- Optimize other process conditions (L/D ratio, steam conditioning, and binders), for lab scale pellet mill.
- Scale up optimized process conditions from lab scale flat die pellet mill to commercial scale ring die pellet mill.
- PDU scale demonstration of integrated preprocessing (fractional milling and high moisture densification and drying) to show a 50% cost reduction compared to 2013 SOT.

Go/No-Go

Scale-up of high moisture densification process. If no-go, evaluate other densification technologies like extrusion to meet project outcome.

Summary

1. **Overview**: Improve the efficiencies of preprocessing operations (size reduction, drying and pelletization) to support DOE feedstock cost of $80/dry ton
2. **Approach**: Conducted TEA to validate the technical and economical viability of the preprocessing technologies developed. Technical feasibility of the processes were evaluated using lab scale and pilot scale systems.
3. **Technical Accomplishments/Progress/Results:**
   - Preprocessing costs reduced by $10.40/dry ton in 2014 using fractional milling
   - Process conditions optimized for lab scale high moisture pelletization process for corn stover and lodgepole pine.
4. **Relevance:**
   - Contributes to DOE feedstock cost target of $80/dry ton
   - Develop energy efficient preprocessing technologies to handle low and high moisture biomass feedstocks to utilize billion ton of biomass available in USA for biofuels
   - Addresses feedstock barriers like Ft-K: Physical State Alteration, Ft-L: Material Handling, and Ft-M: Integration and Scale-Up.
5. **Future work:**
   - Scale-up of lab scale processes
   - Integrated demonstration of fractional milling, high moisture pelletization and drying at commercial scale.

Additional slides

Additional slides-Nomenclature

HMPPFM:	Higher moisture pelleting plus fractional milling
SOT:	State of Technology
DT:	Dry ton
w.b.	Wet basis
AOP:	Annual operating plan
CPP:	Conventional pelletization process
FMC:	Feedstock moisture content
DS:	Die speed
PHT:	Preheating temperature
AFEX:	Ammonia fiber explosion
BD:	Bulk density
D	Durability
SEC	Specific energy consumption (kg/m3)

Additional slides: 3 – Technical Accomplishments/ Fractional milling

Table 1. Cost comparison to the herbaceous 2013 SOT Design Case

	2013 SOT		2014 Q3 PMM	
Operation	Parameter	Cost ($/dry T, 2011$)	Parameter	Cost ($/dry T, 2011$)
Preprocessing				
Grinder 1	**2_in screen,** 2 dry ton/hr, 39kWhr/dry ton, 30% moisture	$16.80	**6_in screen**, 5 dry ton/hr, 16 kWhr /dry ton, 30% moisture	$8.20
Drying	12% moisture reduction, 100 dry ton/hr, 350 kWhr /dry ton	$15.20	12% moisture reduction, 100 dry ton/hr, 350 kWhr /dry ton	$15.20
Fractionation	N/A		Modeled as a trommel screen 5 dry ton/hr, 40% Bypass of Grinder 2	$7.50
Grinder 2	¼ in screen, 2 dry ton/hr, 78 kWhr /dry ton, 12% moisture	$11.60	¼ in screen, 5 dry ton/hr, 21 kWhr /dry ton 12% moisture	$2.30
Total		43.60		33.20
Savings				10.40

Additional slides-3-Technical Accomplishments-Densification

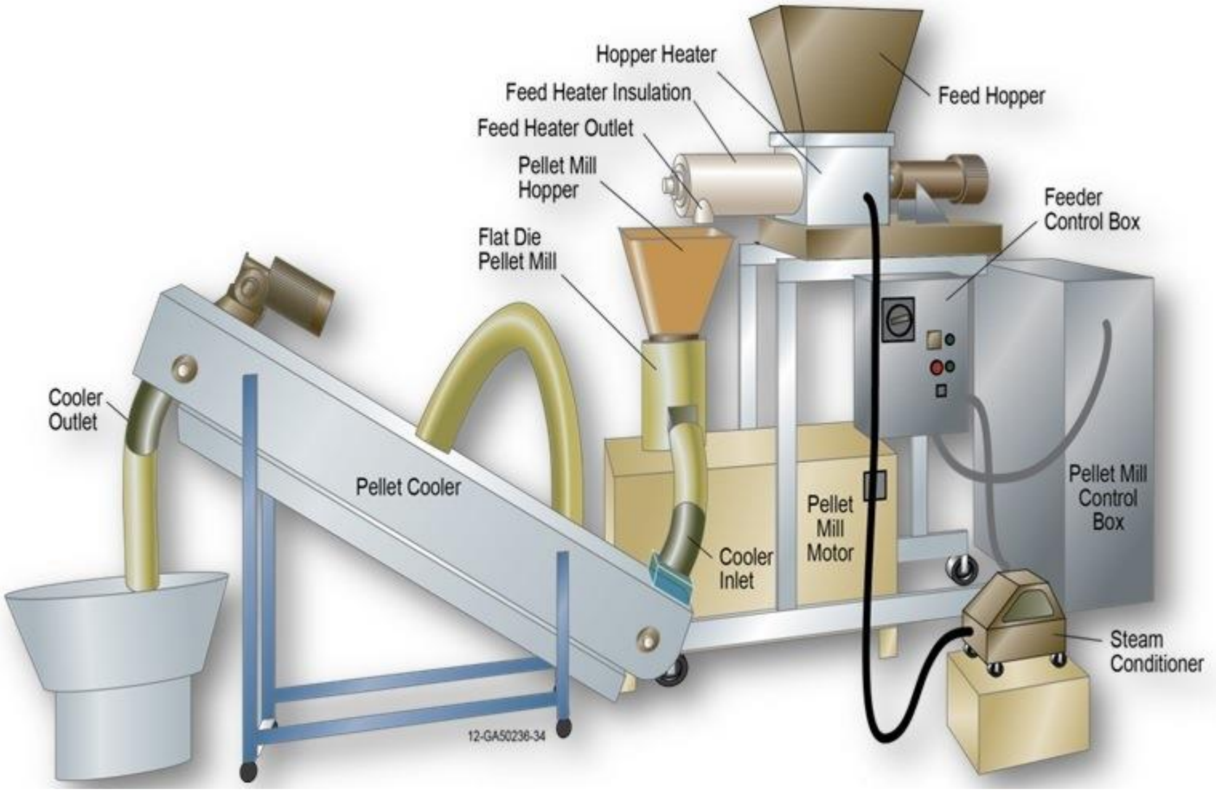


Fig.1 Flat die pellet mill

Jaya Shankar Tumuluru.2104. Effect of process variables on the density and durability of pellets made from high moisture corn stover. Biosystems Engineering, 199, 44-57.

Additional slides-3-Technical Accomplishments-Densification

- Pellet properties (density, and durability) and specific energy consumption varied based on the feedstock type.
- Experimental studies conducted at optimized process conditions for corn stover and lodgepole pine validated the predicted quality attributes.
- Studies on high moisture AFEX pretreated corn stover (26%, w.b.) indicated that good quality pellets with density and durability >35lb/ft3 and >96% are achievable. The studies indicated pelleted AFEX treated corn stover biomass performed better in enzymatic conversion.

1. J.S. Tumuluru. 2015. High Moisture Corn Stover Pelleting in a Flat Die Pellet Mill fitted with a 6 mm Die: Physical Properties and Specific Energy Consumption. Energy Science and Engineering (under review)
2. Amber N. Hoover, Jaya Shankar Tumuluru, Farzaneh Teymouri, Janette Moore, Garold Gresham. 2014. Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion (AFEX) pretreated corn stover, Bioresource Technology, 164, 128-135.

Additional Slides-Collaborations and Technical Personnel.

Industry collaborations

- The following list of industry collaborators will be engaged as appropriate through existing projects or through future targeted User Facility projects to assist with testing, development, scale-up and demonstration of milling of herbaceous and woody biomass (Vermeer Corporation and Forest Concepts, LLC), separations (Vecoplan, LLC and/or Rotex Inc.), drying (Forest Concepts, LLC), and high moisture pelleting (Bliss Industries, LLC). The industries identified for collaboration in the present project has worked on preprocessing of both herbaceous and woody biomass. Additional collaboration will also be planned with universities who have specific expertise on pelleting and extrusion processes.

INL Personnel to support the project

- The PI of this team, Dr. Jaya Tumuluru, has extensive experience on biomass preprocessing, thermal pretreatment, storage and modeling and optimization. He has published more than 37 peer review publications in high impact factor journals like Biofuels, Bioproducts, and Biorefineries, Applied Energy, Bioresource Technology, Biomass and Bioenergy, etc., presented more than 40 papers in national and international conferences and authored 4 book chapters. He has reviewed articles for high impact factor bioenergy research journals, proposals for both national (SBIR phase-1 & 2) and international (NSERC, Canada, OMFRA, Canada, and French Research Academy France). He has received outstanding reviewer awards from The Institution of Chemical Engineers (IChemE)-2011, and American Society of Agricultural and Biological Engineers-2012 & 2013.
- Mr. Neal Yancey has worked at INL for the last 17 years as a research engineer. He has a MS degree in Engineering from Utah State University. He is the principle researcher for biomass size reduction R&D, and the lead research engineer for the Process Demonstration Unit at the INL for the last 7 years. His research in feedstock preprocessing has been focused on optimizing size reduction equipment by evaluating the effects of moisture, equipment configuration, and crop type on grinder performance and has led to 11 publications and presentations.
- Dr. Tyler Westover is a research engineer/scientist for biofuels department, INL. His work supports the Department of Energy's Bioenergy Technology Program in developing improved methods to produce biofuels from woody and herbaceous sources. Dr. Westover's work focuses on characterizing the effects of mechanical and thermal pretreatments that convert plant material to uniform format feedstocks and in developing rapid screening techniques for assessing the value of those feedstocks. Dr Westover holds a Doctorate degree from Purdue University and a Bachelor's degree from Brigham Young University, both in Mechanical Engineering.
- The other personnel who are involved in this projects to support fractional milling and high moisture pelletization are Craig C Conner (Research Engineer, INL), Richard McCulloch (Research Scientist), Kara Kafferty (Research scientist), Mitch Plummer (Modeler), and Student Interns.

Responses to Previous Reviewers' Comments

Collaboration with industry or other groups working on this area would aid the rate of progress and likely positive outputs of the project.

Reply: We agree with the reviewers that Industry collaborations will be crucial. Presently all the advanced preprocessing projects are new projects which have started after the DOE densification workshop conducted at INL in Oct, 2011. As noted in the approach slide most of these tasks are in Technoeconomic analysis (TEA) stage to look into feasibility of technology. We believe TEA to be the necessary precursor to identify and attract best/appropriate collaborations.

Presently we are collaborating with the equipment manufacturers to assess the suitability of existing equipment for advanced preprocessing tasks. Buhler Sortex Inc. and Key Technology Inc. (Visys), will be evaluating some of their automated sorting and fractionation equipment for mechanical separation; Biomass Briquetting Systems, WEIMA America, Inc., and K.R. Komarek Inc for producing the densified products; and waste haulers, manufacturing of waste sorting equipment's and engineering firms who specialize in waste characterization for the formulation task

Having said this, the challenge we have with advanced preprocessing technologies as we have mentioned in the presentation is acceptability of new feedstocks and unproven processes. Our plan is to continue to leverage the interface task to test the product performance and use engineering task for scale-up of new technologies based on the fundamental knowledge developed in this task. This approach will help us to attract industrial partners for commercial deployment.

Statement on pelleting of high moisture BM was that pellet quality is adequate and lower energy cost, but the spec limits were not described. Author answered this orally, but a clearer understanding of the specific goals of this project would be helpful. Methodology for optimizing the pellets produced with wet biomass was not described.

Reply: Goal is to show how high moisture pelletization can help to reduce the drying costs while producing a pellet of desired quality attributes like bulk density and durability. We demonstrated the feasibility of this approach. Optimization of the quality attributes is a challenge what we have identified and included in our future work. In case of optimization of quality of pellets produced using wet biomass; we are planning to use both statistical methods (response surface methodology) and genetic algorithm for optimizing the process conditions to produce high durable and density pellets at low specific energy consumption. One of the methods we have developed during my PhD to find individual and common optimum process conditions for extrusion process using response surface methodology and genetic algorithm will be used in the present pelletization study (Shankar and Bandyopadhyay, 2004).

Publications, Patents, Presentations, Awards, and Commercialization

Peer Reviewed Publications

1. Jaya Shankar Tumuluru.2104. Effect of process variables on the density and durability of pellets made from high moisture corn stover. Biosystems Engineering, 199, 44-57.
2. Jaya Shankar Tumuluru, L. G. Tabil, Y. Song, K. L. Iroba, and V. Meda. 2014. Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. Bioenergy Research (published online).
3. Amber N. Hoover, Jaya Shankar Tumuluru, Farzaneh Teymouri, Janette Moore, Garold Gresham. 2014. Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion (AFEX) pretreated corn stover, Bioresource Technology, 164, 128-135.
4. Jaya Shankar Tumuluru, L. G. Tabil, Y. Song, K. L. Iroba, V. Meda. 2014. Grinding energy and physical properties of chopped and hammer milled barley, wheat, oat and canola straws. Biomass and Bioenergy, 60, 58-67.
5. Jaya Shankar Tumuluru, Shahab Sokhansanj, C. Jim Lim, Tony Bi, Xingya Kuang, and Staffan Melin. 2013. Effect of high and low storage temperatures on off-gas emissions and properties of wood pellets. International Journal of Wood Products, 4 (4), 207-216.
6. Yancey N.A, Jaya Shankar Tumuluru and Wright CT. 2013. Grinding and Densification Studies on Raw and Formulated Woody and Herbaceous Biomass Feedstocks. Journal of Biobased Material and Bioenergy, 7(5), 549-558.
7. Madhura Sarkar, Ajay Kumar, Jaya Shankar Tumuluru, Krushna N. Patil, and Danielle D. Bellmer. 2014. Gasification Performance of Switchgrass Pretreated with Torrefaction and Densification. Applied Energy, 127, 194-201.
8. Madhura Sarkar, Ajay Kumar, Jaya Shankar Tumuluru, Krushna N. Patil and Danielle Bellmer. 2014. Thermal devolatilization kinetics of switchgrass pretreated with torrefaction and densification. Transactions of ASABE, 57(4): 1199-1210.

Conference Proceedings

1. Jaya Shankar Tumuluru. 2014. Effect of torrefaction parameters on proximate and ultimate composition of lodgepole pine. ASABE Annual Meeting, Paper Number 141898037, 2014 Montreal, QC Canada, July 12-13, 2014. @2014
2. Jaya Shankar Tumuluru, K.G. Cafferty, K.L. Kenney 2014. Techno-economic analysis of conventional, high moisture pelletization and briquetting process. ASABE Annual Meeting, Paper Number 141911360, 2014 Montreal, QC Canada, July 12-13, 2014. @2014.

Publications, Patents, Presentations, Awards, and Commercialization

Book chapters

1. Karlen DL, Galdos MV, Rabelo SC, Franco HCJ, Boomi A, Li S, Li S-Z, Jaya Shankar Tumuluru, Ovard L. 2014. Selected global examples of cellulosic cropping systems trends. “In Cellulosic Energy Cropping Systems. Wiley: West Sussex, UK
2. Fahimeh Yazdanpanah, Shahab Sokhansanj, Hamid Rezaei, C. Jim Lim, Anthony K. Lau, X. Tony Bi, S. Melin, Jaya Shankar Tumuluru and Chang Soo Kim (2014). Measurement of Off-Gases in Wood Pellet Storage, Advances in Gas Chromatography, Dr Xinghua Guo (Ed.), ISBN: 978-953-51-1227-3, InTech, DOI: 10.5772/58301.
3. Searcy EM, Hess JR, Jaya Shankar Tumuluru, Ovard, L, Muth, DJ, Jacobson, J, Jeffers, B, Cafferty, K, Tremborg, E, Wild, M, Deutmeyer, M, Nikolaisen, L, Ranta, T, Hoefnagels, R. 2013. Optimization of biomass transport and logistics. “In International Bioenergy Trade. Goh, M., Sheng, C., Andre, F (Eds.), Springer Publications

DOE Milestones

1. Jaya Shankar Tumuluru, Kevin L. Kenney & Kara G. Cafferty. 2013. Develop a techno economic analysis of pelletization and briquetting to define densification costs and impacts on quality and conversion performance (FY-13 Q4 Milestone)
2. Neal Yancey and Craig C. Conner. 2013. Preprocessing designs for controlling biomass particle size distributions (FY-13 Q4 Milestone).
3. Jaya Shankar Tumuluru, Richard McCulloch, & Craig C. Conner. 2014. Demonstrate technical feasibility and identify process conditions for pelletizing high moisture (28-38%) corn stover and achieving pellet quality requirements of bulk density >30 lb/ft3 (>480 kg/m3), durability > 95% and a specific energy consumption < 75kWhr/ton. This will involve development of a multivariate optimization tool to optimize the models developed for the pellet physical attributes and energy consumption utilizing laboratory generated in FY13 (FY-14 Q2 Milestone).
4. Neal Yancey, and Kevin L. Kenney. 2014.Demonstrate a $10/ton Cost Saving Through Fractional Milling (Joule : 30th June 2014).
5. Jaya Shankar Tumuluru, Craig C. Conner, and Kevin L. Kenney. 2014. Demonstrate technical feasibility and identify process conditions for pelletizing high moisture (33-39%) woody biomass and achieving pellet quality requirements of bulk density >30 lb/ft3 (>480 kg/m3), durability > 95% and a specific energy consumption 50-100kWhr/ton. This will involve completing the pelletization tests on high moisture (30-39%, w.b.) woody biomass; evaluate the pellet quality attributes and analysis of the data using optimization model developed in Q2 (FY-14 Q4 milestone).
6. Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen and J. S.Tumuluru (2014). Techno-economic analysis of a biomass depot. Idaho Falls, ID, USA, Idaho National Laboratory. Report INL/EXT-14-33225 (FY-14 Q4 milestone).

Publications, Patents, Presentations, Awards, and Commercialization

Conference Presentations

1. Jaya Shankar Tumuluru, K. G. Cafferty, and K.L. Kenney. 2014. Techno-economic analysis of conventional, high moisture pelletization and briquetting process. American Society of Agricultural and Biological Engineers Annual Meeting, Montreal, Canada; 07/2014
2. N. A. Yancey, Jaya Shankar Tumuluru, C. C. Conner, C. Grosshans, and C. Coupland. 2014. Managing moisture in baled biomass prior to storage and preprocessing of biomass for lignocellulosic conversion. American Society of Agricultural and Biological Engineers Annual Meeting; 07/2014
3. Jaya Shankar Tumuluru. 2014. Effect of torrefaction parameters on proximate and ultimate composition of lodgepole pine. American Society of Agricultural and Biological Engineers Annual Meeting, Montreal Canada; 07/2014
4. Jaya Shankar Tumuluru, Craig C Conner, Richard McCulloch, and Kevin L. Kenney. 2014. specific energy consumption and pellet properties of high moisture woody and herbaceous biomass. American Society of Agricultural and Biological Engineers Annual Meeting, Montreal, Canada; 07/2014
5. Madhura Sarkar, Ajay Kumar, Jaya Shankar Tumuluru, Krishna N. Patil, and D. Bellmer. 2014. Effect of torrefaction and densification on syngas generated from switchgrass gasification. American Society of Agricultural and Biological Engineers Annual Meeting; 07/2014
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9. A. Kumar, M. Sarkar, Jaya Shankar Tumuluru, K.N. Patil, D. Bellmer, R.L. Huhnke. 2013. Effects of torrefaction and densification on quality of syngas generated from fluidized-bed gasification of switchgrass Ajay Kumar, Oklahoma State University, Stillwater, OK. American Society of Agricultural and Biological Engineers Annual Meeting; 07/2013.

Publications, Patents, Presentations, Awards, and Commercialization

Trade magazine interviews

1. Jaya Shankar Tumuluru. 2013. Crop-Based Pellets for Power, Fuel and Ag Heat. Biomass Magazine, December 19, 2013**.**
   Website link: http://biomassmagazine.com/articles/9777/crop-based-pellets-for-power-fuel-and-ag-heat
2. Jaya Shankar Tumuluru. 2013. Stover pellets pack in the pounds. Ethanol Producer magazine. September 17, 2014.
   Website link: http://www.ethanolproducer.com/articles/11434/stover-pellets-pack-in-the-pounds

Patent filed

1. Jaya Shankar Tumuluru, J. S. 2014. Systems And Methods Of Forming Densified Biomass (patent filed on 7/7/2014).

Awards

1. Outstanding reviewer award for Food and Process Engineering Division, American Society of Agricultural and Biological Engineers for the year 2013 (given to top 10 reviewers out of more than 900 reviewer who participate each year in their peer review process).
2. Outstanding reviewer award for Food and Process Engineering Division, American Society of Agricultural and Biological Engineers for the year 2014 (given to top 10 reviewers out of more than 900 reviewer who participate each year in their peer review process).
3. Outstanding excellence in publication award. 2013. Given to top publisher in EEST directorate, Idaho National Laboratory.
4. Association of Agricultural, Biological, and Food Engineers of Indian Origin (AABFEIO) best paper award for the paper **titled**: Thermal devolatilization kinetics of switchgrass pretreated with torrefaction and densification. **Authors**: Madhura Sarkar, Ajay Kumar, Jaya Shankar Tumuluru, Krushna N. Patil and Danielle Bellmer. 2014. Journal: Transactions of ASABE, 57(4): 1199-1210.