Feedstock Supply System Logistics

April 7, 2011

DOE Biomass Program
Feedstocks Platform Review

Shahab Sokhansanj and Erin Webb
ORNL Environmental Sciences Division

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

Project goal

Apply science and engineering fundamentals toward development of mathematical models and advanced biomass processing in support of a commercial feedstock supply for integrated biorefineries

Objectives

1. Bioenergy Feedstock Supply System Modeling
   Develop mathematical models to represent current and advanced unit operations and changes in biomass that occur along supply chain

2. Advanced Biomass Processing
   Develop and analyze advanced designs to transform bulky cellulosic feedstock to a free-flowing granular format or to stable packages for ease of handling and efficient transport, storage, and conversion

Oak Ridge National Laboratory

Approach

1. Bioenergy Feedstock Supply Modeling

- Calibrate mathematical models with field and/or lab data. Examples include:
  - Controlled environment drying experiments for calibration of field drying model for switchgrass, miscanthus, and energy sorghum
  - Wood chip storage (logging residue) – moisture relations, self-heating, dry matter loss
  - Size reduction experiments to correlate particle size and power requirements
- Develop partnerships with academia and industry for sharing data and algorithms
  - Engage feedstock logistics modeling community at technical and professional meetings
- Work with INL to incorporate new models into Biomass Logistics Model and to apply BLM for analysis of feedstock supply chains

Oak Ridge National Laboratory

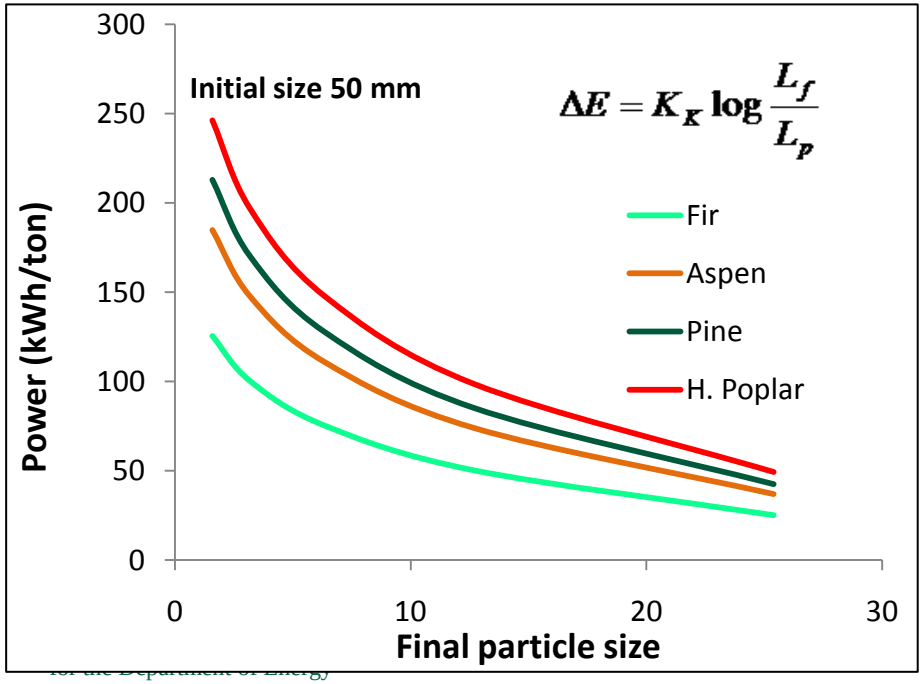
Approach
2. Advanced Biomass Processing

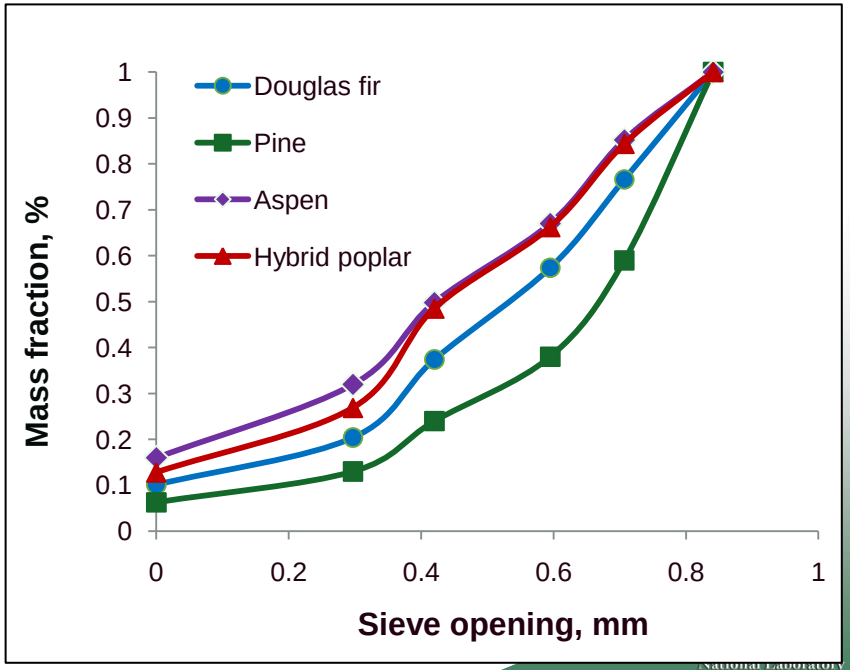
- Test thermal and steam treatments to improve properties of biomass pellets
- Measure effects of thermal and steam treatments on bulk density, heat value, durability, and hydrophobicity of pellets
- **Project management**
  - Shahab Sokhansanj based in Vancouver with strong relationship to Univ. of British Columbia
  - Internal biweekly meetings
  - Bi-weekly meetings with INL and DOE technology manager

Technical Accomplishments – Feedstock Supply Modeling

Power requirements of size reduction

- Calibrated equation used for mineral products to predict power required to achieve various particle sizes during grinding
- Characterization of logging residue
- Results
  - Function worked well to explain experimental data
  - Parameters varied with tree species





Technical Accomplishments – Feedstock Supply Modeling

Predicting field drying

Controlled environment experiments underway at UK to calibrate field drying model

Thin-layer drying model (Nilsson, 1999) where moisture content (M) sum of internal and external MC

Internal moisture content

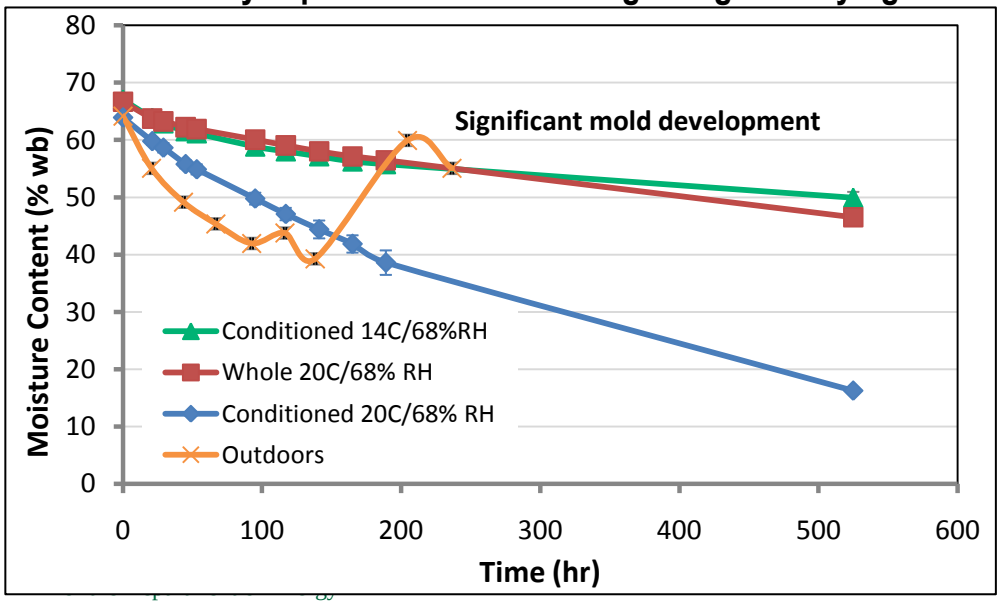
$$dM_i/dt = -a(E_p)(M_i - M_{eq})$$

External moisture content

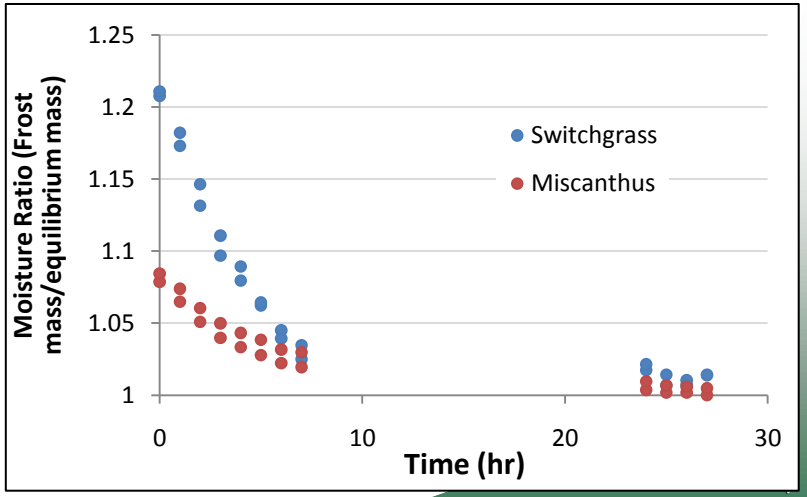
$$dM_{e,w}/dt = -bP - cE_p$$

Switchgrass harvest December 2010 with frost

Preliminary experimental data - Forage sorghum drying



Environmental chambers also used to measure time to remove frost at 10C and 60% RH



Technical Accomplishments – Feedstock Supply Modeling

Temperature & moisture in wood chip storage

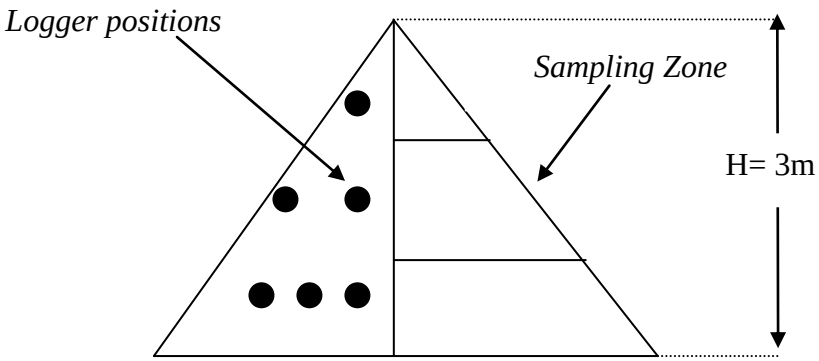
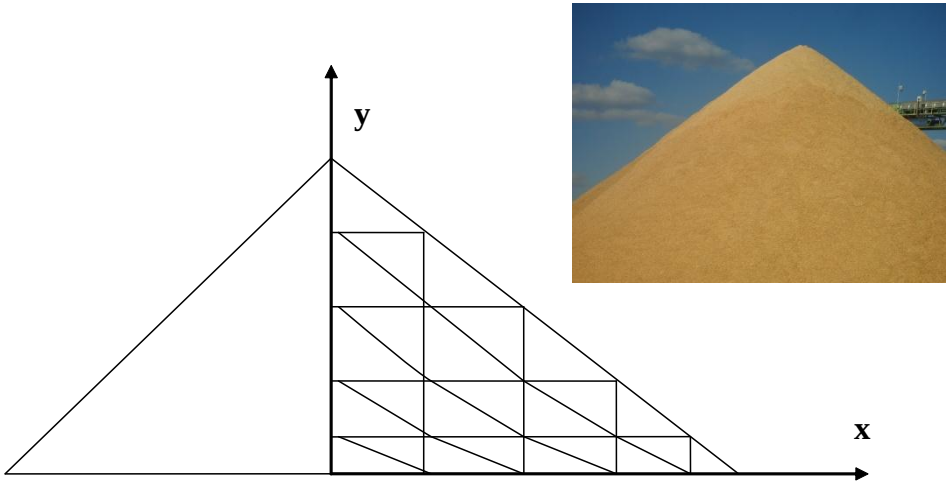
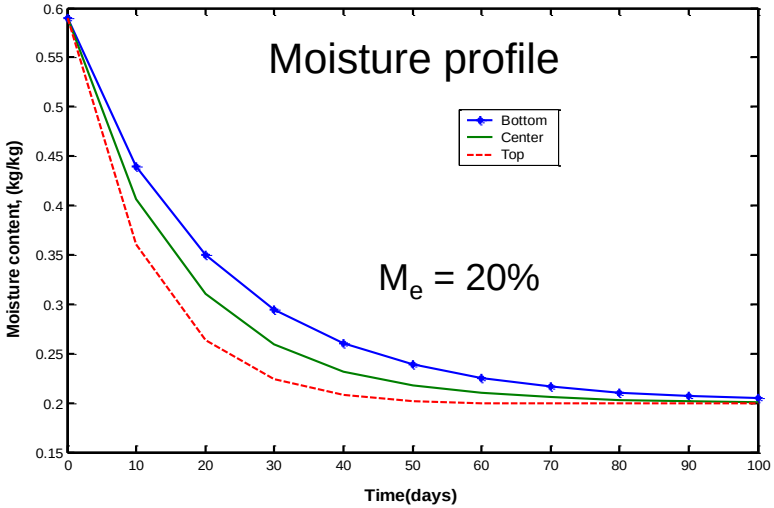
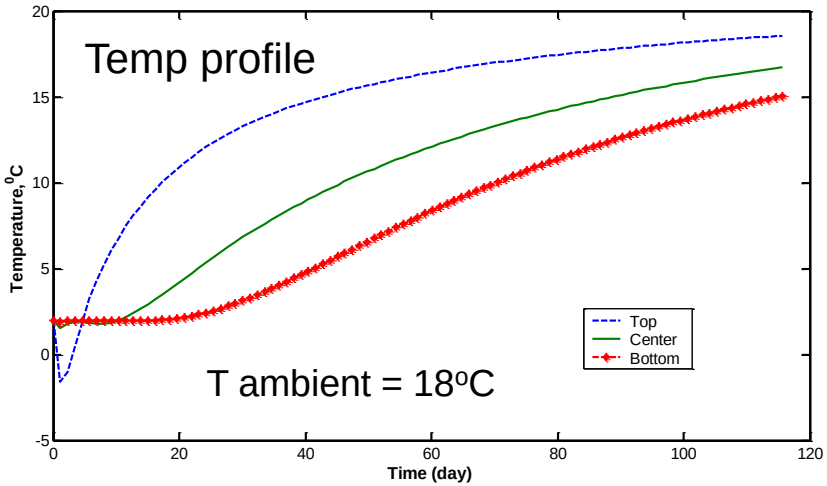


Diagram of wood chips pile & location of temperature sensors



Discretization of wood chips pile





Afzal, Bedane, Sokhansanj, and Mahmood. 2010. *BioResource* 5(1):55-69

OAK RIDGE National Laboratory

Technical Accomplishments

Developing partnerships for model and data sharing

Contribute models & algorithms for BLM
Test and analyze supply chain simulations
Knowledge gained in processing research shared with PDU

Idaho National Laboratory

Collaborative processing experimentation and modeling

UBC

Field drying experiments

UNIVERSITY OF KENTUCKY

Collaborative pelletization research

Share logistics models

AGCO

POET

FDC Enterprises Grasslands Services
Creating Superior Quality Grasslands

Collaborative model development and testing

UNIVERSITY OF ARKANSAS

Developing new simulations of advanced logistics systems

Genera energy

OAK RIDGE National Laboratory

Determining torrefaction parameters

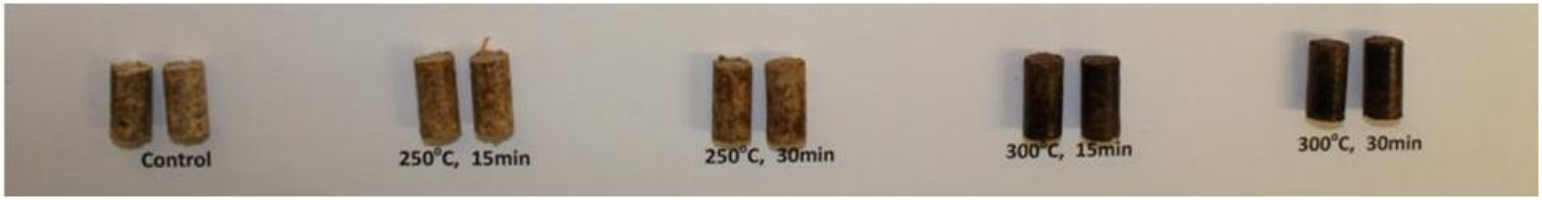
- Goal: Evaluate densification of torrified biomass
- Preliminary experiments were performed to determine best torrefaction settings
- Important findings:
  - 250°C for 15 min minimizes mass loss while improving heat value
  - Increasing severity of torrefaction increases mass loss making more uneconomical

Particle size (mm)	Temp (°C)	Duration (Min)	Mass loss (%)	Heat value increase (%)
6.1	250	15	6.4 ± 0.3	10.5 ± 2.85
6.1	250	30	8.5 ± 0.0	9.3 ± 0.2
0.8	250	15	11.7 ± 0.4	10.3 ± 1.1
0.8	250	30	9.5 ± 1.4	10.7 ± 1.5
6.1	300	15	32.5 ± 0.3	19.9 ± 2.4
6.1	300	30	35.1 ± 0.1	19.4 ± 0.2
0.8	300	15	35.6 ± 0.4	18.6 ± 0.2
0.8	300	30	40.5 ± 6.2	19.2 ± 1.8

Oak Ridge National Laboratory

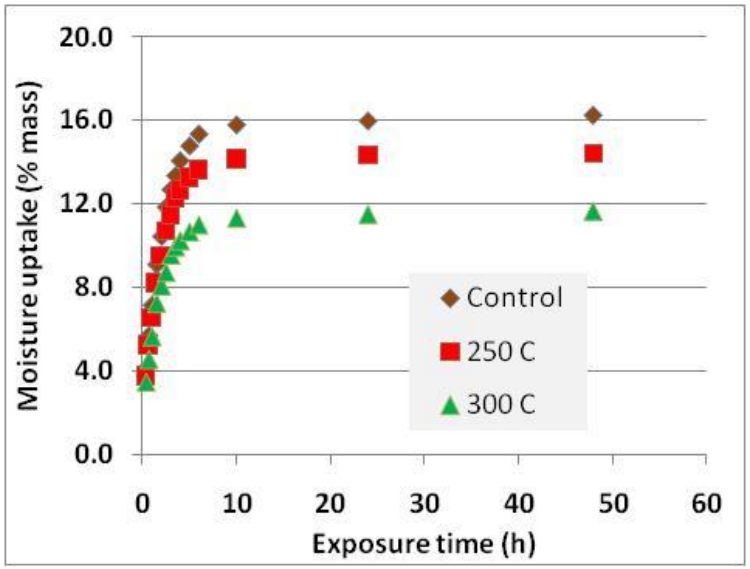
Technical Accomplishments – Advanced Biomass Processing

Pros and cons of pelletizing torrified wood

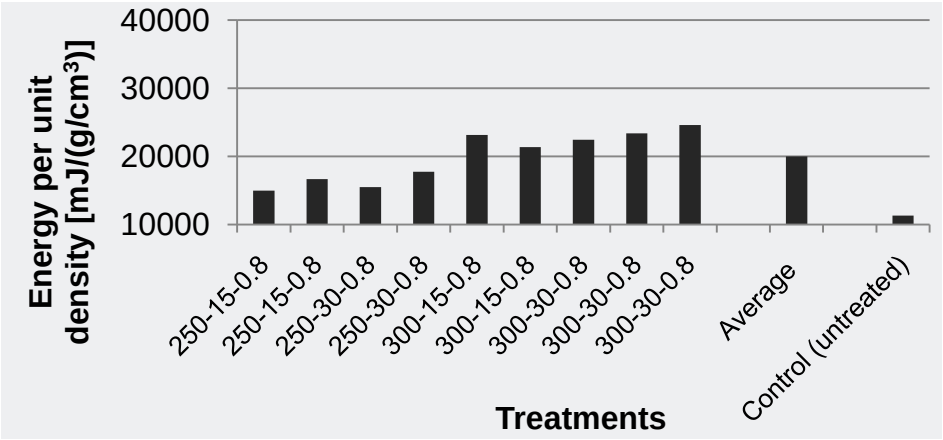


With increasing heat treatment,

- Pellets were hydrophobic, BUT
- More power required to form pellets
- Pellet density decreased
- Durability decreased
- Pellets were darker

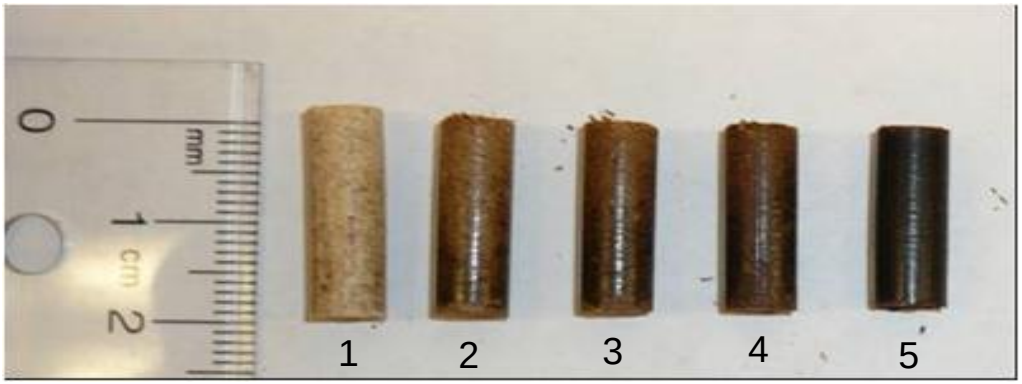


Moisture adsorption - hydrophobicity



Specific energy inputs of pelleting increased with torrefaction

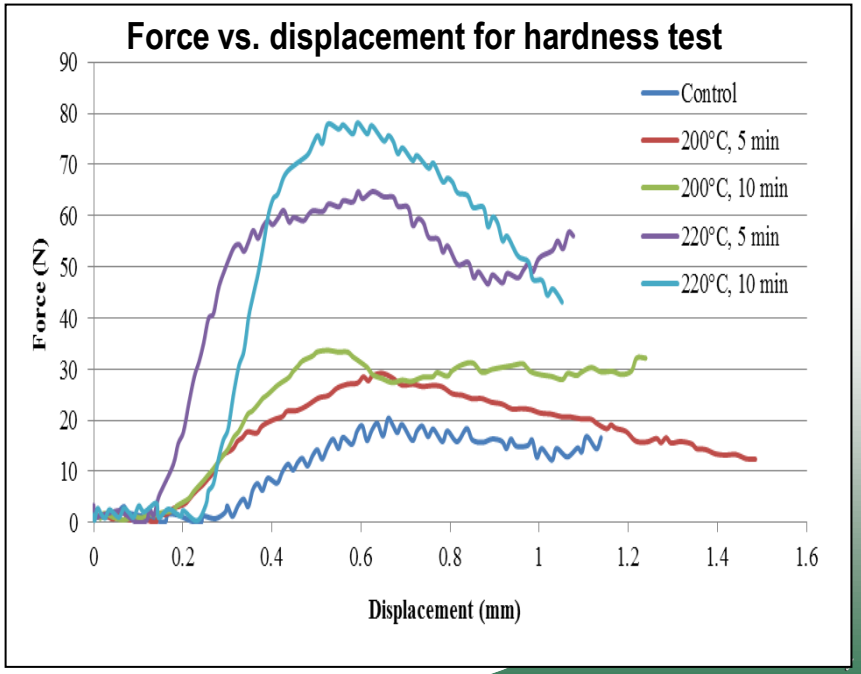
Steam treatment improves properties of pellets



Wood pellets made from steam treated biomass

1. Control
2. 200°C for 5 min
3. 200°C for 10 min
4. 220°C for 5 min
5. 220°C for 10 min

- Pellets of biomass treated with steam at 220°C for 5 minutes showed more than **3 times** higher mechanical strength than that of control pellets
- Pellets of biomass treated with steam also had a **reduced** equilibrium moisture content by **2–4 percentage points** and a **reduced expansion after pelletization**



Technical Accomplishments – Advanced Biomass Processing

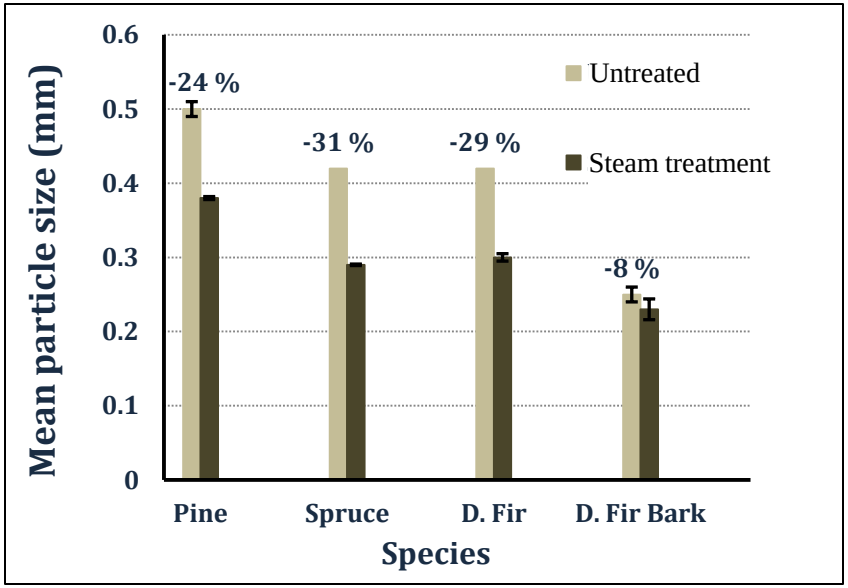
Steam treatment reduces particle size, increases bulk density

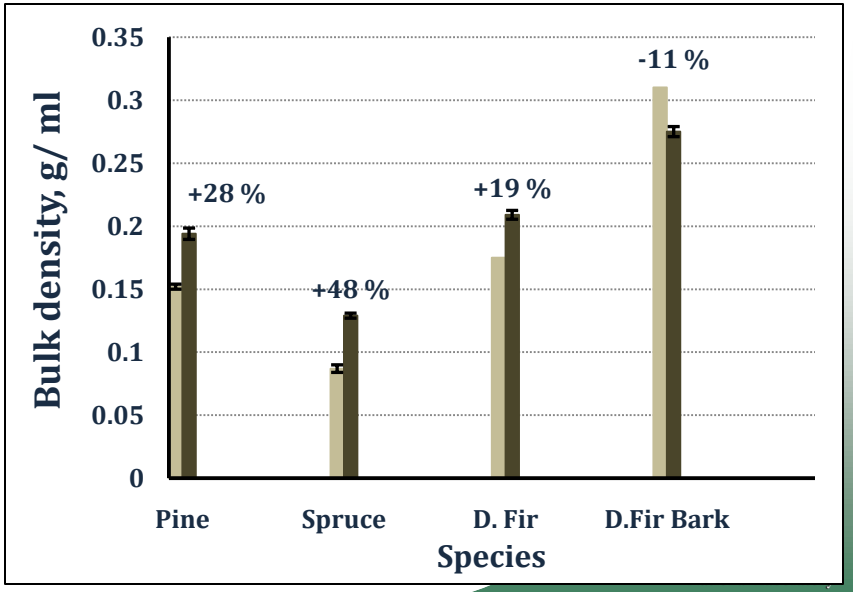
Particle size before and after treatment

- Particles passed 1/8" hammer mill
- Particle size reduced by steam treatment
- Bark had the least reduction in particle size

Bulk density before and after treatment

- Particles passed 1/8" hammer mill
- After steam treatment, bulk density of particles increased except for the bark





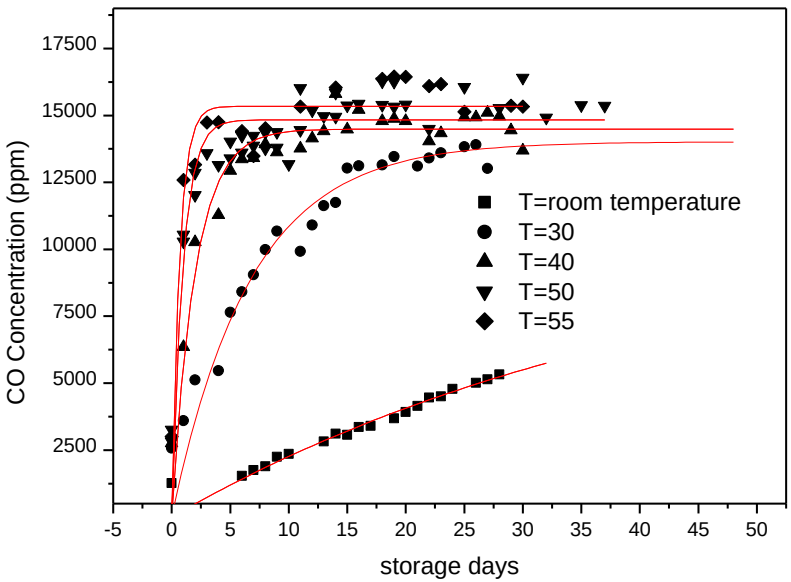
Added benefits of steam treatment, decreased particle size and increased bulk density (except bark)

Bark behaves differently in many processes, may be justification for separation step

Technical Accomplishments - Advanced Biomass Processing

Measuring emissions from pellet storage

Lab-scale pellet storage experiments performed to evaluate emissions from various stored products



Experiments ongoing in large storage container (4' dia, 16' high)

CO_2 and CO emissions from stored pellets. Storage period ended when emissions ceased.

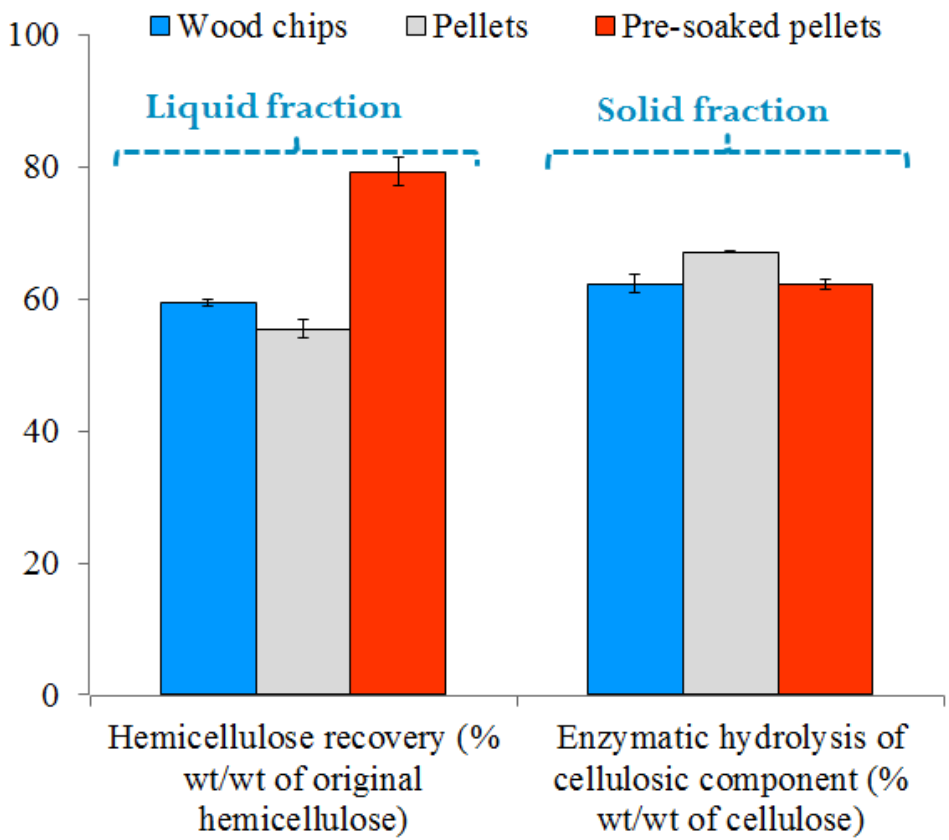
Material	Storage time (days)	CO_2 (ppm)		CO (ppm)	
		20°C	40°C	20°C	40°C
Fine (broken) pellets	56	5,434	38,327	7,662	15,086
Coarse pellets	56	5,128	36,210	5,510	14,334
Low temp Pellets	42	2,156	30,547	335	13,973
Torrified chips	27	12,446	25,084	259	4,833
Switchgrass	56	1,878	43,104	367	8,914

Tumuluru, Kuang, Sokhansanj, Lim, Bi, Melin. 2010. *Canadian Biosystems Engineering* 52: 8.1-8.9

OAK RIDGE National Laboratory

Are pellets similar to wood chips in terms of their suitability for biochemical conversion?

In preliminary experiments, pellets and wood chips behaved similarly during pretreatment and enzymatic hydrolysis of softwood chips



- Pelletization had no adverse effect on feedstock sugar content
- Pellets disintegrated in water easily
- Lower particle size of disintegrated pellets favour enzymatic hydrolysis after steam pretreatment
- Without pre-soaking, high density & dryness of the pellets resulted in slightly higher sugar degradation during steam pretreatment
- Pre-soaking improved hemicellulose sugar recovery of the pellets

Oak Ridge National Laboratory

Relevance

Accomplishments in this project contribute to the Feedstocks Platform strategic goal to "…**develop sustainable technologies to provide a secure, reliable and affordable biomass feedstock supply for the U.S. bioenergy industry** …" (MYPP, 2010)

- Feedstock Supply System Modeling Task
  - Improving accuracy and reliability of feedstock logistics simulations for a variety of feedstocks in wide range of ambient conditions and regional management practices
- Advanced Biomass Processing Task
  - Increasing bulk density of raw biomass and converting it to a flowable feedstock
  - Developing technology for utilizing a wide range of biomass species and plant parts (bark, stemwood, needles, leaves)
  - Reducing the cost and environmental footprint of densification by decreasing energy and power input
  - Increasing storage stability of biomass for one or multi-year storage

OAK RIDGE National Laboratory

Critical Success Factors

- Critical success factors:
  - Feedstock logistics models
    - Consistency in modeling assumptions
    - Broad range of field and lab data used in models to account for variability due to range of feedstocks, technologies, and regions being considered
  - Advanced biomass processing technologies
    - Experimentation to investigate impacts of varying biomass properties and effects on system performance and upstream conversion
    - Developing high-quality, engineered feedstocks that minimizes costs and energy use
- Top challenges

Challenge	Efforts to address
Variability in data and modeling assumptions	• Strengthening collaborative relationships for data and model sharing • Using lab-scale experiments to simulate a wide range of conditions for model calibration and field data for validation
High costs and energy use to achieve high-quality, stable, and flowable feedstock	Experimentation to optimize processing technologies for increased heat and bulk density, hydrophobicity, and mechanical strength

Future Work

- Build collaborations with five high-tonnage logistics projects for developing a common modeling protocol to be used in evaluating new logistics systems and validating models
- Strengthen linkages with resource analysis and sustainability projects as part of efforts to better understand regional differences in feedstock supply system caused by weather, cultural management practices, feedstock type, etc.
- Capitalize on ORNL expertise in transportation modeling to develop stronger joint capability (with INL) in analysis of biomass transport systems
- Optimize pelletization parameters to improve quality of torrified wood pellets and reduce energy requirements of densification
- Additional investigations of behavior of different biomass types and fractions in processing operations (torrefaction, densification, size reduction)

Oak Ridge National Laboratory

Summary

- Project goal: Apply science and engineering fundamentals toward development of mathematical models and advanced biomass processing in support of a commercial feedstock supply for integrated biorefineries
- Primary research activities
  - Develop mathematical models of feedstock supply operations and material processes via collaborative efforts with INL and partners in academia and industry
  - Develop and analyze advanced designs to transform bulky cellulosic feedstocks to a free flowing granular format or to stable packages for ease of handling and efficient transport, storage, and conversion
- Outcomes of this project include:
  - Improving accuracy and reliability of feedstock logistics models
  - Increasing bulk density of raw biomass and converting it to a flowable feedstock
  - Reducing the cost and environmental footprint of densification
  - Increasing storage stability of biomass

Oak Ridge National Laboratory

Oak Ridge National Laboratory:
Meeting the challenges of the 21st century

www.ornl.gov

Response from 2009 Peer Review

- "The costs associated with the collection of the needed data can be considerable and may mean that the time horizon to acquisition of the data could be great"
  - *Agreed. We are relying heavily on lab-scale experiments such as the controlled environment field drying tests and small-scale pellet storage experiments to collect data for model calibration. Controlled, lab experiments allow us to simulate a wide range of conditions. Similar field data would be too costly. We are collaborating with INL, academia, and industry partners to validate models with field data.*
- "Put the model in a form that industry can use and test the value of it"
  - *The IBSAL model developed at ORNL has been shared with some industry and academia partners (including: FDC Enterprises, AGCO, Univ of Nebraska, Univ of Arkansas, Texas A&M University).*
  - *Within the past two years, ORNL has chosen to focus our logistics modeling efforts in this project to applying fundamental engineering science to developing mathematical models of unit operations and biomass material changes. We then work with INL to incorporate the models into their simulation tool which is being designed for public use.*

Oak Ridge National Laboratory

Response from 2009 Peer Review

- "This presentation [from 2009 Peer Review] didn't provide much detail about the analytical approach of IBSAL"
  - *This 2011 presentation seeks to make the mathematical models for the processes (field drying and dry matter loss) and operations (grinding) that we have focused on most recently more transparent.*

- "Validation is a complex process and no details provided on how that will be done"
  - *Calibration and validation of individual mathematical models for unit operations and physical processes (e.g., field drying and dry matter loss) ongoing with lab and field data*
  - *In future work, we plan to work with the five DOE sponsored high-tonnage logistics projects to develop a common simulation framework for which to compare the logistics systems developed in these projects. This is also an opportunity for validation of our models.*

OAK RIDGE National Laboratory

Publications

Selected publications and presentations on modeling and logistics 2009-2011

- Ebadian, Mahmood, Taraneh Sowlati, Shahab Sokhansanj, Mark Stumborg, Lawrence Townley-Smith. 2011. The development and application of a new simulation model for multi-agricultural biomass logistics system in bioenergy production. Accepted with revision. (Biosystems Engineering Journal (UK) 2011-03-15.
- Mobini, M., T. Sowlati, S. Sokhansanj. 2010. Forest biomass supply logistics for a power plant using the discrete-event simulation approach. Applied Energy 88(2011):1241-1250.
- Naimi, L.J., S. Sokhansanj, A.R. Womac, X. Bi, C.J. Lim, C. Igathinathane, A.K. Lau, T. Sowlati, S. Melin, M. Emami, M. Afzal. 2011. Development of a population balance model to simulate fractionation of ground switchgrass. Transactions of the ASABE 54 (1):219-227.
- Stephen, Jamie, Shahab Sokhansanj, Xiatao Bi, Taraneh Sowlati, C. Jim Lim, Mark Stumborg, Lawrence Townley-Smith, Tony Sauder, Trevor Kloeck. 2010. Analysis of Biomass Feedstock Availability and Variability for the Peace River Region of Alberta, Canada. Biosystems Engineering 105(2010):103-111.
- Sokhansanj, S., S. Mani, S. Tagore, A.F. Turhollow. 2010. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant - Part 1: Cost of feedstock supply logistics. Biomass and Bioenergy 34(1):75-81.
- Ghafghazi, S., T. Sowlati, S. Sokhansanj, X. Bi, S. Melin. 2011. Life cycle assessment of base-load heat sources for district heating system options. The International Journal of Life Cycle Assessment (Accepted 2011-01-25)
- Ghafghazi, S., T. Sowlati, S. Sokhansanj, S. Melin. 2010. Techno-economic analysis of renewable energy source options for a district heating project. Accepted International Journal of Energy Research Published online in Wiley Inter Science (www.interscience.wiley.com). DOI: 10.1002/er.1637
- Stephen, Jamie, Shahab Sokhansanj, Xiatao Bi, Taraneh Sowlati, C. Jim Lim, Mark Stumborg, Lawrence Townley-Smith, Tony Sauder, Trevor Kloeck. 2010. The Impact of Biomass Feedstock Supply Variability on the Delivered Price to a Biorefinery in the Peace River Region of Alberta, Canada 105(2010) 298-305.
- Sokhansanj, S., S. Mani, C. Igathinathane, Sam Tagore. 2010. Heat and power production from stover for corn ethanol plants. In Plant Biotechnology for Sustainable Production of Energy and Co-products, ed. P.N. Mascia et al. (eds) Biotechnology in Agriculture and Forestry 66, Springer – Verlag Berlin Heidelberg. Pages 345-362
- Sokhansanj, S., S. Mani, A. Turhollow, A. Kumar, B. Bransby, L. Lynd, M. Laser. 2009. Large scale production, harvest and logistics of switchgrass (*Panicum vigatum L.*) – current technology and envisioning a mature technology. Biofuel, Bioproduct, Biorefinery (2009) 3:124-141.

Publications

Selected publications and presentations on Advanced Processing 2009-2011

- Lam, P.K., S. Sokhansanj, C.J. Lim, X. Bi, S. Melin. 2011. Energy Input and Quality of Pellets Made from Steam Exploded Douglas Fir (*Pseudotsuga menziesii*). Accepted Journal of Energy & Fuel (2011-02-15)
- Tumuluru, Jaya Shankar, Xingya Kuang, Shahab Sokhansanj, C. Jim Lim, Tony Bi, and Staffan Melin. 2010. Development of laboratory studies on the off-gassing of wood pellets. Canadian Biosystems Engineering. 52: 8.1-8.9.
- Bitra, V.S.P., A.R. Womac, C. Igathinathane, S. Sokhansanj. 2010. Knife mill comminution energy analysis of switchgrass, wheat straw, and corn stover and characterization of particle size distribution. Transactions of the ASAE 53(5):1639-1651.
- Igathinathane' A. W. Womac, S. Sokhansanj. 2010. Corn stalk orientation effect on mechanical cutting. Biosystems Engineering 107(2010): 97-106.
- Nehru Chenvanan, Alvin R. Womac, Venkata S. P. Bitra, C. Igathanathane, YueChuan T. Yang, Petre I. Miu, Shahab Sokhansanj. 2010. Bulk density and compaction behavior of knife mill chopped switchgrass wheat straw and corn stover. Bioresource Technology 101(2010) 207-214
- Liu, Lu, X. Philip Ye, Alvin R. Womac, and Shahab Sokhansanj. 2010. Variability of biomass chemical composition and rapid analysis using FT-NIR techniques. Carbohydrate Polymers 81 (2010):820-829.
- Yazdanpanah, F., S. Sokhansanj, A.K. Lau, C.J. Lim, X. Bi, S. Melin, M. Afzal. 2010 Permeability of Wood pellets in the presence of Fines. Bioresource Technology 101 (2010):5565-5570.
- Igathinathane, C., Jaya Shankar Tumuluru, S. Sokhansanj, X. Bi, C.J. Lim, S. Melin, E. Mohammad. 2010. Simple and inexpensive method of wood pellets macro-porosity measurement. Bioresource Technology 101 (2010):6528-6537.
- Afzal, M.T., A.H. Bedane, S. Sokhansanj, W. Mahmood. 2010. Storage of comminuted forest biomass and its effect on fuel quality. BioResource 5(1):55-69.
- Bitra, Venkata S.P., Alvin R. Womaca, Yuechuan T. Yang, Petre I. Miu, C. Igathinathane, Shahab Sokhansanj. 2009. Mathematical model parameters for describing the particle size spectra of knife-milled corn stover. 104(2009):369-383.
- Kuang , Xingya, Tumuluru Jaya, Shankar, Shahab Sokhansanj, C. Jim Lim, Xiaotao T. Bi, Staffan Melin. 2009. Effects of Headspace Volume Ratio and Oxygen Level on Off-gas Emissions from Stored Wood Pellets. Annals of Occupational Hygiene 53(8):807-813
- Igathinathane, C., S. Melin, S. Sokhansanj, X.T. Bi, C.J. Lim, L.O.Pordesimo, E.P. Columbus. 2009. Machine vision based particle size and size distribution determination of airborne dust particles of wood and bark pellets. Powder Technology 196 (2009):202-212.
- Sokhansanj, S. J. Peng, J. Lim, X. Bi. 2010. Optimum Torrefaction and pelletization of biomass feedstock . TCS 2010 Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, Iowa State University, Ames, Iowa September 21-13, 2010

Publications

Selected publications and presentations on Advanced Processing 2009-2011 (continued from previous slide)

- Bitra, V.S.P., A. Womac, C. Igathinathane, P.I. Miu, Yuechuan T. Yang, David. Smith, N. Chevanan, S. Sokhansanj. 2009. Direct mechanical energy measures of knife mill size reduction of switchgrass, wheat straw, and corn stover. Bioresource Technology 100 (2009):6578-6585.
- Kuang , Xingya, Tumuluru Jaya Shankar, Xiaotao T. Bi, C. Jim Lim, Shahab Sokhansanj, Staffan Melin. 2009. Rate and peak concentrations of off-gas emissions in stored wood pellets—sensitivities to temperature, relative humidity, and headspace volume. Annals of Occupational Hygiene 53(8):789-796.
- Bitra, Venkat S.P., Alvin R. Womac , Yuechuan T. Yang , C. Igathinathane, Petre I. Miu, Nehru Chevanan, Shahab Sokhansanj. 2009. Knife mill operating factors effect on switchgrass particle size distributions. Bioresource Technology. 100(2009):5176-5188.
- Nehru C., A.R. Womac, V.S. P. Bitra, D. C. Yoder, S .Sokhansanj. 2009. Flowability parameters for chopped switchgrass, wheat straw and corn stover. Powder Technology 193(2009) 79-86.
- Igathinathane, C., L.O. Pordesimo, E.P. Columbus, W.D. Batchelor, S. Sokhansanj. 2009. Sieve less particle size distribution analysis of particulate materials through computer vision. Computers and Electronics in Agriculture. Computers and Electronics in Agriculture, 66(2):147-158.
- Bitra, V.S.P., A. Womac, N. Chevanan, P.I. Miu, C. Igathinathane, S. Sokhansanj, D. Smith. 2009. Direct mechanical energy measures of hammer mill comminution of switchgrass, wheat straw, and corn stover and analysis of their particle size distributions. Powder Technology 193 (2009) 32-45.
- Igathinathane, C., Pordesimo, L. O., Womac, A. R., and Sokhansanj, S. 2009. Hygroscopic moisture sorption kinetics modeling of corn stover and its fractions. Applied Engineering in Agriculture, 25(1):65-73.
- Igathinathane, C. A. R. Womac, S. Sokhansanj, S. Narayan. 2009. Size reduction of high and low moisture corn stalks by linear knife grid system. Biomass & Bioenergy 33(2009):547-557.
- Zaini, P. , S. Sokhansanj, X. Bi, S. Mani, J. Kadla. 2009. Density, heating value, and composition of pellets made from lodgepole pine (*Pinus concorta* Douglas) infested with Mountain Pine Beetle (*Dendroctonus ponderosae* Hopkins). Canadian Biosystems Engineering 50:3.47-3.55.

Book Chapters

- Sokhansanj, S., J. Richard Hess. 2009. Biomass Supply Logistics and Infrastructure. Biofuels Methods and Protocols. Jonathan Mielenz (ed) Humana Press, New York. Pp 1-25.
- Ileleji, K.E., S. Sokhansanj, J.S. Cundiff. 2010. Farm gate delivery of lignocellulosic feedstocks from plant biomass for biofuel production. In Biofuels from agricultural wastes and byproducts. Ed: Hans P. Blaschek, Thaddeus C. Ezeji and Jurgen Sheffran. Willey-BlackwellAmes IA. Pages 117-160.

OAK RIDGE National Laboratory