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Biochemical Feedstock Interface

BETO 2015 Project Peer Review

WBS 2.2.1.100, 2.2.1.101, & 2.2.1.102

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Goal Statement

Goal:

- Understand the impact of feedstock logistics & preprocessing on blend conversion performance

Relevance to BETO and Industry:

- Enable access to a variety of biomass resources for development of a sustainable and economical biomass supply chain for biofuel production
  - Low-quality, low-cost resources (non-recyclable/waste)
- Inform the bioenergy industry on use of feedstock blending and preprocessing to enable logistics and achieve bioconversion targets

Outcome:

- Reduce risk to the supply chain by enabling access to a variety of biomass resources for biofuel production

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Quad Chart Overview

Timeline

- Start date: 2005
- End date: 2017
- Percent complete: 83%

Budget

	Total Costs FY 2010 to FY 2012	FY 2013 Costs	FY 2014 Costs	Total Planned Funding (FY 2015 to Project End Date)
DOE Funded	$4,927K	$1,798K	$2,056K	$5,923K
Project Cost Share (Comp.)*				

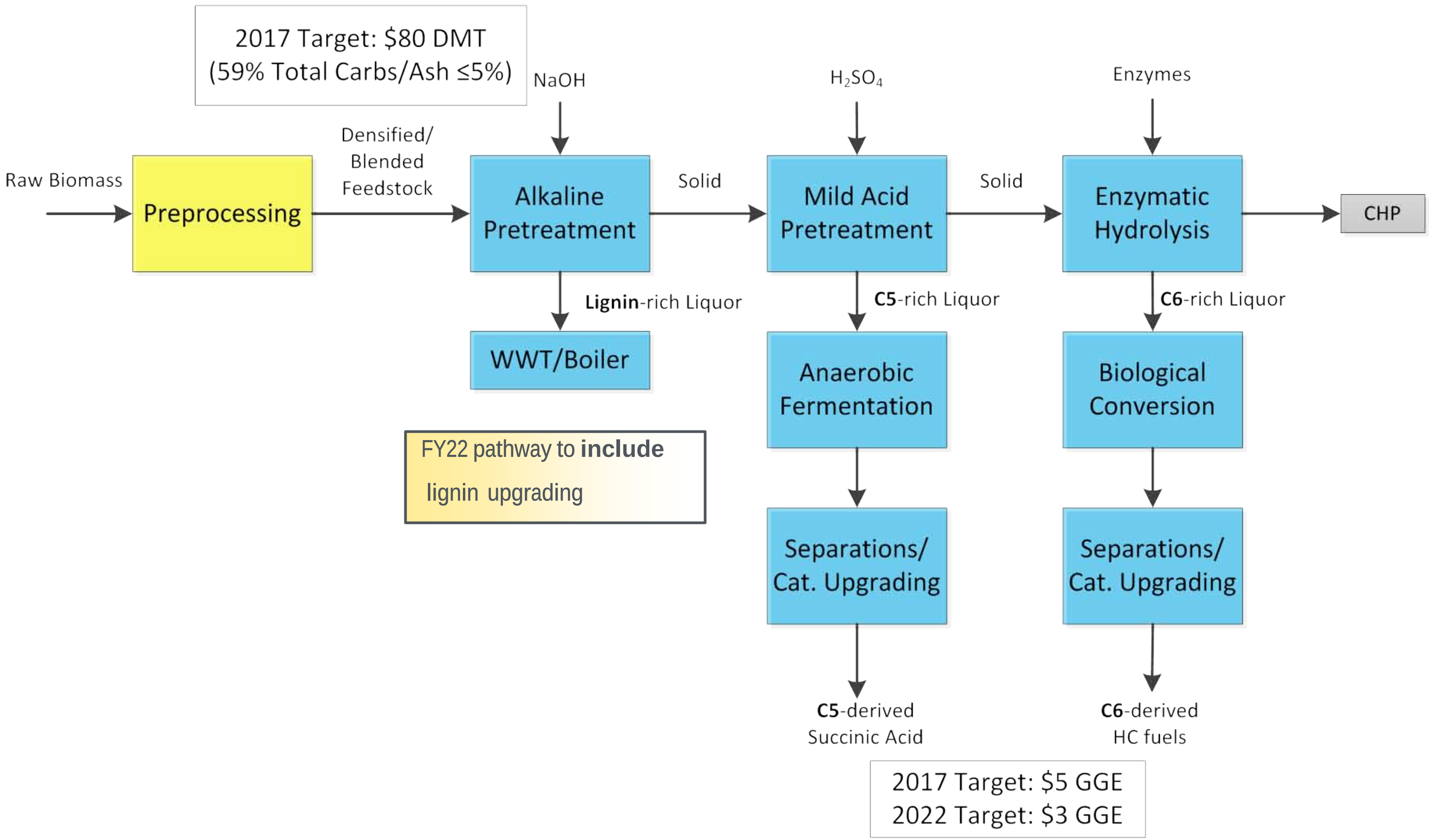
Barriers

– Ft-A, Feedstock Availability and Cost
– Ft-G, Feedstock Quality and Monitoring
– Bt-A, Biomass and Feedstock Variability

Partners

– Idaho National Laboratory: Analysis, Conversion & Feedstock Tasks
– National Renewable Energy Laboratory
– USDA, Agricultural Research Service
– DOE Regional Feedstock Partnership
– MBI International

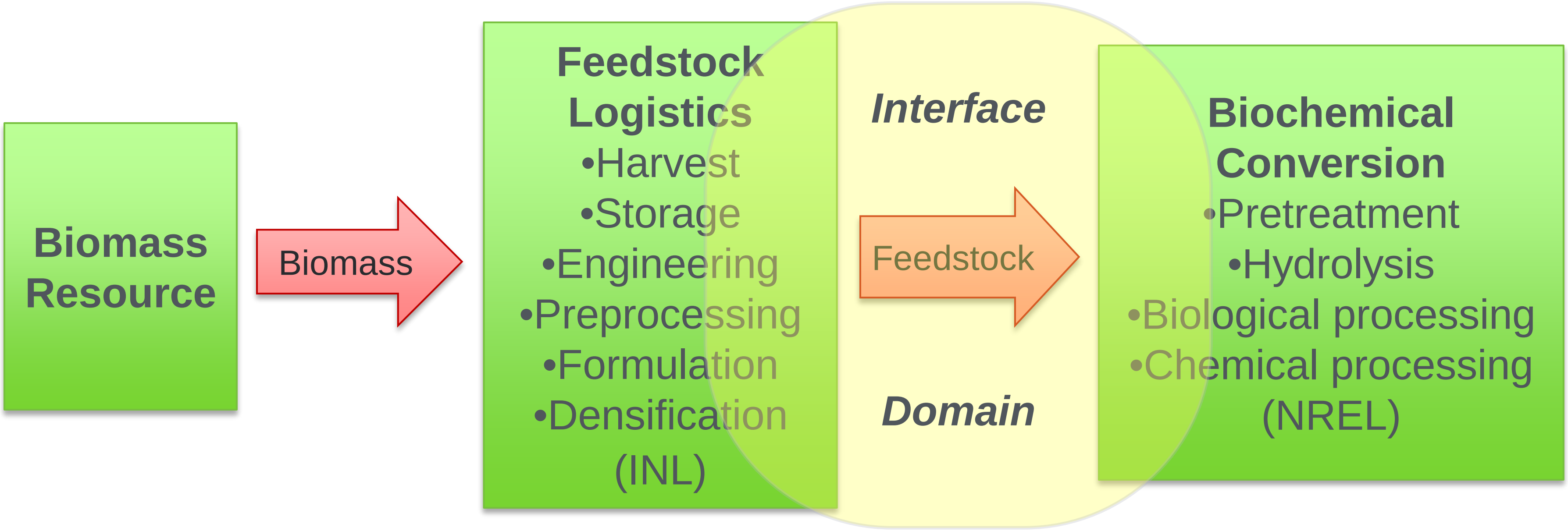
Biochemical Conversion: Path to 2017



1 - Project Overview

Objectives

1. Characterize high-impact feedstocks to identify specification "targets" and "performs like" model feedstocks
2. Provide consistent research and bulk material resources to BETO researchers
3. Enable logistics and optimize biochemical conversion performance using feedstocks/formats



1 - Project Overview

History

- INL and NREL paper was one of the earliest to demonstrate enhanced sugar yields for DAPT of *pelleted* corn stover at high-solids loading
- FDCI: Subtask in FY14 to address the effects of densification and blending on the potential for lignin upgrading

Context

- Major hurdle to economic viability is the cost to access biomass
- Blended feedstock strategy takes advantage of lower end of multiple supply curves to reduce cost
- Ability to apply specifications to feedstocks, ensuring both quality and quantity
- **Reduces risk to the supply chain**

2nd Objectives

- Measure the effects of blending on quality and conversion performance
- Quantify the impacts of blending and preprocessing on the potential to contribute value-added chemicals from both sugars and lignin
- Incorporate performance data into TEAs

2 - Technical Approach

Critical Success Factors

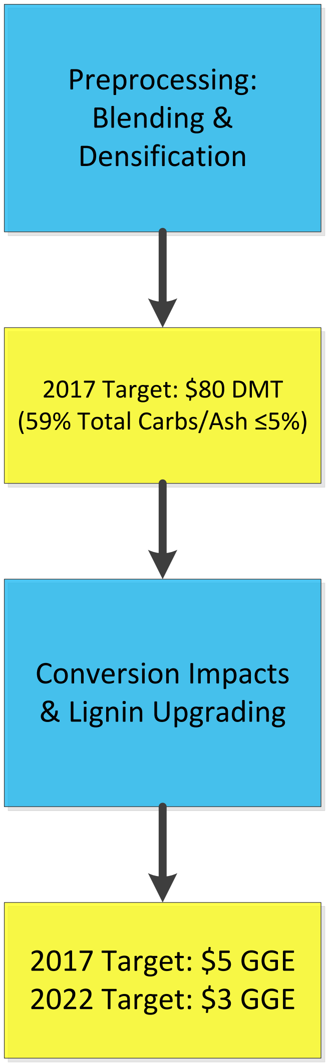
- Quantifying the effects of feedstock logistics, blending, and preprocessing on conversion performance
  - Value-added chemicals derived from *sugars and lignin*
- Developing models for prediction of blend composition and performance
- Developing optimized blends capable of meeting 2017 and 2022 performance and cost targets in support of biological conversion of sugars to hydrocarbons

Challenges

- Heterogeneity of feedstock mixtures
- Predicting blend composition and performance
  - Do all blends behave as linear mixtures of their constituents?

Approach

- Leverage characterization data to select feedstocks for blends that meet quality targets (59% CHOs); blends informed by analysis task
- Screen pretreatment efficacy and enzymatic digestibility (INL)
- *Bench-scale to continuous conversion processes under process-relevant conditions for production of sugars and lignin-derived co-products (NREL)*



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2 - Management Approach

Critical Success Factors

- Integration of targets for Biochemical Conversion and Feedstock Logistics
- Collaboration between INL and NREL projects strengthens impact of results
  - Laboratory partners broaden expertise, perspective, and technical capabilities
  - Inter-project communication of results drives progress
- Enable BETO mission to transform renewable biomass resources into commercially viable, high-performance biofuels and bioproducts

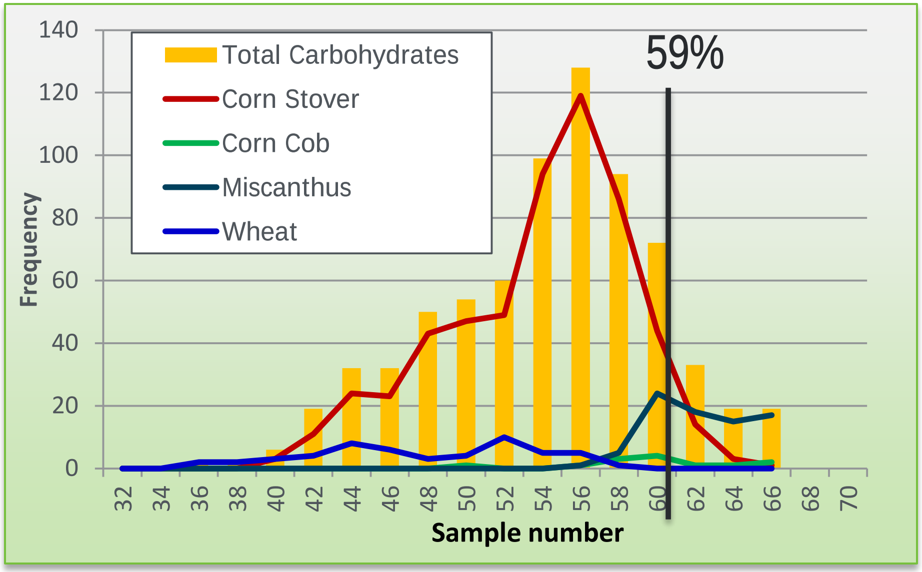
Challenges

- Inter-laboratory data integration from analysis and feedstock logistics through conversion
- Staffing and time constraints
- Infinite blend permutations
- Moving from batch conversion testing to continuous bioconversion at biorefinery scale

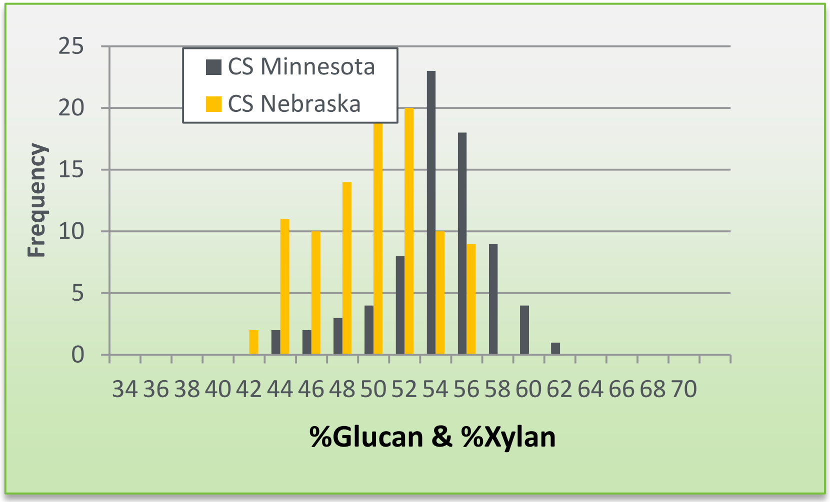
Approach

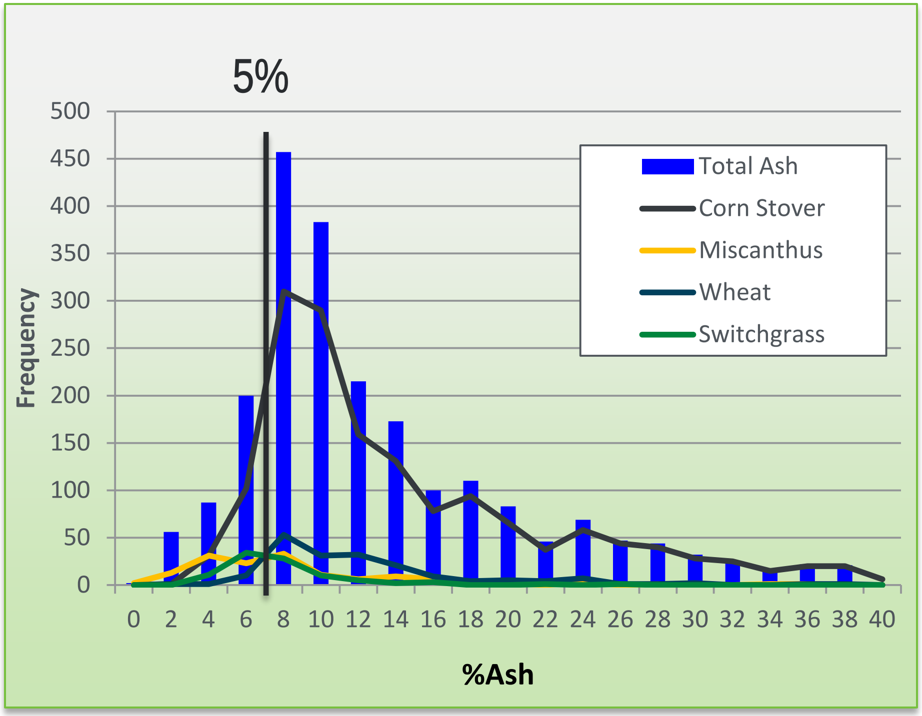
- Planning meetings and monthly calls
- Collaborative AOP and milestone development to achieve FY 2017 demonstration
- Collaboration enables results that span analysis, feedstock, and conversion platforms

Variability in Biomass - Challenge for Biorefinery



- Integrating the needs and requirements of BC conversion with limitations (variability) of biomass
- Cost and specification constraints





Obtained from Garold Gresham, Idaho National Laboratory

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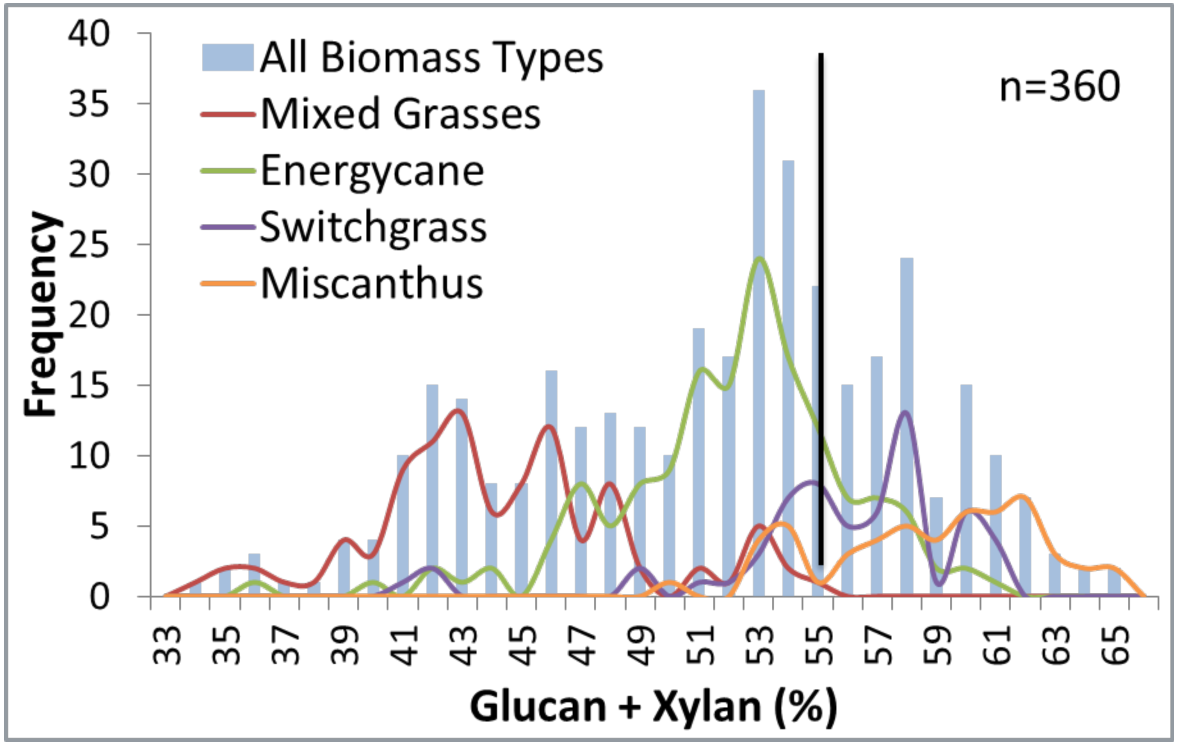
3 – Key Technical Accomplishments

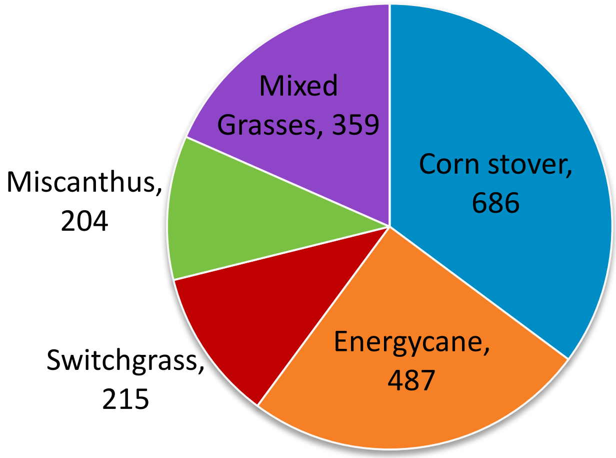
- Focus for FY13-FY15 emphasized densification and blending of feedstocks
  - Feedstocks - type, source and pedigree
    - Acquire data for high-impact feedstocks
    - Examined feedstock quality and performance in response to drought
  - Blending and densification strategies
  - Reduced energy required for pelleting blended feedstocks
  - Bench-scale reactivity testing:
    - Reactivity testing in densified feedstocks
    - Prediction of blend performance
  - Mid-scale testing using larger reactor systems to map blend and densified feedstock performance
  - Lignin recovery and potential upgrading potential (<u>new focus for FY14)</u>

Regional Feedstock Partnership

- Incorporated in the Bioenergy Feedstock Library
  - 2009 thru 2014 sample sets; n≈3000
  - Compiled pedigree and analytical data
- Collected quality data for “high impact” FSs
- Data supports RFP Synthesis & Design Case Report, SOT, blend options & Analysis



NIR Predicted Composition
n=2037



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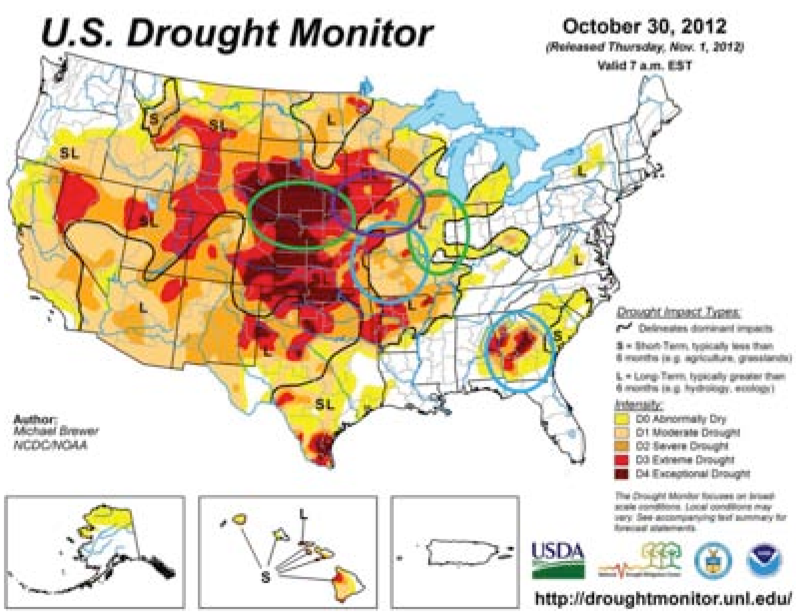
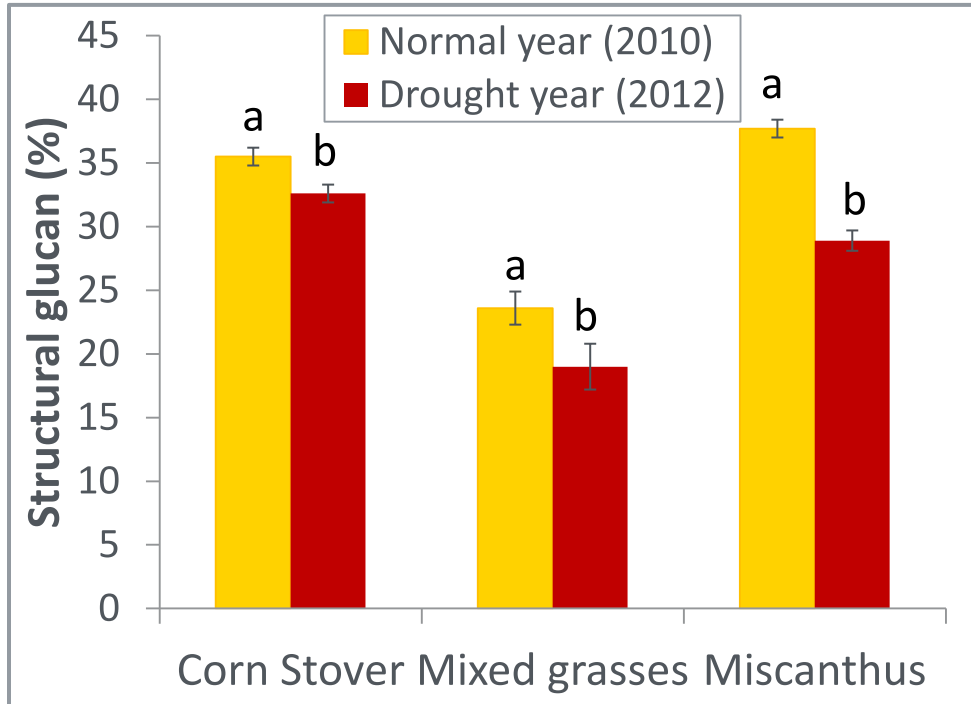
Regional Feedstock Partnership (continued)

Drought Impacts:

- Dry biomass yields were lower for mixed grasses and *Miscanthus*
- Feedstock composition was significantly different
- Theoretical ethanol yield decreased by 10 to 15%





"Drought effects on composition and yield for corn stover, mixed grasses, and *Miscanthus* as bioenergy feedstocks," *Biofuels* 5(3): 275-291, 2014.

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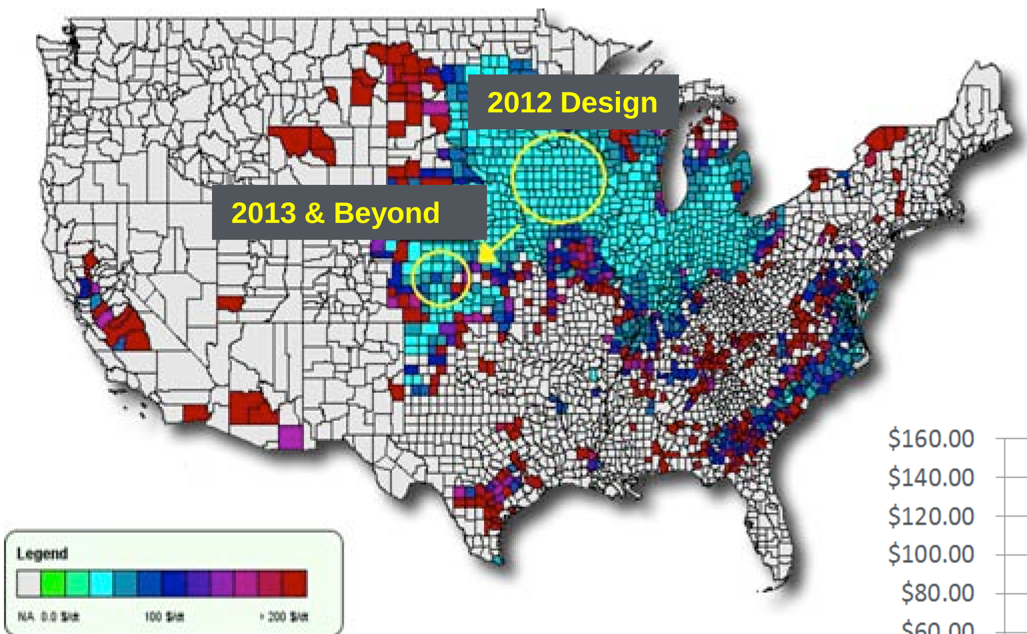
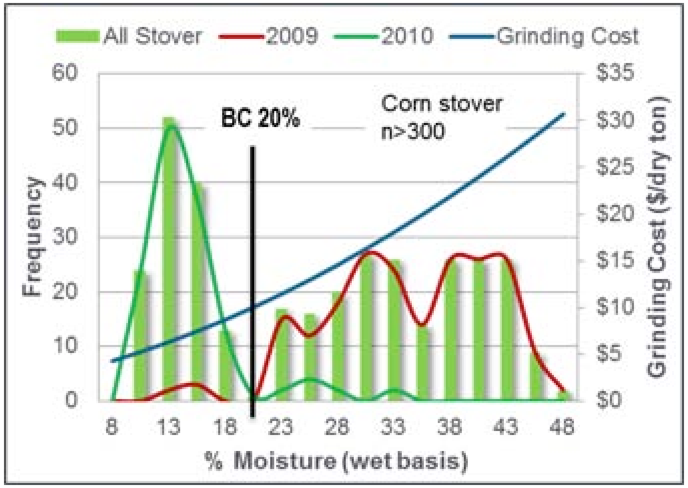
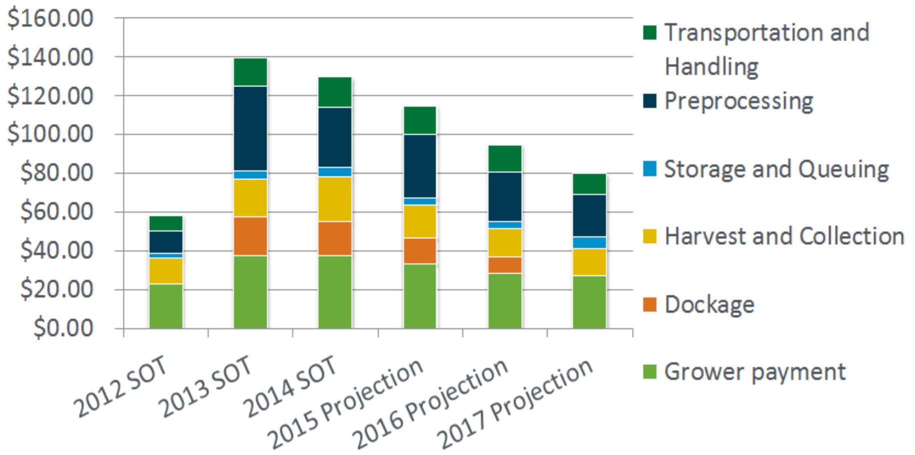
2017 Design: Industry Relevant Supply System







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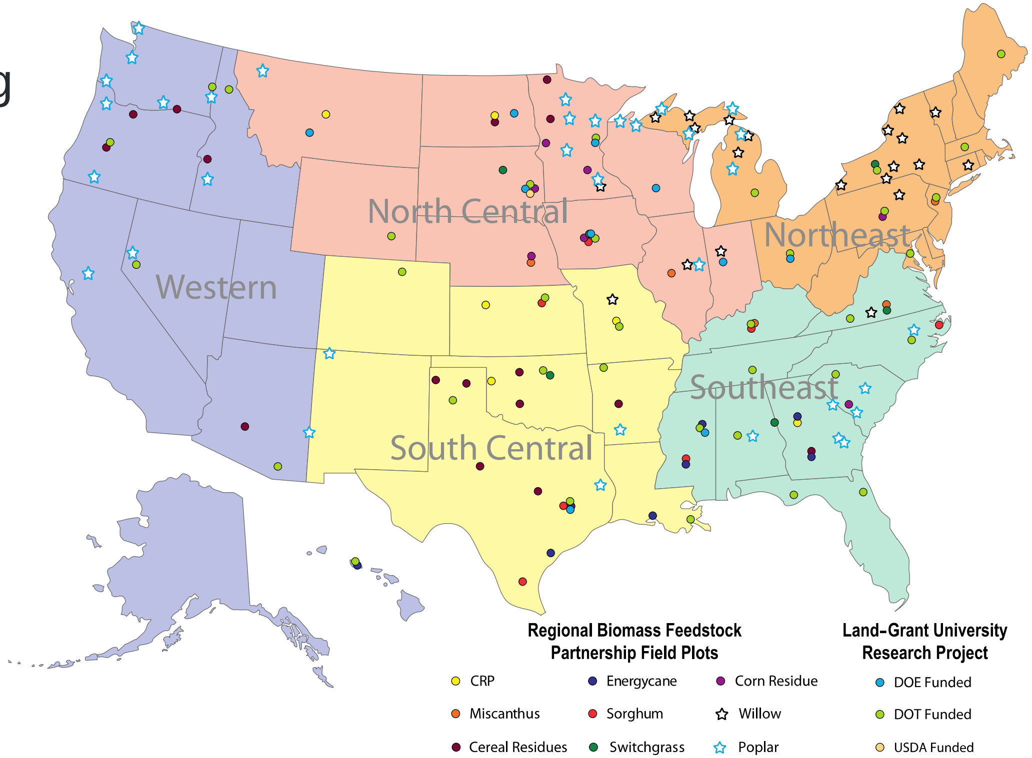
Feedstock and Blend Selection (FY 2014)

- Collected feedstocks successfully grown in RP field trials for blending and densification experiments/testing
- Provides realistic view of potential for co-location of bioenergy feedstocks
- Hybrid poplar has unique lignin composition when compared to herbaceous materials, requires higher severity PT conditions
  - Offers insight to how preprocessing alters lignin in woody versus herbaceous biomass
  - Potential for lignin upgrading in woody versus herbaceous biomass
- Selection of three binary blends and one ternary blend (CS+SWG+HP) for comparison to single species feedstock



Feedstock	Single Species	Binary Blend	Ternary Blend
Corn Stover (CS)	X	CS + SWG	CS + SWG + HP
Switchgrass (SWG)	X		
Poplar (HP)	X		

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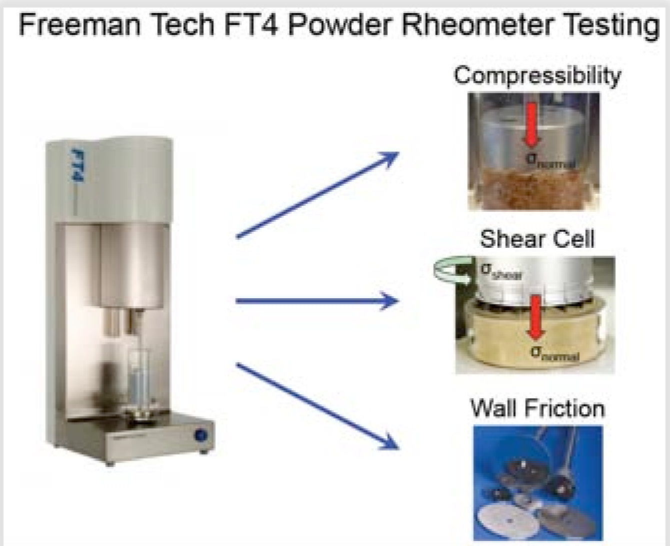
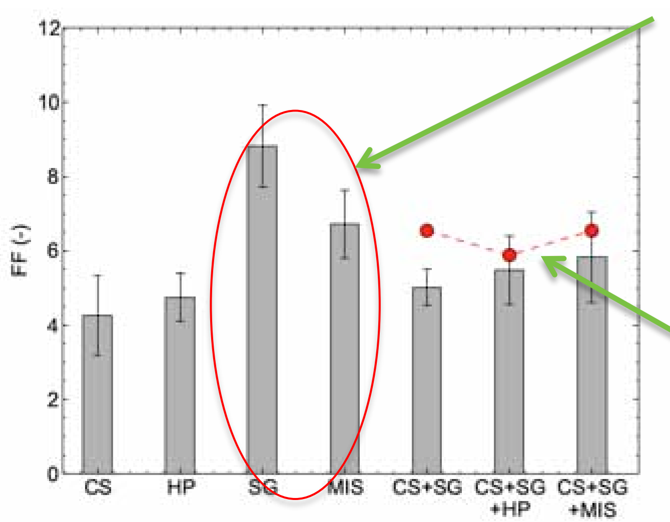
Blend Properties - How Well do They Flow?

- Can we predict blend/pellet performance at continuous scale?
- How do these materials flow inside a feeder?
- Are they compressible?
- Do blended feedstocks have different rheological properties?
- What mixing properties will they exhibit after pretreatment?



Higher resistance

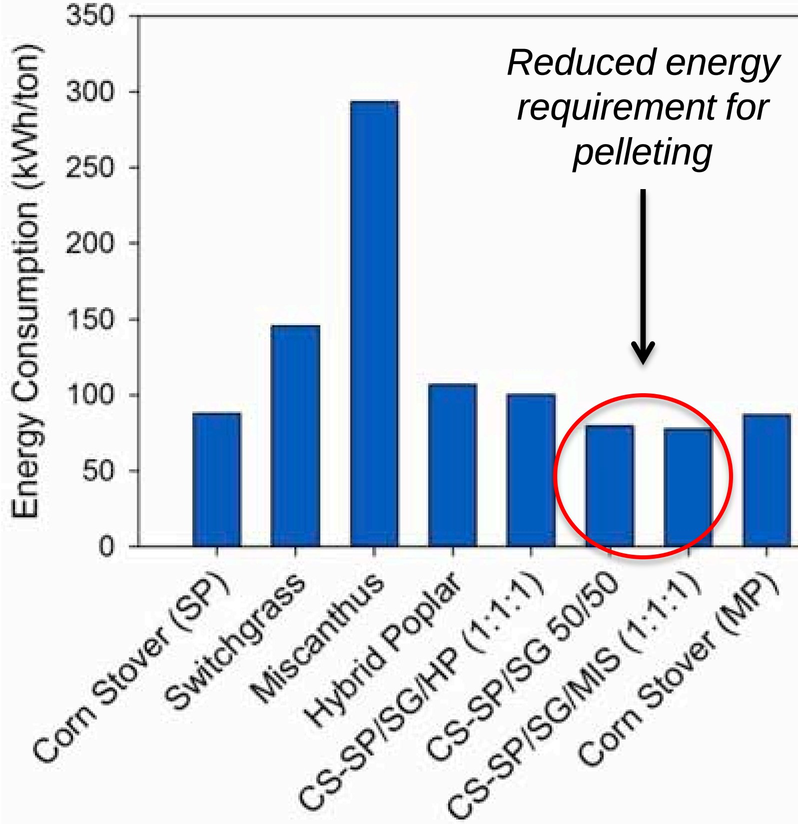


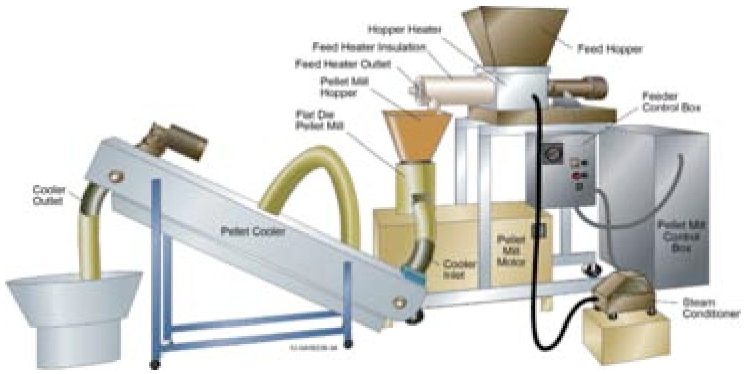
Flow function of single feedstocks and INL blends

- Predicting flow behavior in screw feeders in pretreatment reactors is a critical criteria
- Assessment of particle size, wall friction, and compressibility to predict feedstock flow
- *Blended feedstocks have better flow behavior*

Energy Consumption for Pelleting

- Electrical energy consumption measured during pelleting
- Production of *Miscanthus* pellets required highest energy input
- Pelleted blends required similar energy inputs to pure CS





"Evaluating the Pelletization of Pure and Blended Lignocellulosic Biomass Feedstocks," in preparation for submission to *Fuel Processing Technology*

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Blend Composition - Achieving Carbohydrate Content

Feedstock	% Total Ash	% Lignin	% Glucan	% Xylan	% Galactan	% Arabinan
SP-CS	6.89	15.78	36.92	21.19	1.55	3.46
SWG	4.24	18.53	36.59	23.15	1.63	3.58
MSW paper A	11.40	7.20	64.07	10.78	0.85	3.17
MIS	3.67	18.38	39.67	20.34	0.00	2.85
CS-SP/SWG 50/50	5.72	17.09	37.07	22.61	1.60	3.51
CS-SP/SWG/MSW (65/25/10)	5.47	15.24	41.64	21.43	1.28	2.83
CS-SP/SWG/MSW (75/15/10)	5.89	14.66	41.49	20.92	1.33	2.82
CS-SP/SWG/MIS (33/33/33)	3.55	17.85	39.23	23.09	1.08	2.80
CS-SP/SWG/MIS(65/25/10)	4.41	17.00	38.58	23.38	1.41	3.00
CS-SP/SWG/MIS (75/15/10)	5.02	16.82	38.52	22.90	1.31	2.92

> 59% Carbohydrates

>66% Carbohydrates

Prediction	% Glucan	% Xylan
CS-SP/SWG 50/50	36.8	22.2

Predicted < measured by ~0.4%

Compositional Analysis

- *All feedstocks and blends exceed the 59% carbohydrate target*
- *Several of the blends and MSW exceed 66% total carbohydrates*

Foundational Research on Feedstock Conversion Performance

- Does densification render biomass more recalcitrant to dilute-acid PT and EH?

- INL & NREL paper was one of the earliest to demonstrate that pelleting did *not* render corn stover more recalcitrant to DAPT under low- or high-solids conditions, & even *enhanced* sugar and ethanol yields

- Growing body of literature shows a neutral or positive effect of pelleting on sugar yields from biomass

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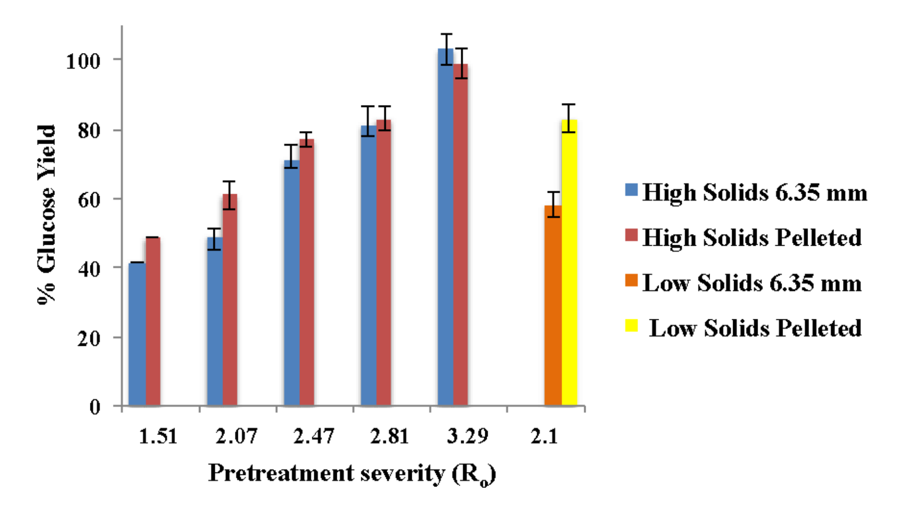
RESEARCH ARTICLE

Effect of pelleting on the recalcitrance and bioconversion of dilute-acid pretreated corn stover under low- and high-solids conditions

Biofuels (2013) 4(3), 271-284

Allison E Ray*[1], Amber N Hoover[1], Nick Nagle[2], Xiaowen Chen[2] & Garold L Gresham[1]

Background: Knowledge regarding the performance of densified biomass in biochemical processes is limited. The effects of densification on biochemical conversion are explored here. **Results:** Pelleted corn stover samples were generated from bales that were milled to 6.35 mm. Low-solids acid pretreatment and simultaneous saccharification and fermentation were performed for pelleted and ground stover (6.35 and 2 mm) formats. Monomeric xylose yields were significantly higher for pellets (~60%) than for ground formats (~38%). Pellets achieved approximately 84% of theoretical ethanol yield; ground stover formats had similar profiles, reaching approximately 68% theoretical ethanol yield. Pelleted and 6.35-mm ground stover were evaluated using a ZipperClave® reactor under high-solids, process-relevant conditions for multiple pretreatment severities (Ro); feedstock reactivity increased slightly following combined pretreatment and enzymatic hydrolysis for three of five severities tested. **Conclusion:** Pelleting did not render corn stover more recalcitrant to dilute-acid pretreatment under low- or high-solids conditions, and even enhanced ethanol yields.



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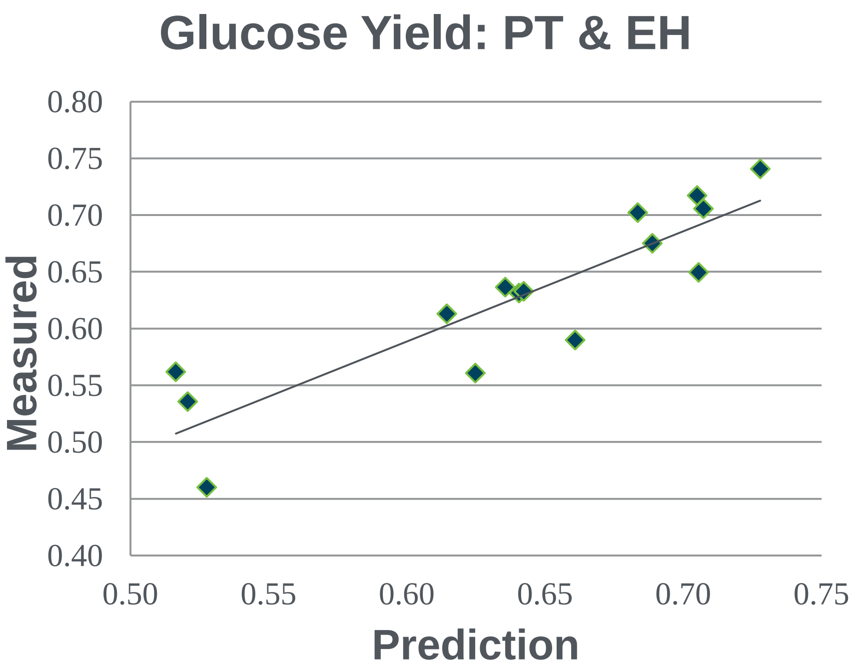
Measured vs. Predicted Glucose Yields from PT/EH

- Glucose yields from combined PT and EH were measured for 15 blends at various ratios
  - CS/SWG/MSW (MSW=paper fraction)
  - CS/SWG/MIS
- Paired t-test was used to compare measured yields to yields predicted from constituent feedstocks
- There were no significant differences in measured versus predicted glucose yields from combined PT/EH for blends
  - p-value=0.1869
  - CI=[-0.0069 0.0322]
  - t-statistic=1.3878
  - df=14
  - sd=0.0353



Root Mean Squared Error: 0.0366
R^2: 0.79, **Adjusted R^2:** 0.774
F-statistic versus constant model: 49
p-value = 9.3e-06

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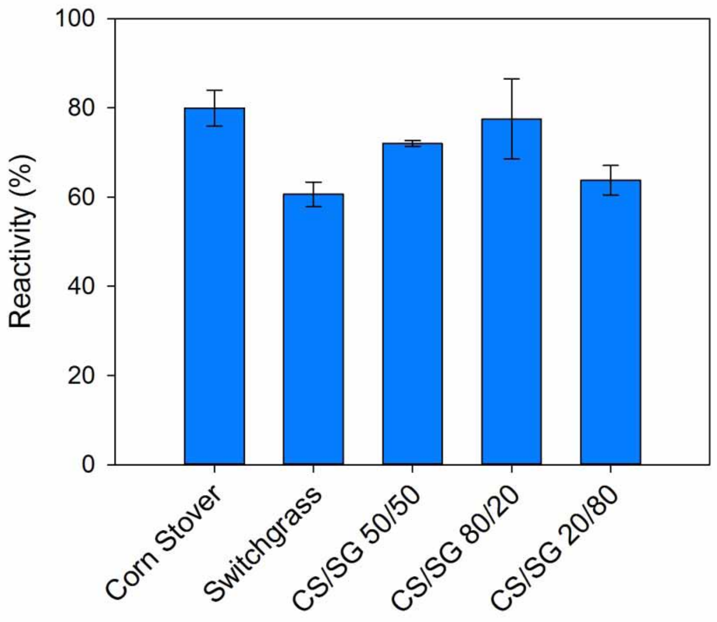
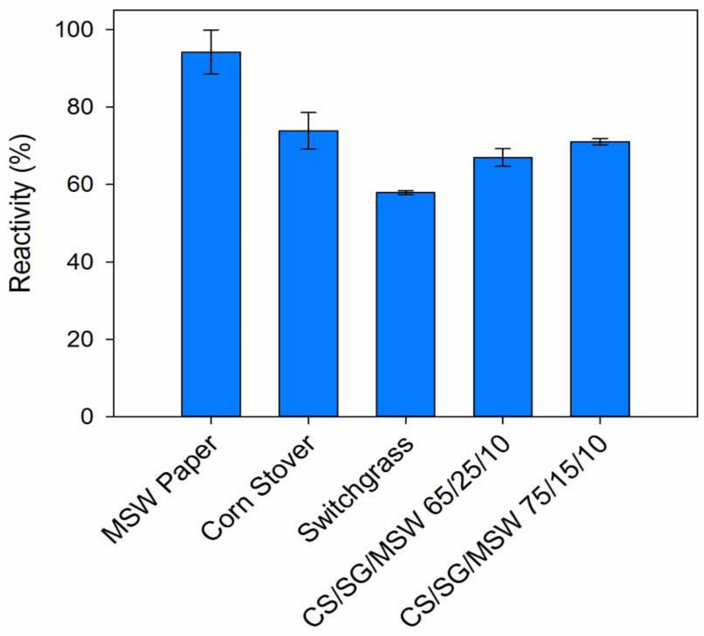
Blend Reactivity

Reactivity=(xylose+glucose)released/(xylose+glucose)initial

- No significant difference in reactivity among CS, 50/50, or 80/20 CS/SG blends
- Binary blends performed like CS





- MSW paper fraction had highest reactivity
- No significant difference in reactivity between corn stover and CS/SG/MSW blends

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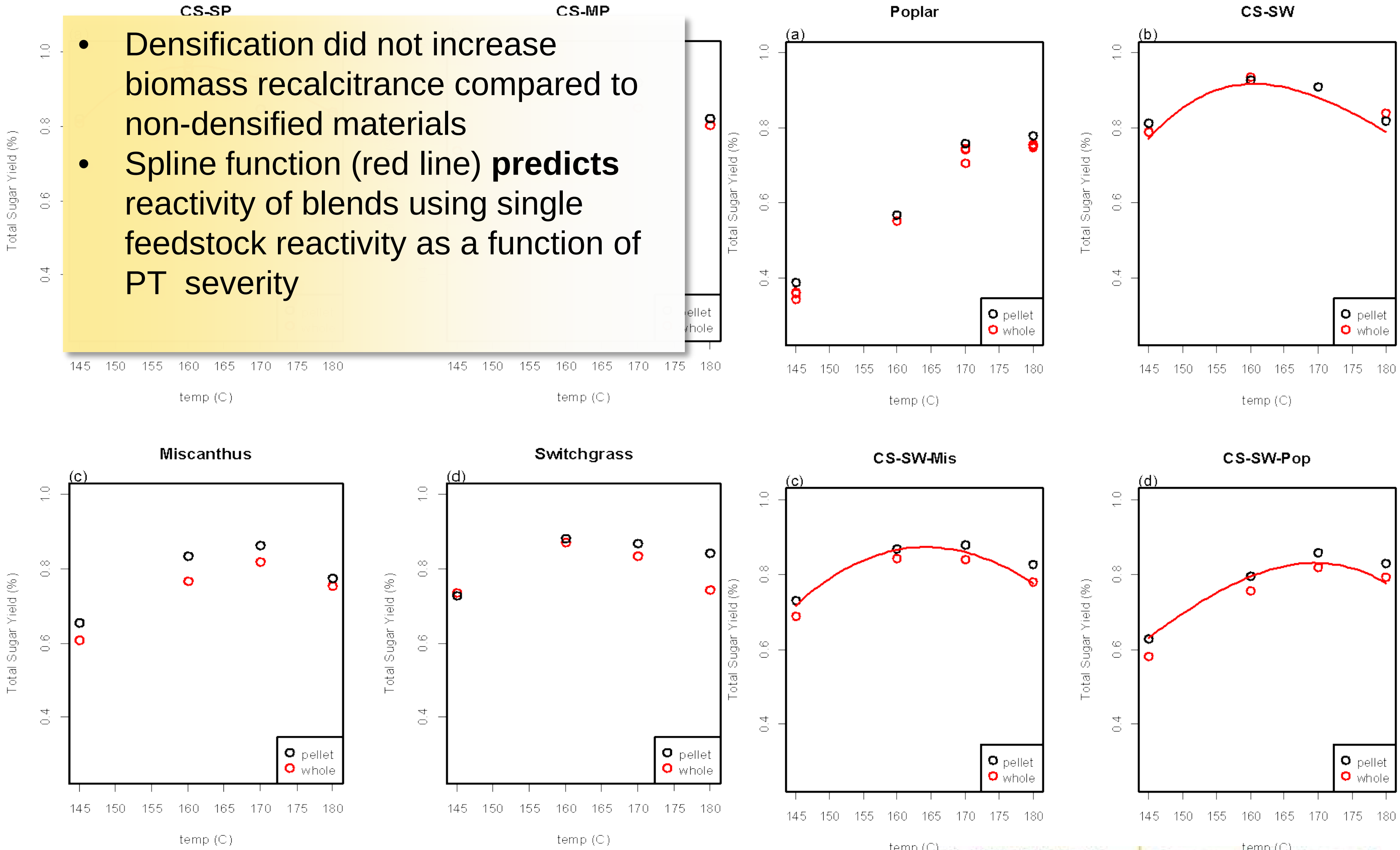
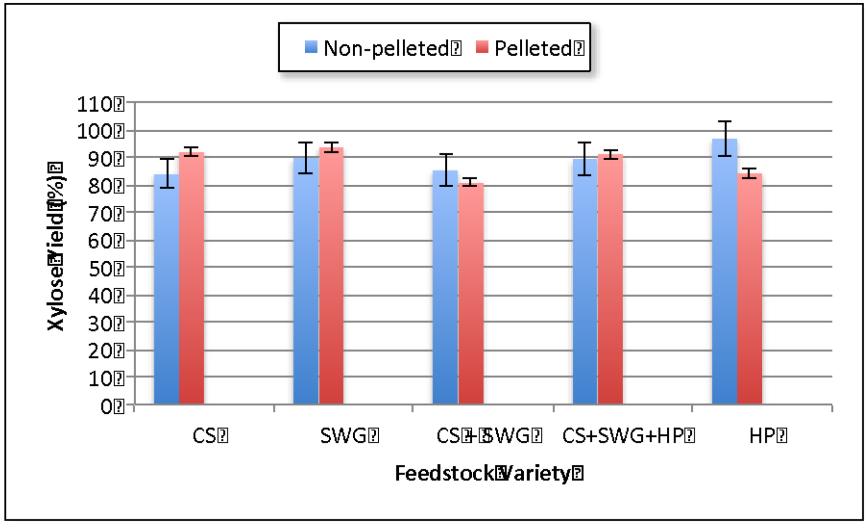
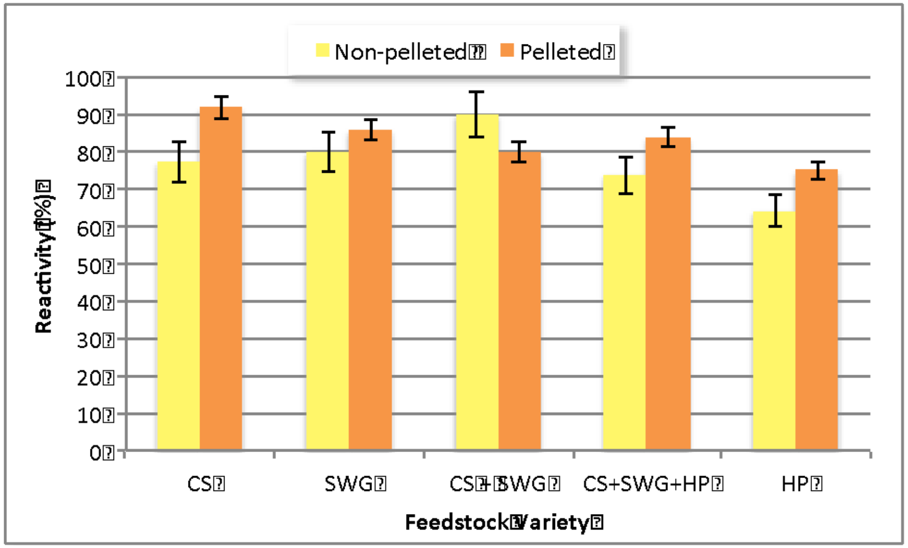
Feedstock Reactivity – Across PT Severity

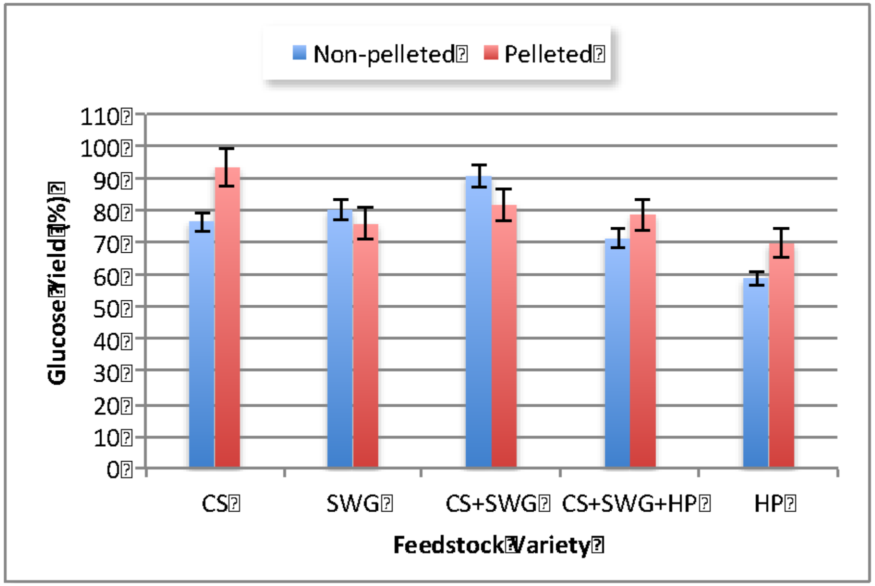
- Densification did not increase biomass recalcitrance compared to non-densified materials
- Spline function (red line) **predicts** reactivity of blends using single feedstock reactivity as a function of PT severity



Feedstock Reactivity (Sugar Release) at Larger-Scale Bioconversion







- Pretreatment using the Zipperclave reactor at high solids loading 25% (w/w)
  - Combined PT + enzymatic hydrolysis
  - Trend for reactivity pellets >non-pelleted feedstocks
    - *Lower in CS+SWG pelleted blend*
  - Blend reactivity can be approximated by averaging individual performance
  - ***These findings agree with smaller PT systems***

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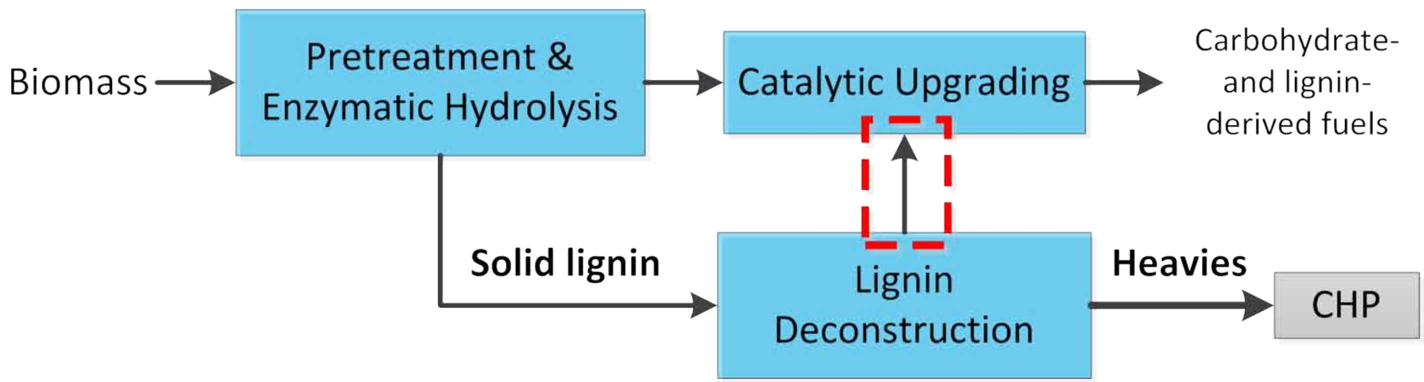
Lignin-Upgrading Potential of Preprocessed Feedstocks

- Joint subtask: INL & NREL for FY14
- Focus on impact of feedstock processing on lignin release & upgrading
- Metric for success is lignin release from solid residues of PT and EH feedstocks/formats
- Characterize post-BCD solid and liquor fraction
- Potential for upgrading into fuels and high-value chemicals

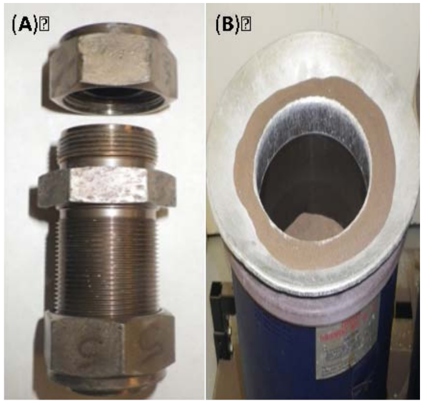


Base Catalyzed Depolymerization (BCD) Experiments

alyzed
depolymerization

Experimental conditions of BCD for FDCI biomass samples.

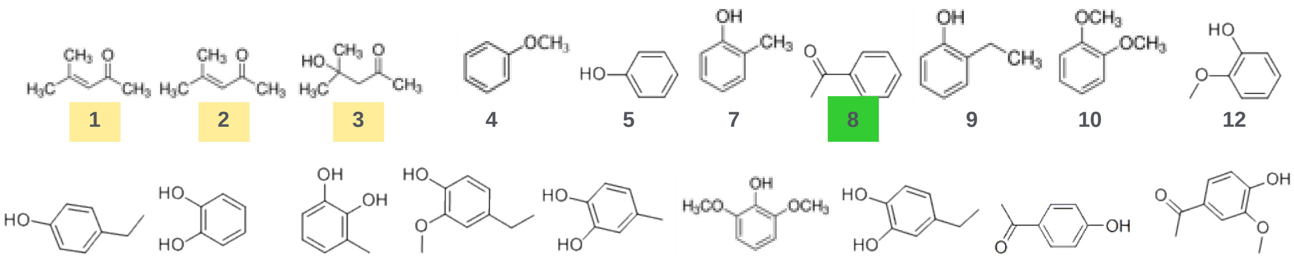
Substrate	Temp (°C)	NaOH (%)	Solid loading (wt %)
FDCI biomass	300	4	10

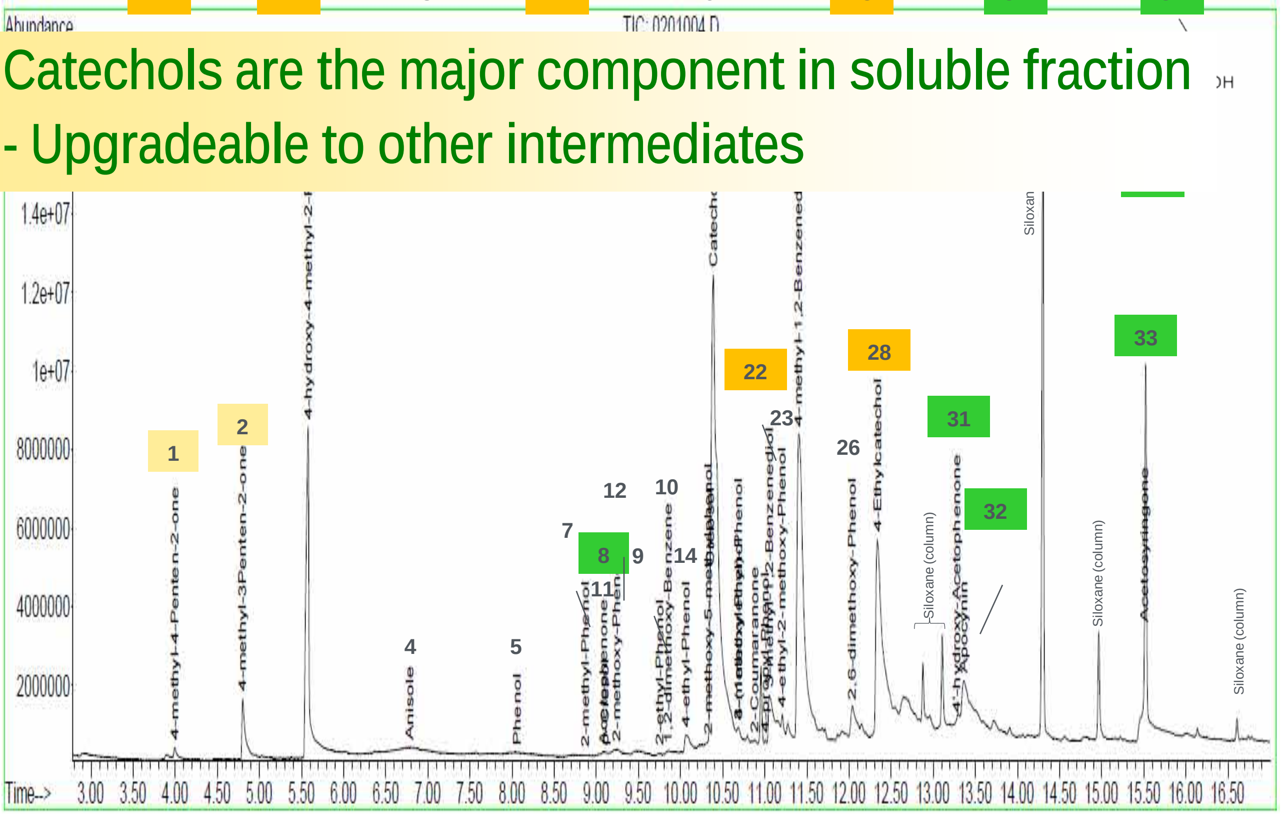


A. Hastelloy reactor body
B. Sand bath

Scheme 1. Schematic of BCD experimental protocol

Preliminary GCMS Analysis of BCD Aqueous Fraction: Corn Stover Grind





Substrate (0.5g)

↓

Batch reaction

→ **Measure gas amount**

↓

Aqueous reaction mixture (products & uncovered lignin)

- Neutralization with 2N-HCl, pH=7
- Centrifuge & wash (9000rpm x 3 times)

↓

Supernatant Lignin/sugar degradation products + salt (DP≤3) [**pH=7**]	Solid residue Unconverted lignin (DP≥4)

↓ (from supernatant)

- **Freeze** dry
- Extraction with acetone

↓

GCMS analysis

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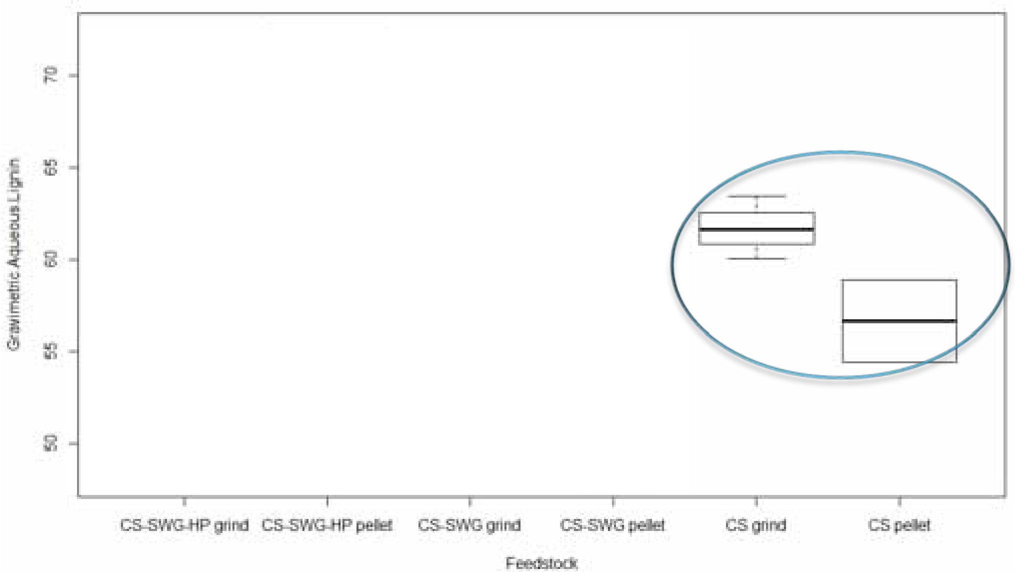
Aqueous lignin recovery



Feedstock	Format	Aqueous Lignin* (%)	Standard Deviation
Corn stover (CS)	Grind	61.71	1.72
Corn stover (CS)	Pellet	56.63	3.17
Switchgrass (SWG)	Grind	56.67	-
Switchgrass (SWG)	Pellet	58.80	-
Hybrid poplar (HP)	Grind	52.05	-
Hybrid poplar (HP)	Pellet	68.87	-
CS+SWG	Grind	62.22	2.17
CS+SWG	Pellet	60.41	10.73
CS+SWG+HP	Grind	63.56	4.89
CS+SWG+HP	Pellet	69.19	4.55

- Aqueous lignin recoveries for CS pellets, CS/SWG, CS/SWG/HP blends (ground and pellets) were equivalent to ground CS
- 50-75% lignin conversion to co-products reduces MFSP & GHG emissions
- Pellets & blends capable of sufficient aqueous lignin recovery (56-69%) to provide a <u>positive impact on MFSP without increasing GHG emissions</u>

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Blended Feedstock Strategy

- Major hurdle to economic viability = cost to access biomass
- Blended Feedstock strategy addresses high cost of biomass access by taking advantage of lower end of multiple supply curves

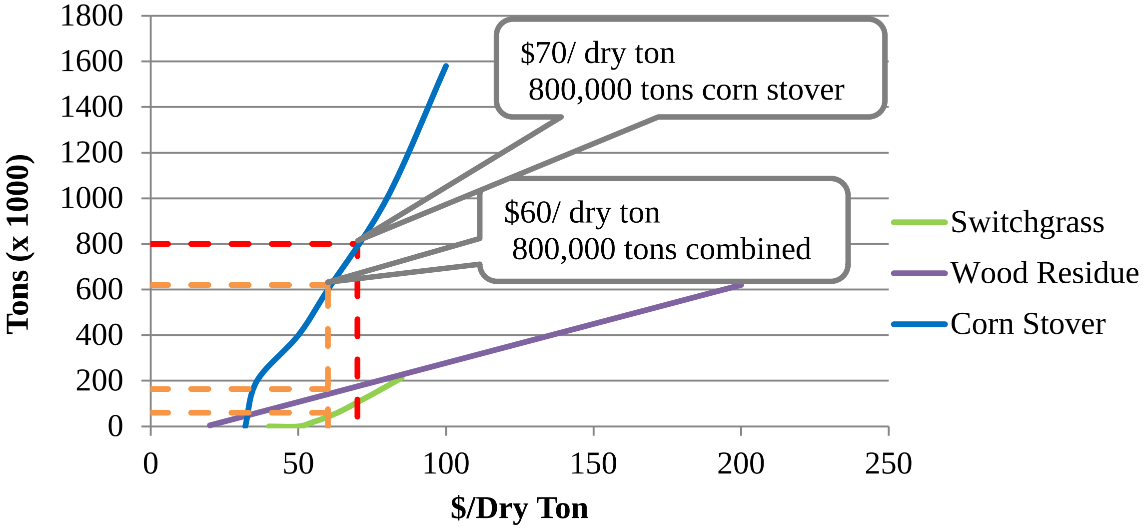

Figure 1. Estimated farm gate price functions for three feedstocks: corn stover, wood residue, and switchgrass. The combined volumes of corn stover, wood residue, and switchgrass cost around $60/dry T for 800,000 tons, while 800,000 tons of corn stover alone cost around $70/dry T.

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Supply Chain Costs: Corn Stover & Switchgrass Blends

- Expanding the resource pool lowers the demand for a single feedstock and significantly reduces the cost for each feedstock
- Blend (50/50 and 80/20) cost is achievable because the MPF=1 (from preliminary data)
- Grower payment has a major impact on total delivered cost

Cost Element ($2011)	Blend	Blend	Blend	Blend	2017 Corn Stover Only
Formulation Contribution	*50/50*	*60/40*	*70/30*	*80/20*	*100/0*
Measured Performance Factor	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*
Total delivered cost ($/dry T)	**98.35**	**98.50**	**97.93**	**103.99**	**115.63**
Grower payment ($/dry T)*	26.50	26.50	25.73	31.49	42.10
Feedstock logistics (excluding grower payment)	**71.85**	**72.00**	**72.2**	**72.50**	**73.53**
Harvest and collection ($/dry T)	12.95	12.50	12.00	11.50	10.53
Transportation ($/dry T)	8.40	8.70	9.10	9.60	11.00
Preprocessing ($/dry T)***	42.50	42.70	42.90	43.10	43.50
Storage ($/dry T)	6.0	6.10	6.20	6.30	6.50
Handling ($/dry T)	2.0	2.0	2.0	2.0	2.00
Ash dockage****	0.00	0.00	0.00	0.00	0.00

*2012 Billion Ton Update Projection for 2017 assuming nominal price translated back to $2011 cost year using a 0.8774 escalation factor
**Corn stover harvesting cost based on single-pass system
Preprocessing includes two-stage grinding and drying and densification (no fractional milling) * Blend lower than ash specification; therefore, no dockage is incurred

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4 – Relevance

- Task bridges the gap between the FS supply chain and production of sugar and lignin-derived fuels and chemicals
  - *Focusing on preprocessing post FY 2013 to improve feedstock cost and biochemical conversion yields*
  - Sugar release is key to achieving 2017 and 2022 goals. Valorization of lignin is key to cost and sustainability (reduction of GHG emissions) FY 2022 targets
  - Task provides preliminary data on preprocessing impacts on aqueous lignin yields
- Contributes data on blended feedstock performance that enables INL to achieve the FY 2017 feedstock delivered cost target of $80/ton and NREL to meet conversion targets
- Informs the bioenergy industry on use of blending and preprocessing to enable logistics and achieve bioconversion targets
- Task supports the design reports, SOTs, and RFP synthesis report

5 - Future Work: FY 2015 Approach

- Evaluate blends capable of meeting quality and conversion targets in FY 2015
  - Agricultural residues, energy crops, and/or municipal solid waste
- Investigate fundamental impact of blending and preprocessing on biomass
  - Physical properties & surface characterization
  - Lignin chemistry and mobility
- Optimized blends for 2017 demonstration
  - Performance correlations for single feedstock and blends
  - Incorporate performance data to TEAs & refine cost estimates
- Supply candidate blends to NREL for evaluation
  - Bench-scale/continuous conversion
  - At least 2 tons for FY 2017 demonstration

Available Resources

FY 2015 Potential Blends	
Feedstock Type	Blend Ratio
Corn Stover/Switchgrass	50/50, 75/25, 25/75
Corn Stover/Miscanthus	50/50
Corn Stover/Hybrid Poplar	50/50
Corn Stover/Switchgrass/Energycane	65/30/5
Corn Stover/Switchgrass/Sorghum	65/30/5
Corn Stover/Switchgrass/Municipal Solid Waste (Grass)	65/30/5
Corn Stover/Switchgrass/Municipal Solid Waste (Paper)	65/30/5
Corn Stover/Switchgrass/(X)	65/30/5

Summary

1) **Overview**
   – Understand impact of feedstock logistics & preprocessing on blend conversion performance
2) **Approach**
   – Use well-characterized Feedstock that present potential biomass resources
   – Select blends capable of meeting quality metrics informed by analysis; contribute quality and performance data to TEA, refine $/DMT
   – Joint collaboration with INL, NREL, and other partners to achieve 2017 targets
3) **Technical Accomplishments/Progress/Results**
   – Blending reduced energy required for pelleting and improved material flow
   – Blend composition and glucose yields from PT and EH predicted from knowledge of constituent feedstocks
   – Blends achieved yields equivalent to corn stover (released sugars and aqueous lignin)
4) **Relevance**
   – Blending and preprocessing to reduce risk, reduce $/DMT, without hindering conversion
   – Pellets and blends capable of sufficient glucose yields & aqueous lignin recovery (56-69%) to provide a positive impact on MFSP without increasing GHG emissions
5) **Future Work**
   – Blend selection for 2017 pilot-scale demonstration
   – Lignin chemistry: affect on preprocessing & conversion

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Responses to Previous Reviewer's Comments

- Reviewer: Analytical screening tools linked to process, but what process is it linked to?; biomass library; feedstock variability; develop rapid screening!
- Response: *As presented, a principal focus of this project is to develop tools and test methods that can be applied both in the laboratory and in the field in real time. The NIR analytical screening tool targets feedstock composition (e.g., extractables, ash, lignin, glucan, and xylan content). As conversion technologies continue to advance, including hybrid combinations of biochemical, thermochemical, and chemical processing steps, and as biomass feedstock resources expand, screening tools must be applicable to multiple logistical and conversion processes. We believe the current techniques and future scope do just that. Continued development of screening techniques is needed and aids in gaining a better understanding of the variability of feedstocks, the impact on logistical operations and advanced preconversion processes, and their impact on the ever-changing conversion processes*.

Responses to Previous Reviewer's Comments

Reviewer : Is this redundant with other national lab efforts? How well known is the library for US researchers? Developing rapid screening tools - how much depth in analysis is needed?
Good - mixed feedstock model. Significance of ash content - good insights
Densification studies – interesting

Response: *The description of the Biomass Resource Library may appear to be redundant. The library, the data contained within, and the analysis and modeling capabilities support a number of projects through the KDF, supplying critical field data and characterization data from a number of feedstocks, across a range of agronomic conditions. Rather than being redundant, it serves more of an enabling function as feedstocks/biomass resources are characterized and providing relevant materials for research efforts across the United States and internationally.*

The Biomass Resource Library is not as well known as we would like and we continue to create value-added resources for the library so that more users will populate the database with physiochemical data. A number of universities, corporations, national laboratories, and user communities have access to the library and we continue to expand and populate its capabilities.

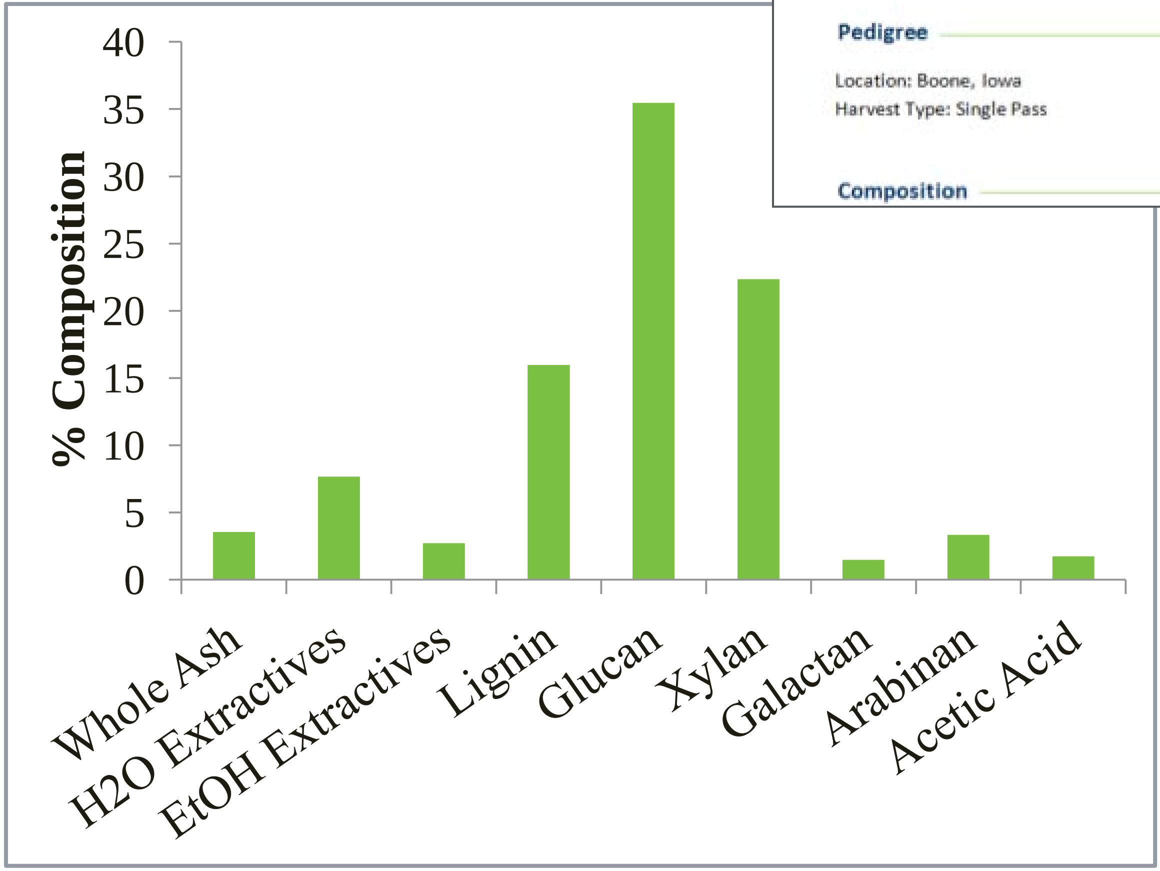
Additional Slides

- Definitions
  - FS/FSs = feedstock /feedstocks
  - RFP = Regional Feedstock Partnership
  - FY = fiscal year
  - CS = corn stover
  - SG = switchgrass
  - MSW = municipal solid waste (refers to paper fraction)
  - MIS = *Miscanthus*
  - HP = hybrid poplar
  - PT = pretreatment
  - DAPT = dilute-acid pretreatment
  - EH = enzymatic hydrolysis
  - FDCI = feedstock densification and conversion impacts
  - MPF = measured performance factor

3 – Feedstock Supply

Provide consistent resources to BETO researchers

Increase bulk material available to supply pilot-scale operations



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Blending and Delivered Feedstock Cost

- Delivered feedstock costs
  a) Corn stover
  b) 80% CS and 20% MSW blend
  c) 50% CS and 50% MSW blend

- Areas shown in light blue (~$80/DMT) hit DOE target

- Blending expands resource availability and reduces feedstock cost

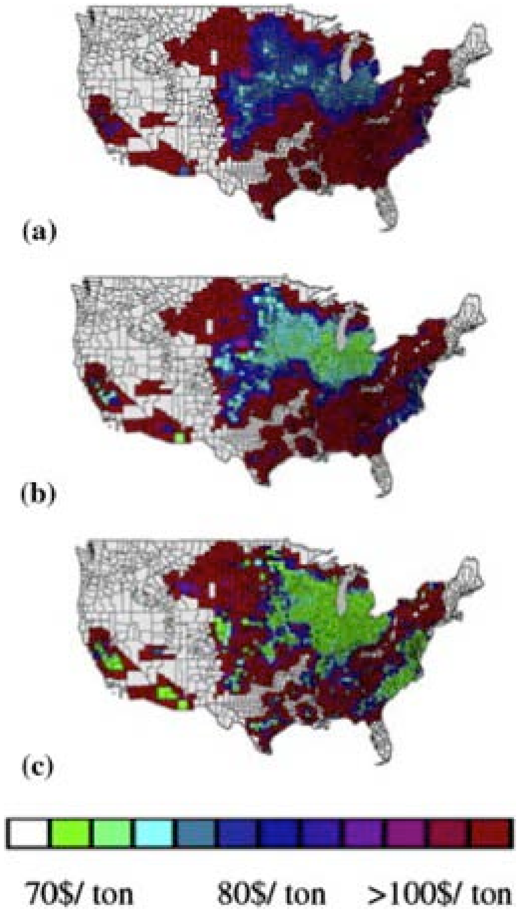

Image credit: Sun, N., F. Xu, N. Sathitsuksanoh, V. S. Thompson, K. Cafferty, C. Li, D. Tanjore, A. Narani, T. R. Pray, B. A. Simmons, and S. Singh (*in press*), "Blending Municipal Solid Waste with Corn Stover for Sugar Production Using Ionic Liquid Process," *Bioresource Technology* doi:10.1016/j.biortech.2015.02.087.

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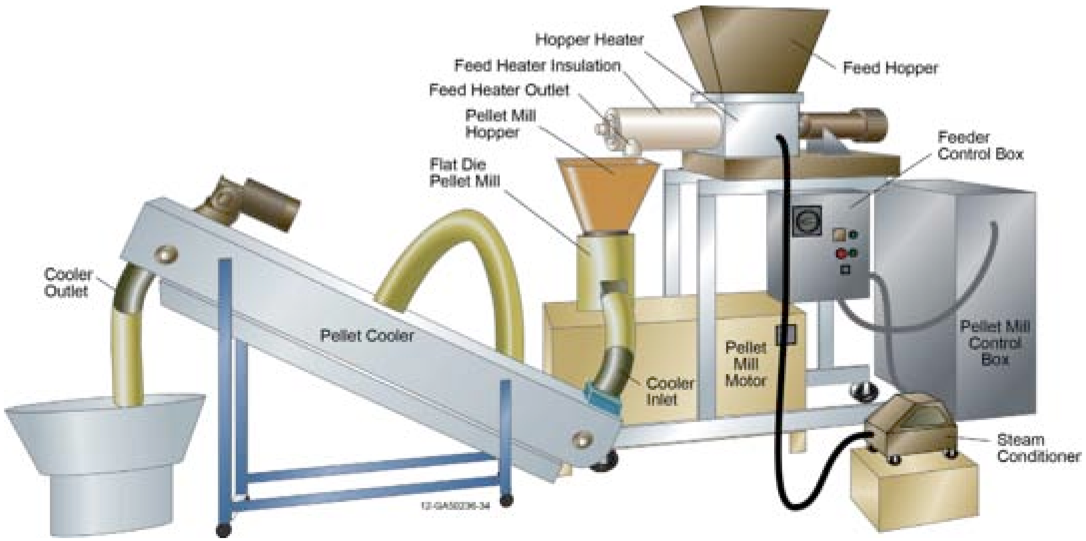
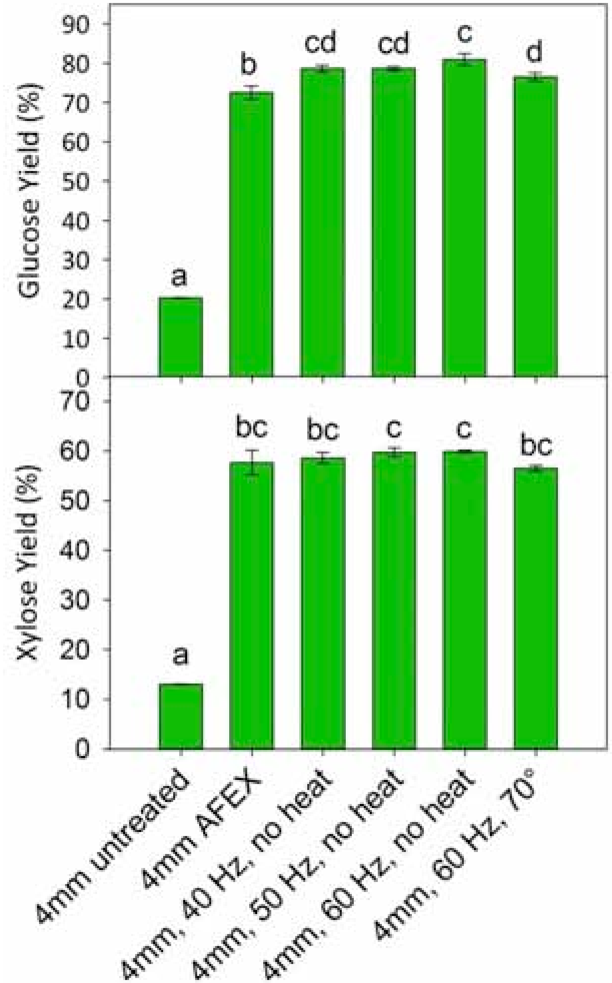
Supplemental Slides: Pelleting Process Variables, AFEX-Pretreated CS

- Highest quality pellets: 4-mm, 60-Hz die speed, no heating
- Die speed had no effect on sugar yields
- Heating or larger grind size for pelleting lowered or did not affect sugar yield





"Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion pretreated corn stover," *Bioresource Technology* 164: 128-135, 2014

Manuscript in process for *Journal of Visualized Experiments*

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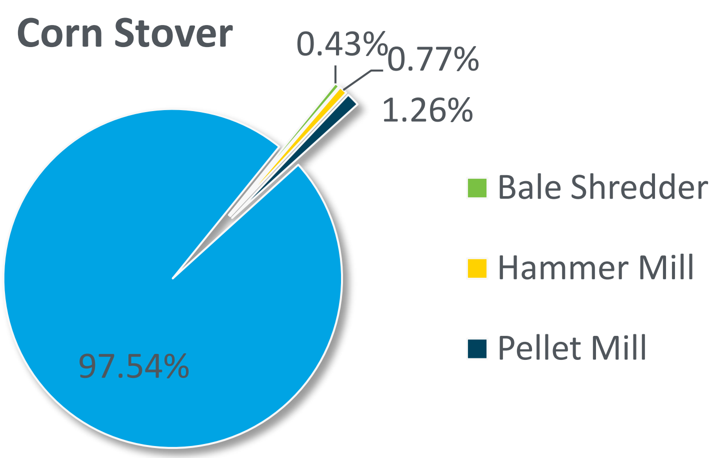
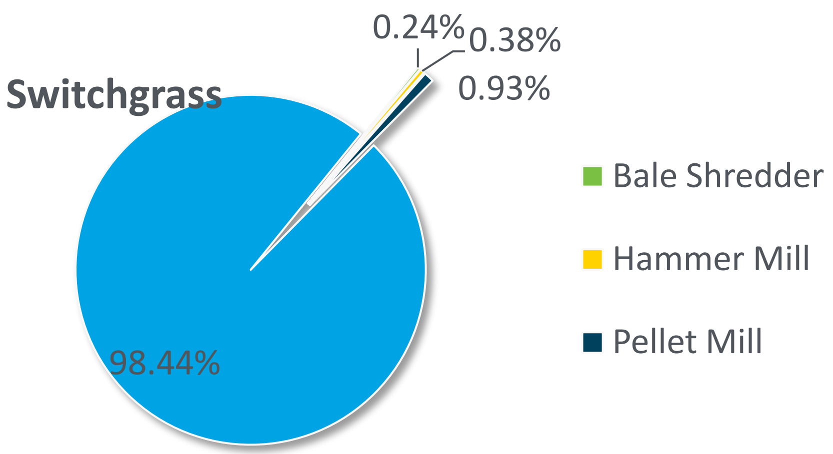
What is the cost of pelleting?

- Energy consumption for 2-stage grinding and pellet mill was recorded for various feedstocks
- Energy consumed for grinding and pelleting represented a small fraction of the energy content of the pelleted material
- Costs cited from literature
  - $51/ton for 6 ton/hr
  - $40/ton at more than 10 ton/hr





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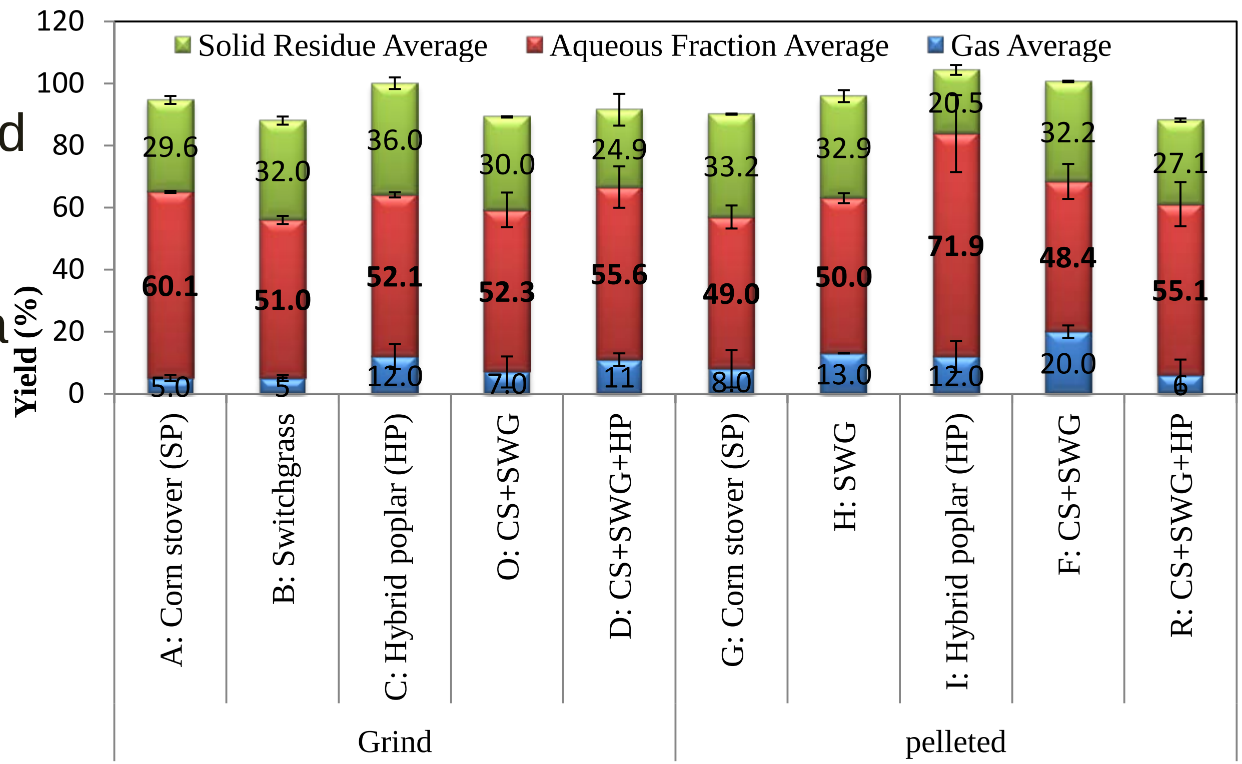
High Yields of Aqueous Lignin after BCD

- Product distribution in gas, aqueous, and solid fraction
- Further analysis of aqueous fraction via
  - GPC
  - NMR
  - GCMS
- Need to identify low-molecular components as proxy for upgrading



Grind corn stover or pelleted poplar increases BCD aqueous fraction

Blended Feedstock Strategy

- Major hurdle to economic viability = cost to access biomass

- Blended FS strategy addresses high cost of biomass access by taking advantage of lower end of multiple supply curves

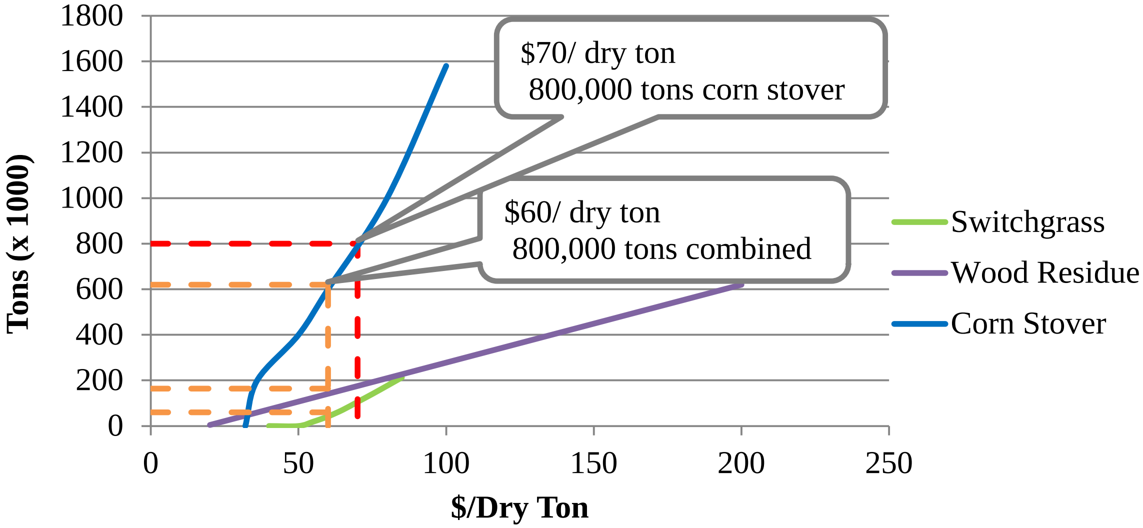


Figure 1. Estimated farm gate price functions for three feedstocks: corn stover, wood residue, and switchgrass. The combined volumes of corn stover, wood residue, and switchgrass cost around $60/dry T for 800,000 tons, while 800,000 tons of corn stover alone cost around $70/dry T.

5 - Future Work: Lignin in Mixed and Densified Feedstocks

- Objective: Determine impacts of lignin chemistry on densification of mixed feedstocks and on downstream conversion processing
- Methods:
  - Base catalyzed extraction of alkaline and acid pretreated biomass
  - Monolignol composition by ^{13}C NMR
  - Inter-unit linkage analysis by $^{13}C/^{1}H$ HSQC NMR
  - Molecular weight distribution by GPC
  - Molecular mobility and dynamics by solid-state NMR
- Expected outcomes:
  - Improved fundamental knowledge of lignin fraction in feedstocks
  - Contribution to optimization of densification of mixed feedstocks
  - Contribution to determination of optimum blends for conversion

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Publications, Patents, Presentations, Awards, and Commercialization

Publications

- Ray, A. E., A. N. Hoover, N. Nagle, X. Chen, and G. L. Gresham (2013) "Effect of pelleting on the recalcitrance and bioconversion of dilute-acid pretreated corn stover under low- and high-solids conditions," *Biofuels* 4(3):271-284.
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- Tumuluru, J., A. Hoover, and G. Gresham (2015 in preparation) "Assessment of the impact of pelleting process variables on pellet quality for AFEX corn stover," *Journal of Visualized Experiments*.
- Crawford, N., A. E. Ray, N. Yancey, and N. Nagle (2015 in preparation) "Evaluating the Pelletization of Pure and Blended Lignocellulosic Biomass Feedstocks."
- Katahira, R., N. Nagle, A. E. Ray, G. Beckham et al. (2015 in preparation) "Impact of biomass processing, blending and densification, on bioconversion and lignin upgrading from herbaceous and woody feedstocks."
- Wolfrum, E. J., N. J. Nagle, R. Ness, D. Peterson, and A. E. Ray (2015 in preparation) "The Effect of Feedstock Densification on Structural Sugar Release and Yield in Biofuel Feedstock and Feedstock Blends."
- Ray, A. E., D. Stevens, G. Sowell, S. Morgan, D. L. Daubaras, K. Cafferty and N. J. Nagle (2015 in preparation) "Dilute-acid pretreatment and enzymatic hydrolysis of corn stover, switchgrass, *Miscanthus*, and paper blends."

Publications, Patents, Presentations, Awards, and Commercialization

Presentations:

- Ray, A. E., A. N. Hoover, N. Nagle, X. Chen, and G. L. Gresham (2013) "Effect of Pelleting on the Recalcitrance and Bioconversion of Dilute-Acid Pretreated Corn Stover under Low- and High-Solids Conditions," selected for oral presentation at the *35th Symposium on Biotechnology for Fuels and Chemicals*, Portland, OR, April 30, 2013.
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- Ray, A. E., D. Stevens, G. Sowell, S. Morgan, L. M. Wendt, D. L. Daubaras, K. Cafferty, and N. J. Nagle (2015) "Dilute-acid pretreatment and enzymatic hydrolysis of corn stover, switchgrass, *Miscanthus*, and paper blends," *Symposium on Biotechnology for Fuels and Chemicals*, San Diego, CA, April 27-30, 2015.
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- Stevens, D., A. E. Ray, A. N. Hoover, D. L. Daubaras, K. Schaller, and K. Cafferty (2015) "Conversion performance corn stover and switchgrass blends using dilute-acid pretreatment and enzymatic hydrolysis," *Symposium on Biotechnology for Fuels and Chemicals*, San Diego, CA, April 27-30, 2015.
- Hoover, A. N., R. Emerson, A. E. Ray, D. Stevens, C. Payne, S. Morgan, J. Lacey, M. Cortez, R. Kallenbach, and M. Sousek (2015) "Impact of drought on composition and sugar yields from dilute-acid pretreatment and enzymatic hydrolysis of *Miscanthus*, mixed perennial grasses, and switchgrass," *Symposium on Biotechnology for Fuels and Chemicals*, San Diego, CA, April 27-30, 2015.
- Wendt, L. M., W. A. Smith, A. E. Ray, D. Stevens, D. L. Daubaras, I. J. Bonner, and M. Buser (2015) "Performance of storage-degraded switchgrass in dilute-acid pretreatment and enzymatic hydrolysis," *Symposium on Biotechnology for Fuels and Chemicals*, San Diego, CA, April 27-30, 2015.