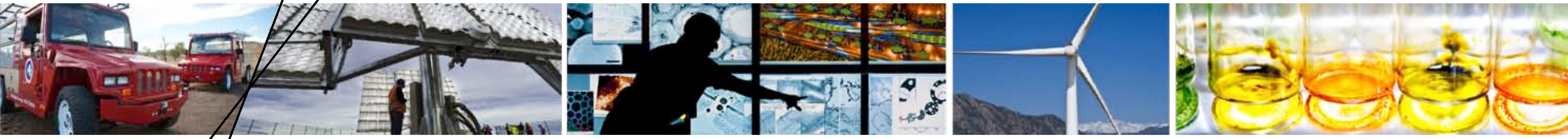
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Lignin Utilization
WBS 2.3.4.100



2015 DOE BioEnergy Technologies Office (BETO) Project Peer Review

Date: March 24th, 2015

Technology Area Review: Biochemical Conversion

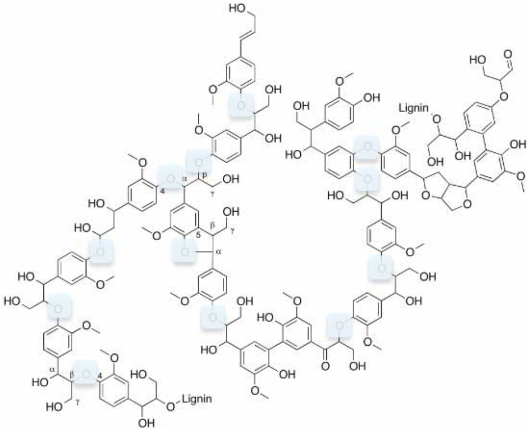
Principal Investigator: Gregg T. Beckham

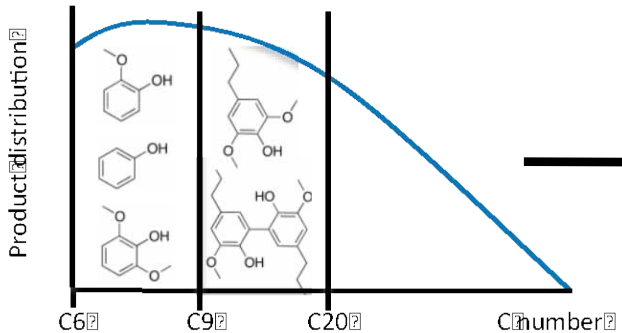
Organization: National Renewable Energy Laboratory

Goal Statement

Goal: develop viable processes to produce valuable co-products from lignin

- Contribute to 2022 cost targets in Biological Conversion and Catalytic Upgrading of Sugars to HCs
- Focus on products with sufficient market size and growth potential to aid bioenergy industry





Fuels and sufficient $\Delta H_{combustion}$

Chemicals and sufficient $\Delta H_{combustion}$

Lignin Depolymerization

- Obtain sufficient lignin in liquid phase
- Understand impact to carbohydrates

Lignin Upgrading

- **New upgrading process represent novel foundation for lignin utilization**
- Leverage new/existing deconstruction processes

Lignin utilization will be a major benefit to the US biorefinery infrastructure

- Conduct TEA/LCA to identify cost drivers and data gaps, and to refine process options
- Collaborate with industry and academics for development of tangible lignin utilization processes
- **Outcome:** demonstrated, scalable processes for converting lignin to valuable co-products

Quad Chart

Timeline

- Start date: October 2012
- End date: September 2017
- Percent complete: 50%

Barriers

- Bt-D Pretreatment Processing and Selectivity
- Bt-I Catalyst Efficiency
- Bt-J Biochemical Conversion Process Integration

Budget

	FY13 Costs	FY14 Costs	Total Planned Funding (FY15-Project End Date)
DOE funded	$886,109	$1,172,790	$3,841,102

Partners and Collaborators

- **Industry partners:** Shell Global Solutions (*CRADA*), POET (*Work-for-Others*), RJ Reynold Tobacco Company (*CRADA*), CRB Innovations, in discussions with several other companies regarding lignin utilization
- **NREL BETO Projects**: Biochemical Platform Analysis, Feedstock Process Interface, Pretreatment and Process Hydrolysis, Biological Lignin Depolymerization, Biological Pyrolysis Oil Upgrading, Pilot Scale Integration, Biochemical Process Modeling and Simulation, Enzyme Engineering and Optimization, Strategic Analysis Platform
- **BETO-funded National Lab Projects:** Oak Ridge National Laboratory (A. Guss), Idaho National Laboratory (A. Ray), Sandia National Laboratory, Joint BioEnergy Institute (J. Gladden, B. Simmons)
- **Office of Science funded efforts:** BioEnergy Science Center, C3Bio (EFRC), Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory (R. Robinson, E. Zink)
- **Academic collaborators:** University of Georgia, Iowa State University, University of Illinois UC, Colorado School of Mines, University of Oxford, Northwestern University, Purdue University, Swedish University of Agricultural Sciences, University of Portsmouth, University of Tennessee Knoxville

Project Overview

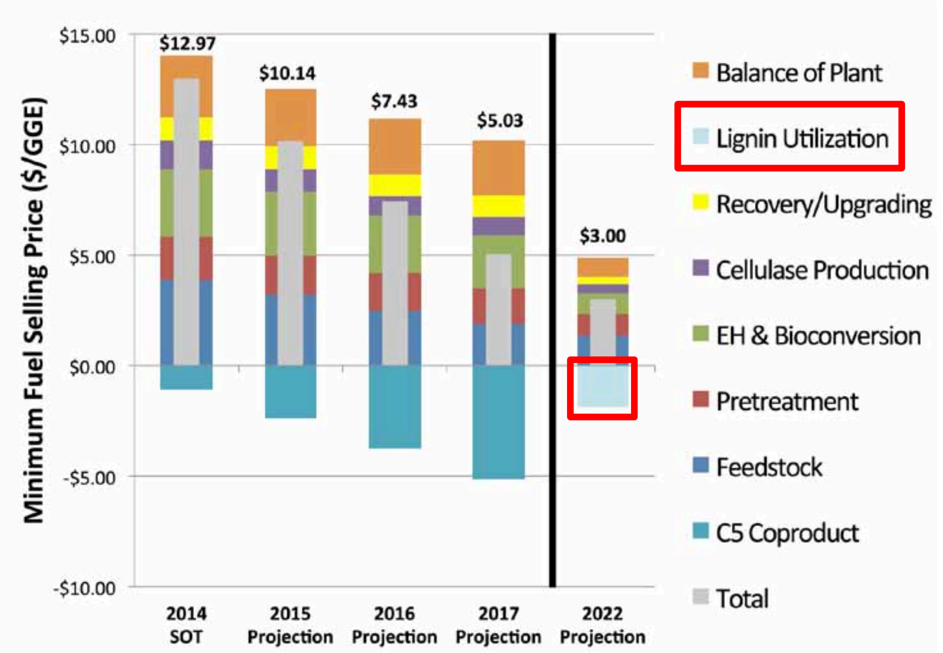
History: Lignin valorization has a very long history, restarted at NREL in ~2012

- BETO seed project on lignin depolymerization catalysis
- Identified as a major cost driver for HC biofuels in the National Advanced Biofuels Consortium

NABC National Advanced Biofuels Consortium

Context: Lignin is a primary biomass polymer

- ~15-30% of biomass
- ~40% of biomass carbon
- Typically slated for heat & power
- Lignin valorization essential for DOE BETO $3/gge cost target by 2022 (**-$1.89/gge**)



Project Objectives:

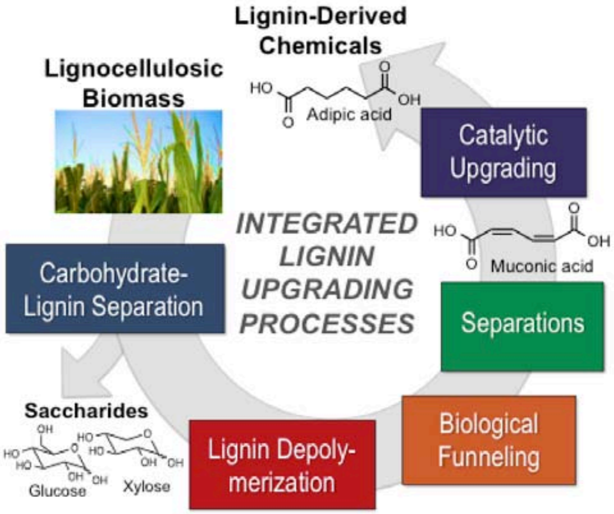
- *Develop industrially-relevant pathway(s) for lignin **isolation** and **upgrading** to meet 2022 cost targets*
- Conduct integrated process development with carbohydrate utilization projects
- Employ TEA/LCA to develop process options based on bench-scale data

Davis *et al.*, NREL Design Report, 2014

Technical Approach

Aim 1: Obtain liquid-phase intermediates

Aim 2: Use biology & catalysis to upgrade lignin



Approach:

- Obtain lignin <u>in pretreatment</u> and/or <u>post-EH residual solids</u>
- Develop lignin depolymerization strategies

Primary challenges and success factors:

- High yields of stable, liquid, low MW products
- Analysis of resulting product distributions
- Impact to both carbohydrates and lignin in pretreatment

Ragauskas, Beckham, Biddy, *et al.*, *Science*, 2014

Approach:

- "Biological Funneling" to obtain single products
- Employ separations and chemical catalysis (if needed) to obtain final target molecule

Primary challenges and success factors:

- Achieve high yields in the biological step
- Co-design of lignin stream, organism, and target product
- Cost-effective separations

Linger, Vardon, Guarnieri, Karp, *et al.*, *PNAS* 2014
Vardon, Franden, Johnson, Karp, *et al.*, *EES* 2015

Management Approach

- *Develop simple, integrated approaches and use TEA/LCA and Go/No-Go's to refine options*
- *Employ fundamentals-driven science/engineering approach with an interdisciplinary team*

Aim 1: Obtain liquid-phase intermediates

FY13: Evaluation of multiple **pretreatments**

FY14: **Stream characterization** for upgrading, evaluation of **depolymerization catalysts**

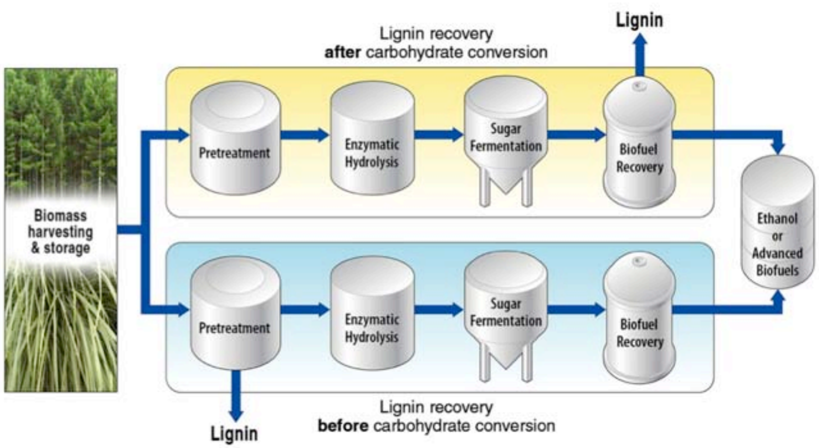
FY15: Finalize **pretreatment** and **catalysis**

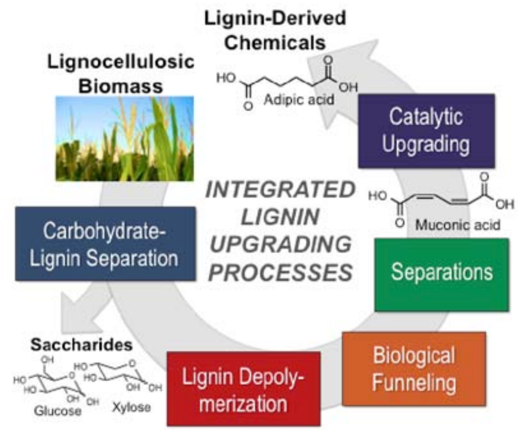
Aim 2: Use biology & catalysis to upgrade lignin

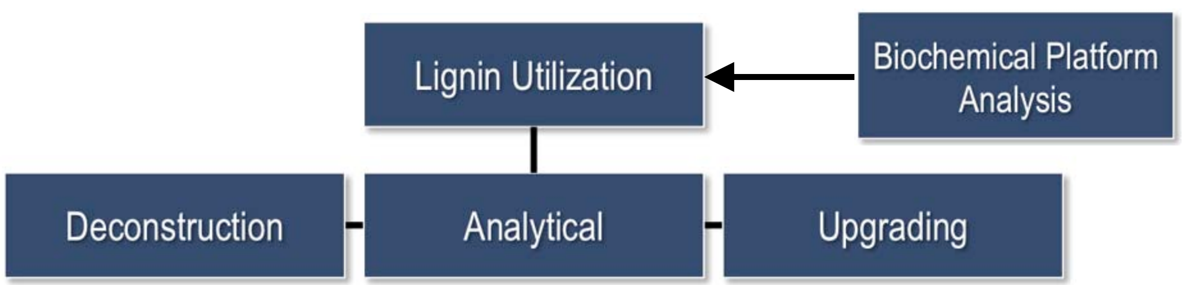
FY13: Proof of concept for **lignin upgrading**

FY14: Conduct co-product modeling to identify targets

FY15: **Down-select and improve upgrading organisms**







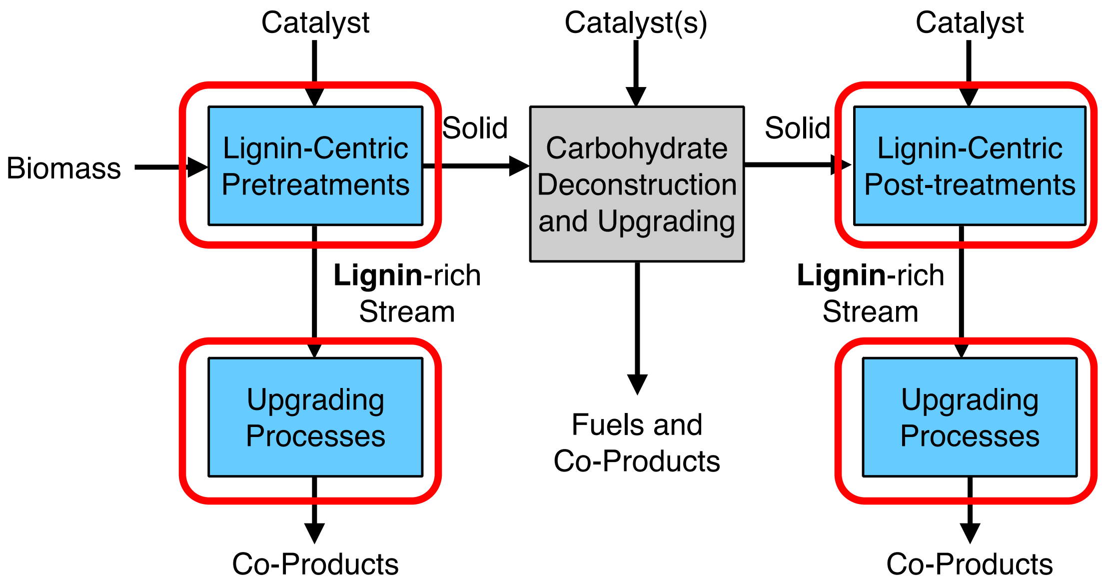
Technical Results – Outline

Pretreatment to obtain lignin-enriched streams

- Clean Fractionation (Organosolv)
- Alkaline pretreatment
- Alkaline peroxide pretreatment
- Ammonia pretreatment
- Deacetylation/Mechanical Refining (Collaboration with PPH)

Lignin-Centric Post-treatments to obtain depolymerized streams

- Homogeneous base catalysis
- Heterogeneous base catalysis
- Heterogeneous metal catalysis (reductive and oxidative)
- *Focus on biorefinery-relevant substrates for depolymerization catalysis*



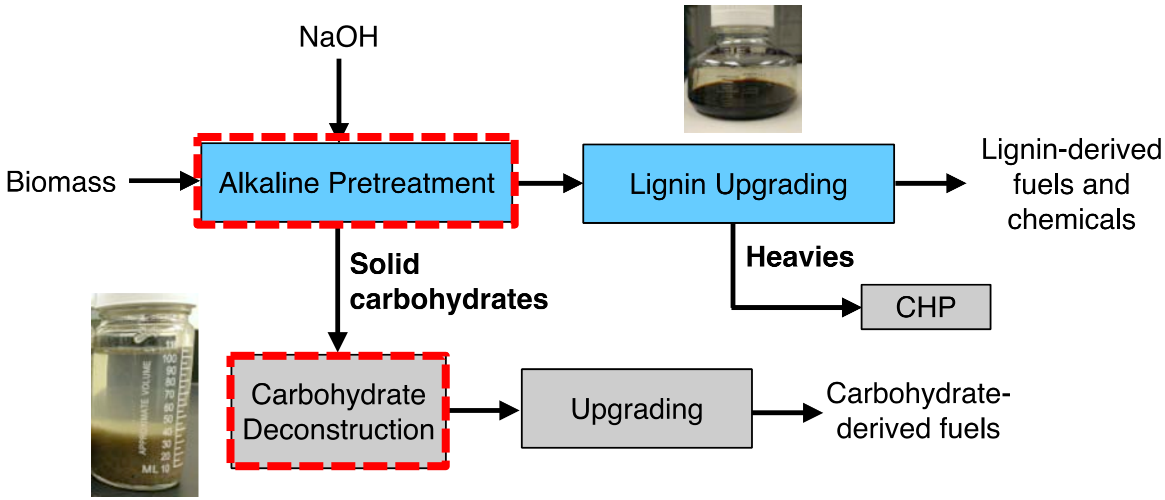
Lignin Upgrading to produce valuable products

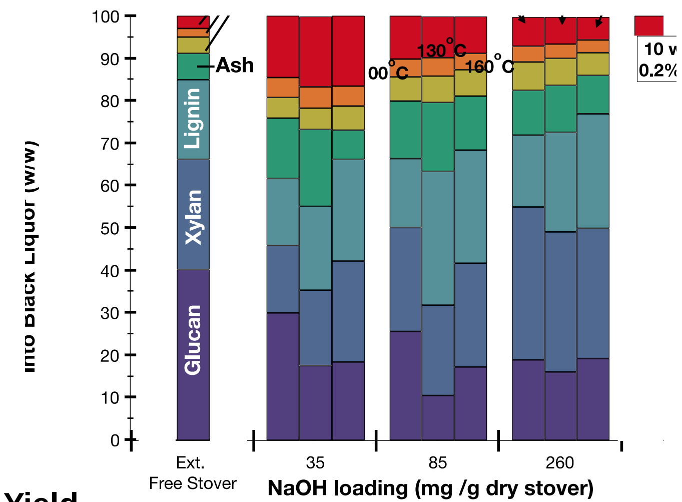
- Biological funneling
- Separations research
- Catalysis for product upgrading
- *Focus on biorefinery-relevant substrates*

Lignin Isolation via Alkaline Pretreatment

Comprehensive TEA-centric approach using NaOH to deconstruct lignin

- *Full mass balances*, *full characterization of resulting lignin streams*
- Cellulose digestibility with industrial enzyme cocktails
- Bench-scale data for TEA/LCA including Materials of Construction and reactor costs

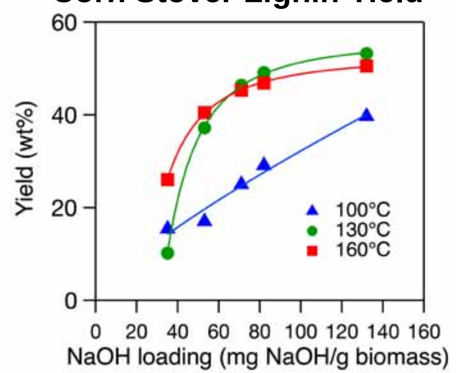




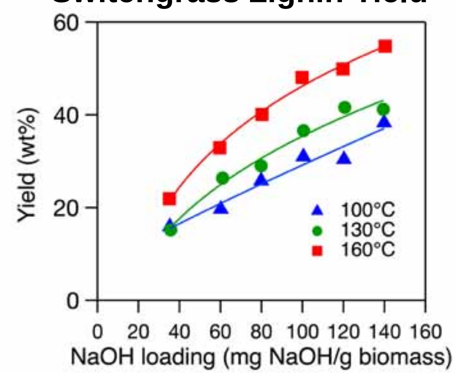
Objective Function

$$f = \frac{Y_{\text{lignin,bl}}}{Y_{\text{glucan,bl}} + Y_{\text{xylan,bl}}}$$

Corn Stover Lignin Yield



Switchgrass Lignin Yield



- Work ongoing with blended/pelleted feedstocks with INL, NREL FI Tasks
- Also with C3Bio GM poplar feedstocks (high S lignin)

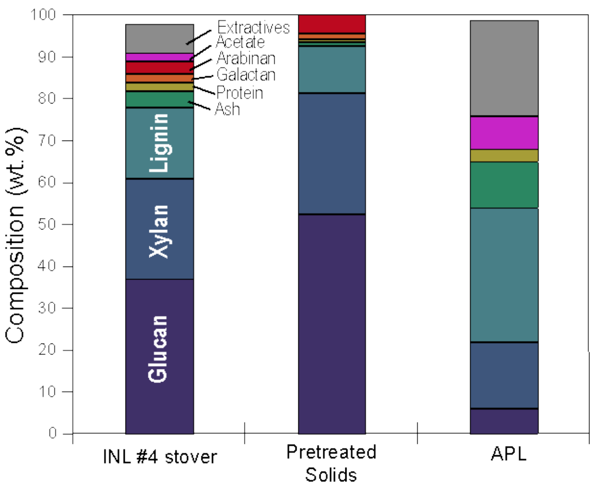
Karp *et al.*, *ACS Sust. Chem. Eng.*, 2014
Karp *et al.*, in review, 2015

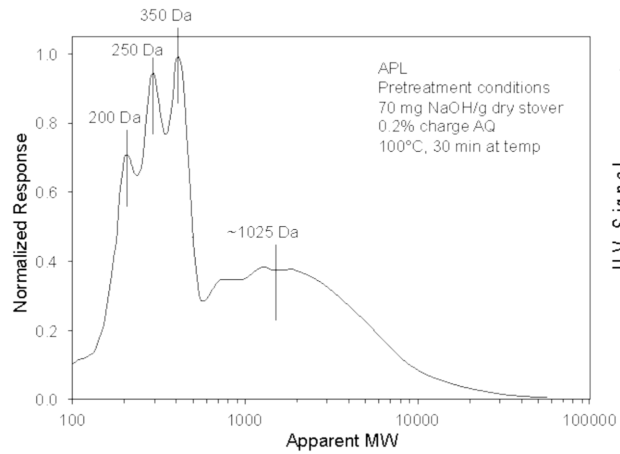
Alkaline Pretreatment at Pilot Scale

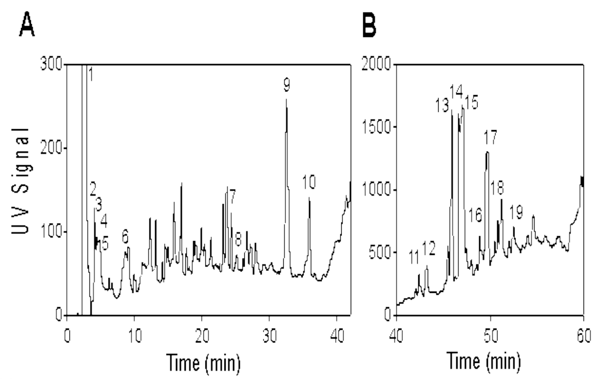
Currently conducting alkaline pretreatment in pilot-scale batch reactors

- First 1900-L run was conducted at 7% solids loadings (same as deacetylation)
- Optimal condition defined from bench-scale runs

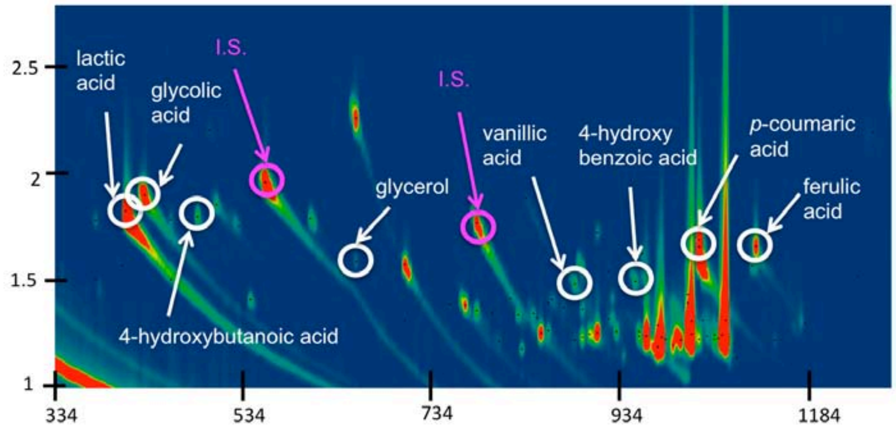
Linger, Vardon, Guarnieri, Karp, *et al.*, *PNAS* 2014

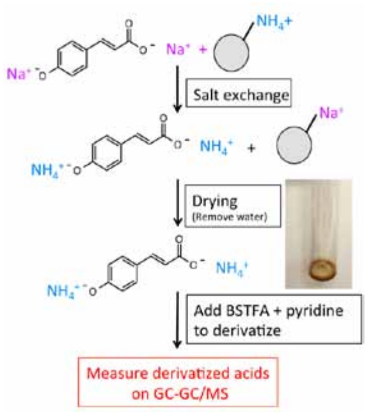




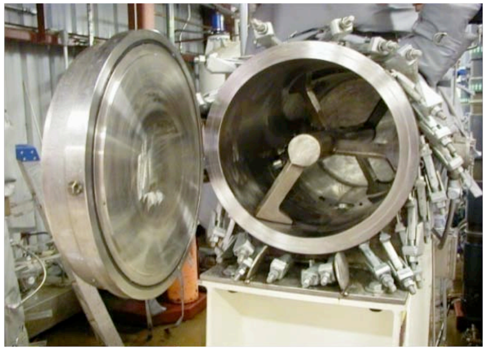


Complex product distribution warrants continued method development





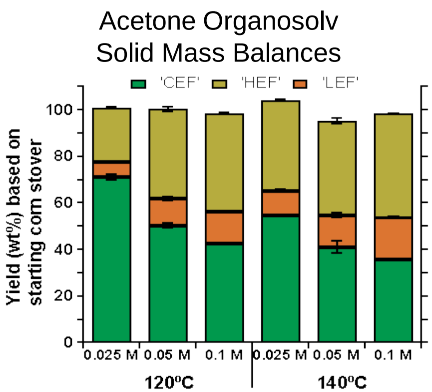
Transitioning to continuous, high-solids pretreatment

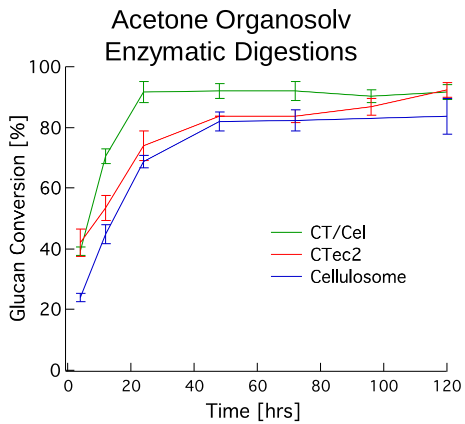


Alternative pretreatments

Organosolv Pretreatment

- H_2O/EtOH/MIBK + H_2SO_4
- H_2O/Acetone/MIBK + H_2SO_4
- **TEA dictated omission of this pathway**

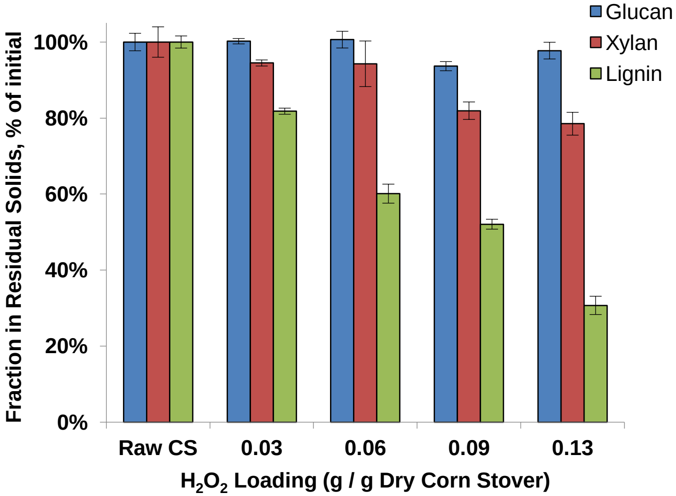




Katahira *et al.*, *ACS Sust. Chem. Eng.*, 2014
Resch *et al.*, *ACS Sust. Chem. Eng.*, 2014

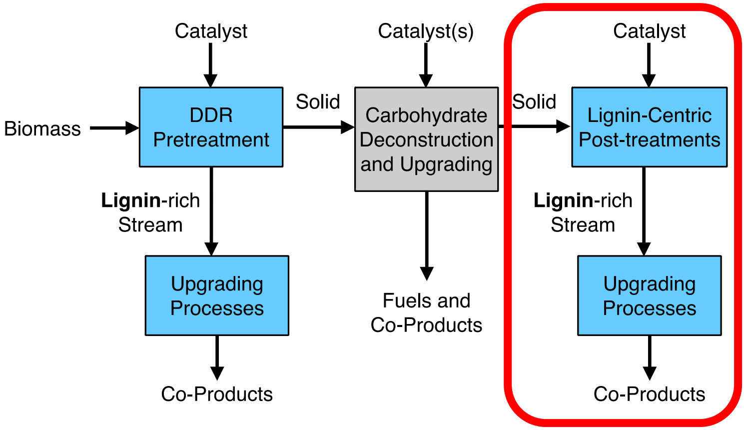
Alkaline Peroxide Pretreatment

- H_2O_2, NaOH, pH ~11.5, T=[25-80 C]
- Analysis on liquor and preliminary TEA ongoing

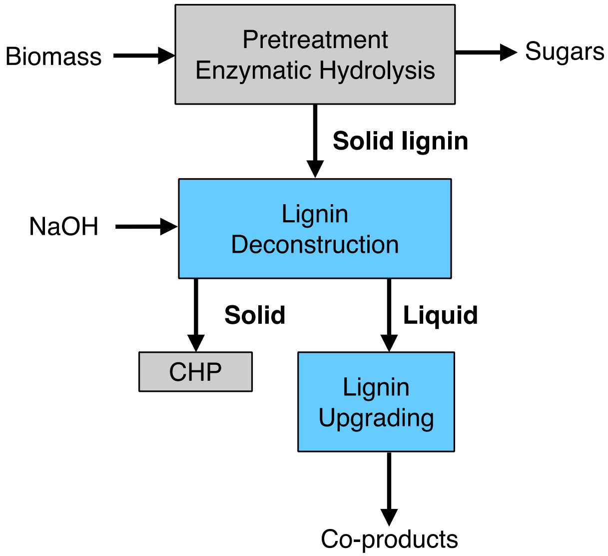


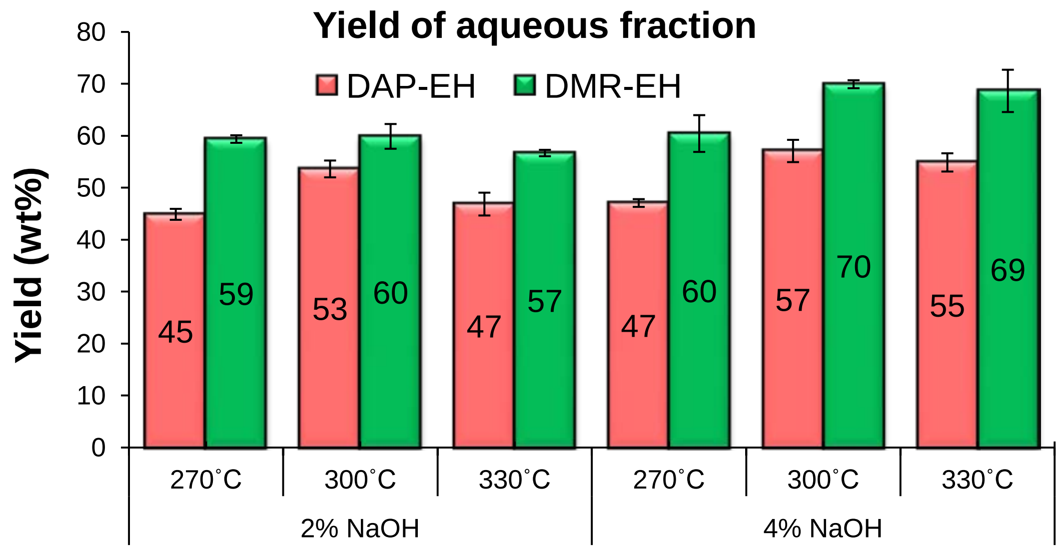
Deacetylation/Mechanical Refining Pretreatment

- Characterizing <u>residual lignin after pretreatment and enzymatic hydrolysis</u> with other NREL BETO projects
- Material for Biol. Lignin Depolymerization (WBS 2.3.2.100)
- Examining catalytic depolymerization of residual lignin



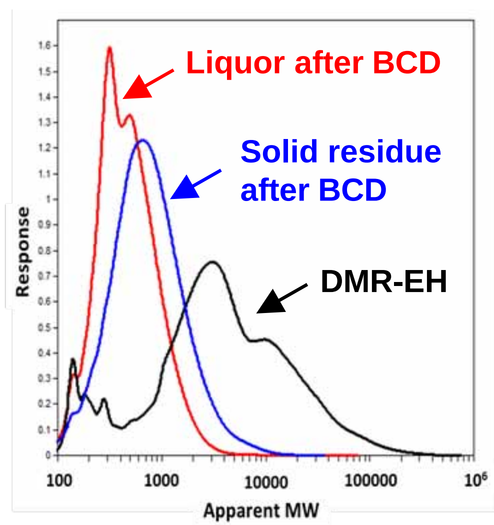
Homogeneous Base Catalysis (Base-Catalyzed Depolymerization)





- Dilute Acid Pretreated, Enzymatically Hydrolyzed (DAP-EH) lignin
- Deacetylated/Mechanical-Refined, Enzymatically Hydrolyzed (DMR-EH) lignin

Substrate	Temp (C)	NaOH, %	Solid loading, %
DAP-EH DMR-EH	330	4 2	10
	300	4 2	10
	270	4 2	10



BCD is an effective process

- **Achieve > 60% liquid yields**
- DDR-EH yields more lignin-derived species than DAP-EH
- GPC reveals low MW distributions
- TEA and upgrading experiments for BCD liquors ongoing currently
- Examining blended/pelleted feedstocks with INL, NREL FI

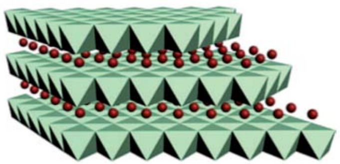
Katahira, Mittal *et al.*, in review

Heterogeneous Base Catalysis

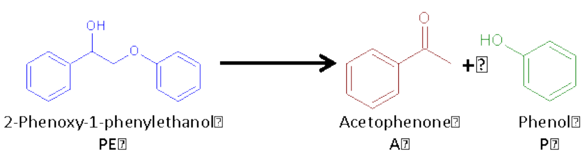
Sturgeon *et al.*, *Green Chem.* 2014
Kruger *et al.*, in review

Hydrotalcite materials can act as heterogeneous base catalysts

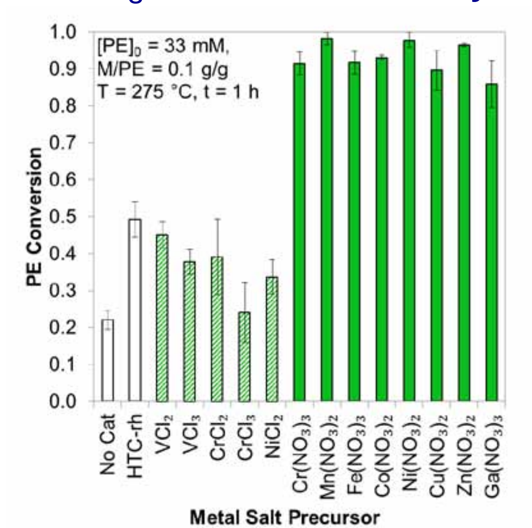
- Effective catalysts for lignin depolymerization
- More recently, interested in catalyst regeneration and recycling



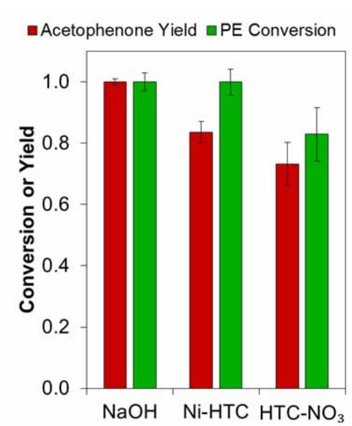
Debecker *et al.* 2009



NO_3^- crucial for activity



HTC-NO_3 as effective as the original Ni-HTC

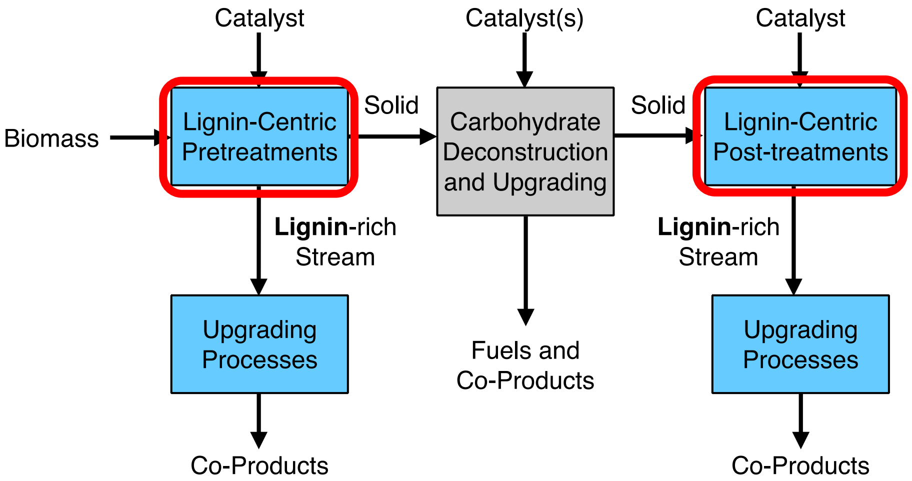


Enables catalyst regeneration

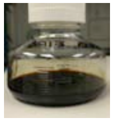
Nitrated-HTC is an effective catalyst for lignin depolymerization

- Requires no transition metals or external H_2
- Catalyst regeneration possible via nitration
- Worked with Shell Global Solutions to develop catalyst technology
- Transitioning technology to industry partners
- Discontinuing this work as a major focus in the project to focus on scale-up of BCD

Summary of Lignin Deconstruction and Isolation



Lignin-Centric Pretreatment to produce liquors for upgrading



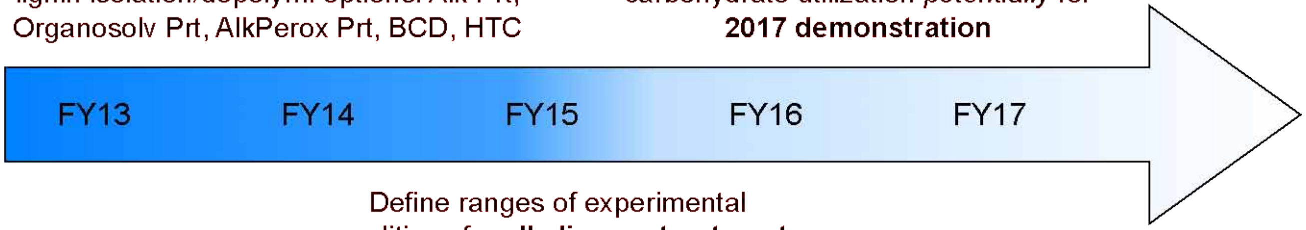
- Alkaline pretreatment
- ~~Organosolv pretreatment~~
- Alk. peroxide pretreatment (TEA ongoing)

Lignin-Centric Post-treatment to produce liquors for upgrading

- Base-catalyzed depolymerization
- ~~Hydrotalcite-catalyzed depolymerization~~
- Examine both DAP-EH and DDR-EH pretreated substrates to maintain relevance to cost target demonstrations

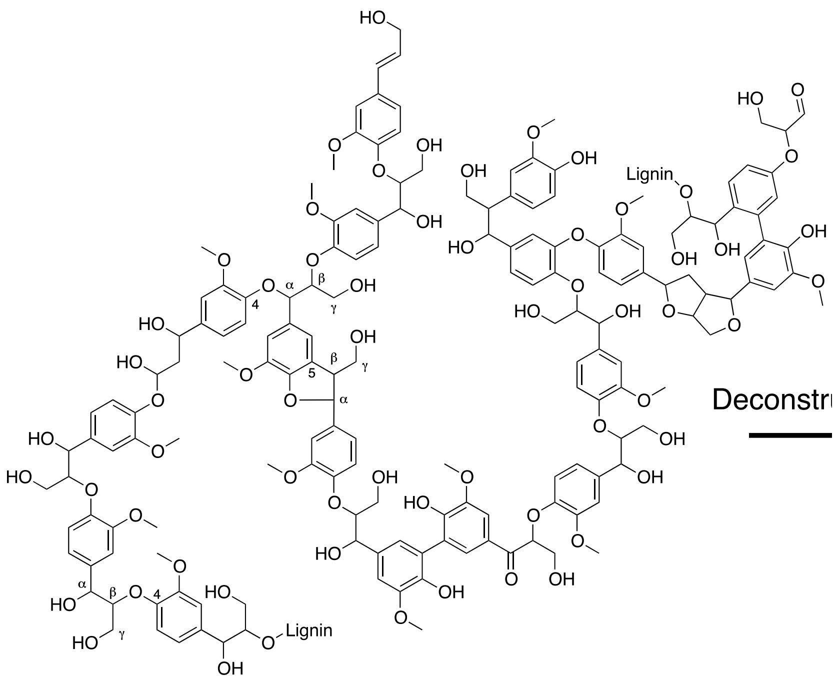
Complete bench-scale evaluation of lignin isolation/depolym. options: Alk Prt, Organosolv Prt, AlkPerox Prt, BCD, HTC

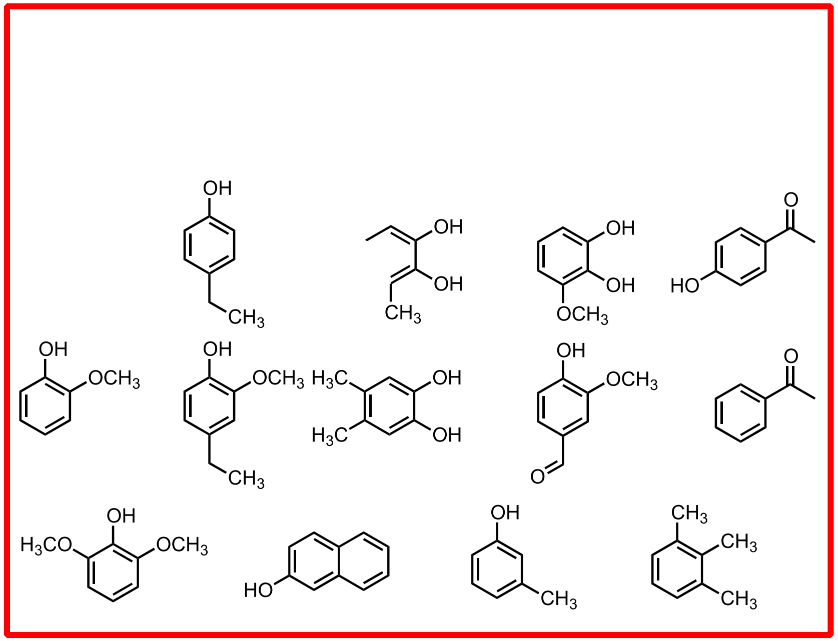
Integrate lignin isolation/upgrading with carbohydrate utilization *potentially* for **2017 demonstration**



Define ranges of experimental conditions for **alkaline pretreatment** and **base-catalyzed depolymerization**

Lignin Upgrading



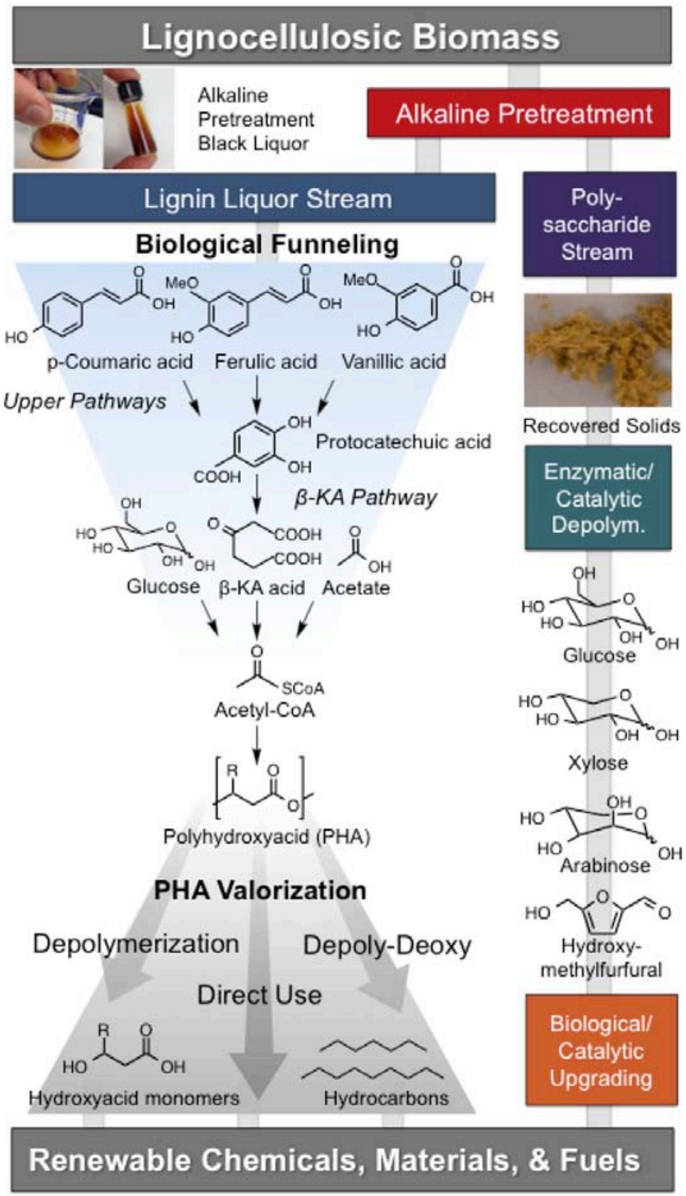


Primary challenge in lignin valorization to co-products is heterogeneity

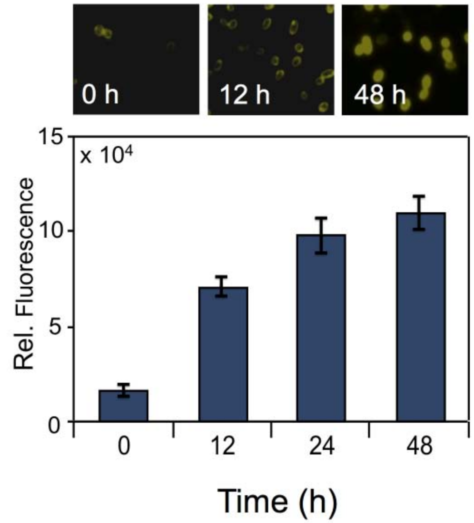
Significant need for innovation to overcome problems with heterogeneous depolymerization products regardless of depolymerization strategy

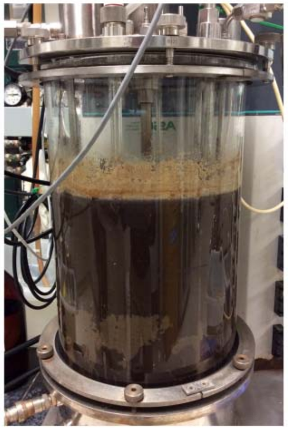
Biological Funneling

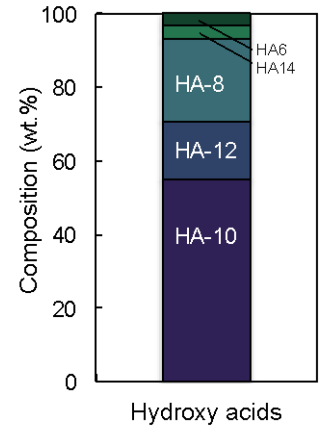
Linger, Vardon, Guarnieri, Karp *et al.*, *PNAS,* 2014



Biological Funneling Cultivations on APL





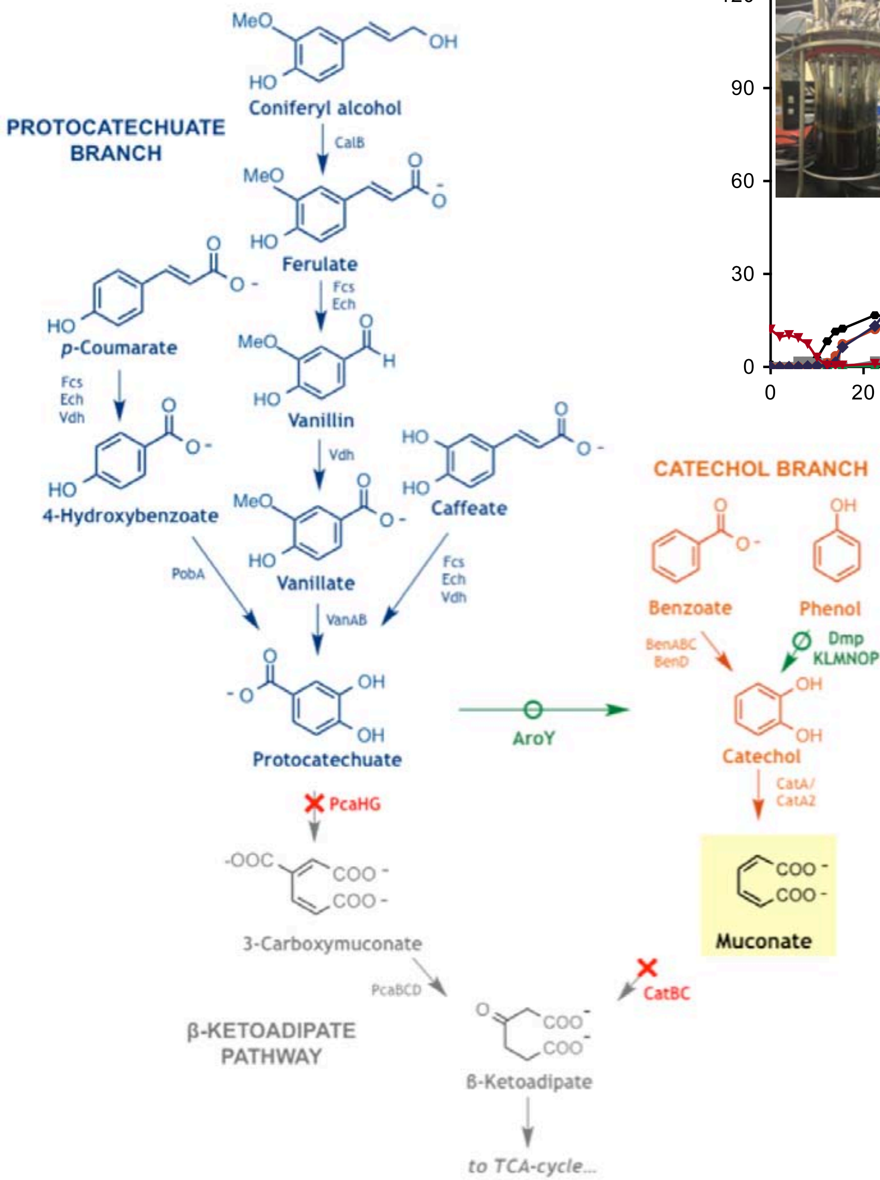


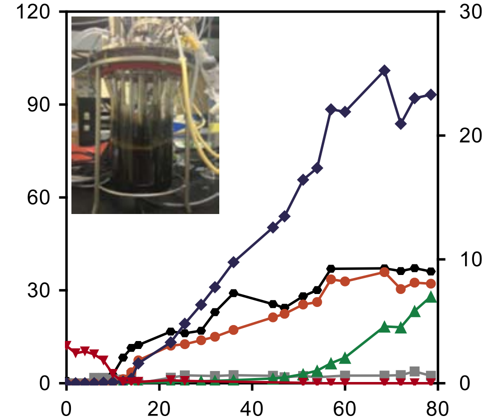
Biological Funneling enables conversion of lignin-derived aromatics into value-added compounds

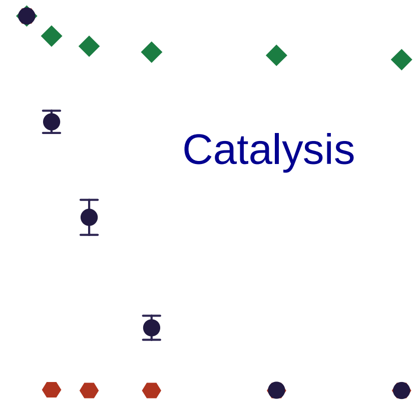
- Significant versatility in lignin stream, organism, and target product
- Demonstrated *mcl*-PHA production in *Pseudomonas putida* KT2440 on alkaline pretreated liquor
- Higher-solids pretreatment will enable more efficient biological conversion step
- Examining mcl-PHA separation and cleanup strategies
- Working with Adam Guss at ORNL and John Gladden at SNL for improvements via metabolic engineering

Adipic acid production from lignin

Vardon, Franden, Johnson, Karp *et al.*, *Energy Env. Sci.*, 2015







Separations

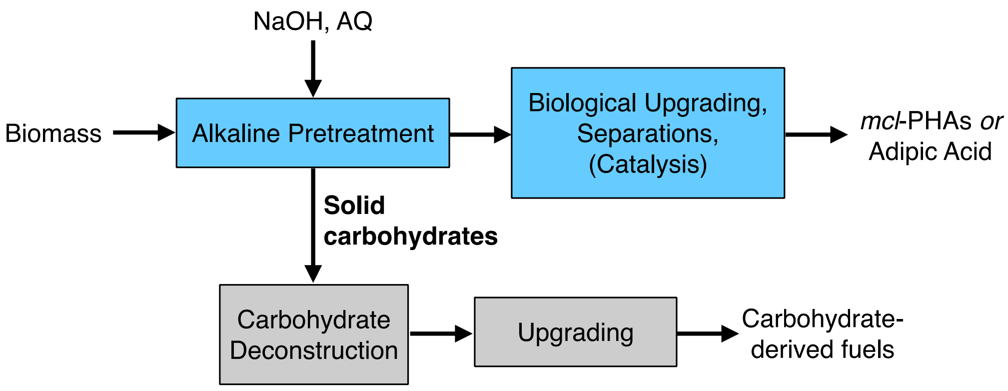
Adipic acid identified as a primary target from lignin from a TEA and LCA perspective

- Combined metabolic engineering, fermentation, separations, and catalysis
- Demonstrated muconic acid production in engineered *P. putida* KT2440 on alkaline pretreated liquor
- Purity is a key cost driver; examining separations options and downstream polymer properties

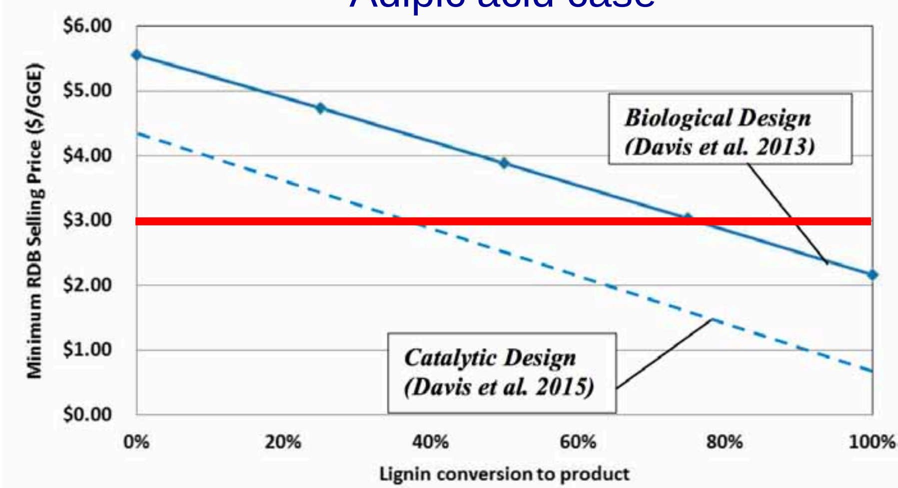
Alkaline Pretreatment/BioFunneling TEA

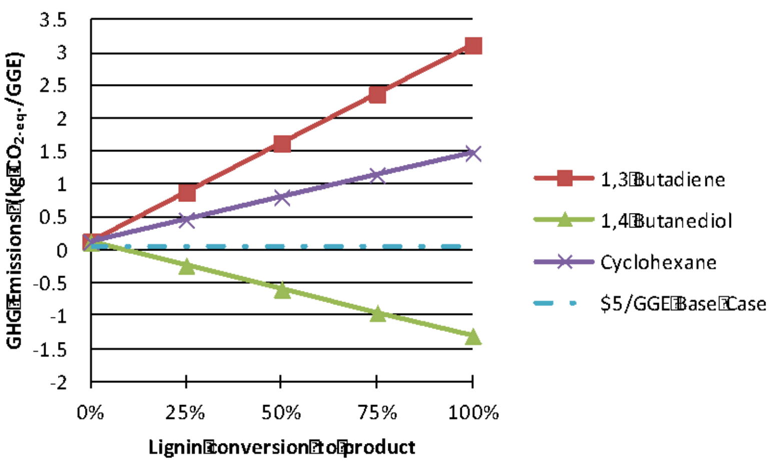
Preliminary TEA shows a pathway to $3/gge with lignin utilization

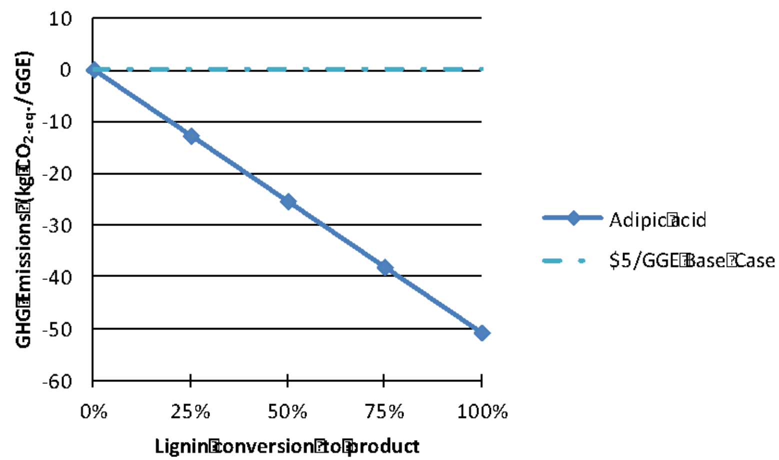
- Alkaline pretreatment conditions based on pilot-scale runs
- Key data gaps (and cost drivers) are **carbon efficiency/yield to products** and **separations**
- TEA being used to focus bench-scale research



Adipic acid case







Relevance

Lignin utilization will be essential to achieve 2017 (potential) and 2022 (definite) HC fuel cost targets

Highlighted in 2011 Review/CTAB and 2014 PRINCE Workshop as a key gap in BC Platform

Key MYPP areas for process improvement via lignin utilization:

Catalyst Efficiency

- Developing chemical catalysts for lignin depolymerization and biocatalysts for lignin upgrading

Biochem. Conv. Process Integration

- Working directly with other BETO-funded tasks in lignin isolation and scale-up
- E.g., DMR-EH depolymerization

Pretreatment Processing/Selectivity

- Developing lignin-centric pretreatments
- Obtain lignin-enriched streams for depolymerization/upgrading

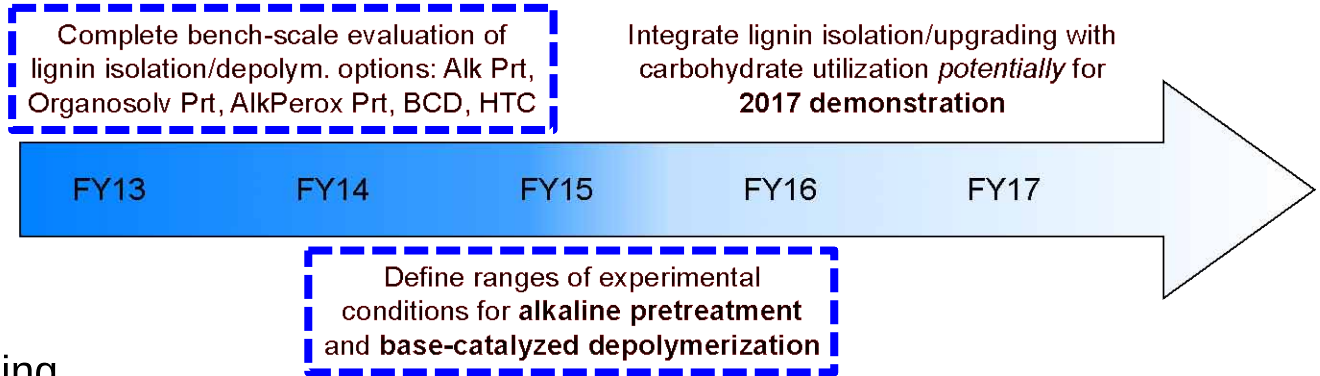
Key Stakeholders and Impacts:

- **Industrial and academic research focused on carbohydrate utilization can leverage lignin utilization processes**
- Work will enable adoption of lignin utilization in modern biorefinery designs
- Lignin impacts the "**Whole Barrel of Oil**" initiative
- **Portfolio of chemicals from lignin will diversify and accelerate development of the biomass value chain**
- Significant amounts of peer-reviewed science and IP will be generated from this work (14 papers)
- Methods to upgrade heterogeneous intermediates can be adapted by the Bio-Oil Platform

Future Work

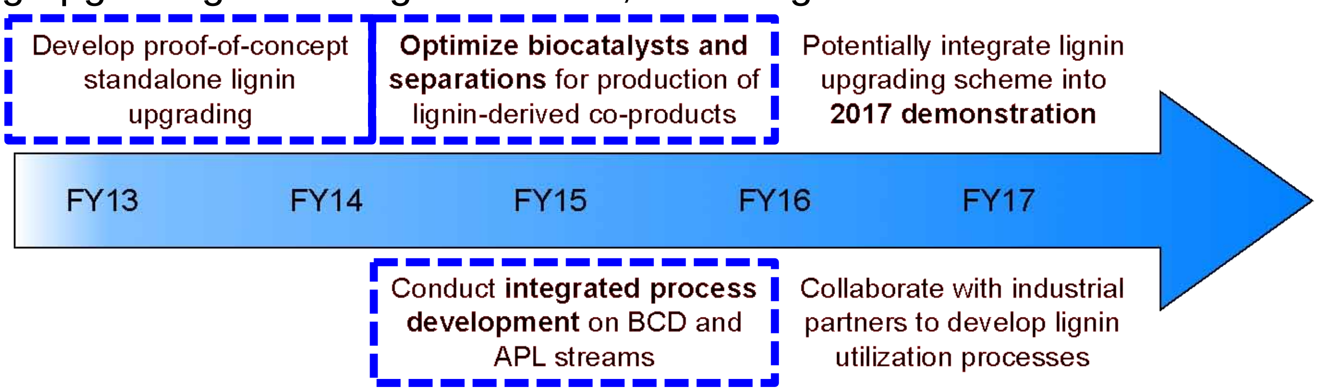
Lignin Isolation/Deconstruction

- Define conditions by end of FY15 for viable isolation efforts on DAP-EH and DDR-EH feedstocks, continue to work with INL and NREL tasks to adapt to different feedstocks
- Transition isolation/deconstruction efforts to single technologies only, ramp up integration efforts with upgrading



Lignin Upgrading

- Working towards intracellular carbon storage products (e.g., PHAs and fatty acids) and secreted products (e.g., adipic acid)
- Emphasizing upgrading and integration R&D, including collaborations with other BETO projects



Summary

1) Approach:
   - **obtain** and **upgrade** lignin to chemicals and/or fuels with fundamentals-driven, interdisciplinary approach underpinned by TEA and LCA
   - collaborate widely with academic, national lab, and industrial partners including BC Platform tasks

2) Technical accomplishments
   - demonstrated **high yields** of liquid products from BCD on process-relevant feedstocks
   - defined a wide range of process conditions for alkaline pretreatment on multiple feedstocks
   - developed a **novel, integrated upgrading approach to overcome lignin heterogeneity** by coupling biology, separations, and catalysis – key to lignin utilization
   - demonstrated Biological Funneling concept for **PHA and adipic acid production from lignin** to date

3) Relevance
   - co-products essential to meet DOE hydrocarbon cost targets
   - addresses Whole Barrel of Oil Initiative and bolsters the biomass value chain

4) Critical success factors and challenges
   - heterogeneity, **economic** *and* **sustainable** production of co-products, high yields of products needed

5) Future work:
   - finalize conditions for isolation/deconstruction of lignin by end of FY15
   - ramp up efforts on lignin upgrading as standalone process and co-utilization with carbohydrates

6) Technology transfer:
   - working with **multiple industry partners** to build commercialization path to lignin utilization
   - **direct** and **functional replacement** chemicals from biomass

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Additional slides

- Previous reviewer comments from 2011 Peer Review related to lignin
- Previous reviewer comments from 2013 Peer Review on Lignin Utilization Project
- Publications
- Patents
- Presentations
- Acronyms

Previous reviewer comments regarding lignin (2011)

Lignin Utilization is a new task, but herein are included comments from the 2011 reviews on the Biochemical Conversion platform related to lignin.

- *“Expansion of the approach to lignin might be worth some analysis as it is a quite significant fraction of the total cellulosic biomass available.”*

- *“Lignin is a major component of biomass, yet it is given relatively little attention in the Platform work (other than its negative impact on saccharification). This is undoubtedly due to the difficulty in making liquid fuels from lignin, especially via a biochemical process. Our perception is that it is reasonable to begin to expand the work directed at finding value-added uses for lignin (there is one such international project). If successful in this effort, then it seems this would have a major impact on the cost of converting the carbohydrate component to ethanol.”*

Previous reviewer comments regarding Lignin Utilization

Are there any other gaps in the portfolio for this technology area? Are there topics that are not being adequately addressed? Are there other areas that BETO should consider funding to meet overall programmatic goals?

"Funding for both the biological and the catalytic pathway should include FOAs for higher-value products that will enhance the economic viability of the hydrocarbon platform. ***Lignin utilization is a key co-product that needs continued research.****"*

Previous reviewer comments regarding Lignin Utilization

- *“Excellent project! Very impressive with great progress in less than a year.”*
- *“Overall, this is a strong project that addresses one of the key hurdles to achieve the 2017 and 2022 MYPP goals; namely the utilization of lignin to create value-added products to support replacement of the whole barrel of oil and achieving the $3/gal metric. This project is a good example of the application of fundamentals-driven science and techno-economic analyses.”*
- *“Seems like a great project; it is too early to see where this will end up but it has promise. How will this be different from other lignin upgrading efforts? PIs need to keep an eye on development of low-lignin transgenic plants.”*
- *“This is a very strong project. The highest and best lignin utilization is an essential component of bioenergy and biochemical production. As the PI mentions, lignin heterogeneity is a major hurdle.”*

Previous reviewer comments regarding Lignin Utilization

- *"This project tackles a very difficult technical challenge that has been studied extensively. The outcome of using lignin and taking to intermediates to make higher-value chemicals could be significant."*

- *"This is a very relevant and important project that allows low-cost feedstock for fuels and chemicals."*

PI Response to Reviewer Comments:

- We thank the reviewers for their positive comments. Regarding the work on plants with genetically modified lignin, we are currently collaborating with several groups on this topic to understand the influence of less recalcitrant lignins on the lignin removal, deconstruction, and upgrading. The genetically modified lignin feedstocks may offer a dramatic reduction in processing costs and simplify lignin upgrading processes, which certainly could be a revolutionary change in biomass conversion.

Publications

<u>Publications in review:</u>

1. J.S. Kruger, N. Cleveland, T. Lammens, P.G. Hamilton, M.J. Biddy, G.T. Beckham, “Nitrate-Intercalated Hydrotalcites for β-O-4 Ether Bond Cleavage”, in review.
2. R. Katahira, A. Mittal, K. McKinney, G.T. Beckham, “Base-catalyzed depolymerization of lignin-enriched residual substrates from biochemical conversion”, in review.
3. E.M. Karp, M.G. Resch, B.S. Donohoe, P.N. Ciesielski, M.H. O’Brien, J.E. Nill, A. Mittal, M.J. Biddy, G.T. Beckham, “Alkaline pretreatment of switchgrass”, in review.
4. A.W. Pelzer, M.R. Sturgeon, A.J. Yanez, G. Chupka, M.H. O’Brien, R. Katahira, R.D. Cortright, L. Woods, G.T. Beckham, L.J. Broadbelt, “Acidolysis of α-O-4 aryl-ether bonds in lignin model compounds: A modeling and experimental study”, in revision.

<u>Publications in print:</u>

4. C.W. Johnson, G.T. Beckham, “Aromatic catabolic pathway selection for optimal production of pyruvate and lactate from lignin”, in press at ***Metabolic Engineering***.
5. D.R. Vardon, M.A. Franden, C.W. Johnson, E.M. Karp, M.T. Guarnieri, J.G. Linger, M.A. Salm, T.J. Strathmann, G.T. Beckham, “Adipic acid production from lignin”, in press at ***Energy and Environmental Science***.
6. J.G. Linger[‡], D.R. Vardon[‡], M.T. Guarnieri[‡], E.M. Karp[‡], G.B. Hunsinger, M.A. Franden, C.W. Johnson, T.J. Strathmann, P.T. Pienkos, G.T. Beckham, “Lignin valorization through integrated biological funneling and chemical catalysis”, ***Proc. Natl. Acad. Sci.*** (2014), 111(33), pp. 12013-12018.
7. A. Ragauskas, G.T. Beckham, M.J. Biddy, R. Chandra, F. Chen, M.F. Davis, B.H. Davison, R.A. Dixon, P. Gilna, M. Keller, P. Langan, A.K. Naskar, J.N. Saddler, T.J. Tschaplinski, G.A. Tuskan, C.E. Wyman, “Lignin Valorization: Improving Lignin Processing in the Biorefinery”, ***Science*** (2014), 344, 1246843.
8. E.M. Karp, B.S. Donohoe, M.H. O’Brien, P.N. Ciesielski, A. Mittal, M.J. Biddy, G.T. Beckham, “Alkaline pretreatment of corn stover: Bench-scale fractionation and stream characterization”, ***ACS Sust. Chem. Eng.*** (2014), 2(6), pp. 1481-1491, featured on cover.

Publications

Publications in print:

9. M.G. Resch, B.S. Donohoe, P.N. Ciesielski, J.E. Nill, L. Magnusson, M.E. Himmel, A. Mittal, R. Katahira, M.J. Biddy, G.T. Beckham, “Clean fractionation pretreatment reduces enzyme loadings for biomass saccharification and reveals the mechanism of free and cellulosomal enzyme synergy“, ***ACS Sust. Chem. Eng***. (2014), 2(6), pp. 1377-1387.
10. R. Katahira, K. McKinney, A. Mittal, P.N. Ciesielski, B.S. Donohoe, S. Black, D.K. Johnson, M.J. Biddy, G.T. Beckham, “Evaluation of clean fractionation pretreatment for the production of renewable fuels and chemicals from corn stover“, ***ACS Sust. Chem. Eng***. (2014), 2(6), pp. 1364-1376.
11. M.R. Sturgeon‡, S. Kim‡, K. Lawrence, R.S. Paton, S.C. Chmely, M.R. Nimlos, T.D. Foust, G.T. Beckham, “An experimental and theoretical study of acid catalysis of aryl-ether linkages: Implications for lignin acidolysis”, ***ACS Sustain. Chem. Eng***. (2014), 2(3), pp. 472-485.
12. M.R. Sturgeon, M.H. O’Brien, P.N. Ciesielski, J. Kruger, S.C. Chmely, R. Katahira, J. Hamlin, K. Lawrence, T.D. Foust, R.M Baldwin, M.J. Biddy, G.T. Beckham, “Lignin depolymerization by nickel supported layered double hydroxide catalysts”, ***Green Chem***. (2014), 16, pp. 824-835.
13. R. Davis, L. Tao, E. Tan, M. Biddy, G.T. Beckham, C. Scarlata, J. Jacobson, K. Cafferty, J. Ross, J. Lukas, D. Knorr, P. Schoen, “Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid Prehydrolysis and Enzymatic Hydrolysis Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons”, NREL Report, (2013).
14. S.C. Chmely, S. Kim, P.N. Ciesielski, G. Jiminez-Oses, R.S. Paton, G.T. Beckham, “Mechanistic study of a Ru-xantphos catalyst for tandem alcohol dehydrogenation and reductive aryl-ether cleavage”, ***ACS Catalysis*** 2013.

Patents

Patents:

- Base-catalyzed depolymerization of lignin with heterogeneous catalysts, application 61/710,240 filed on 10/5/2012

- Lignin conversion to fuels, chemicals, and materials, application 14/563,299 filed on 12/8/2014

Presentations

1. Valorization of lignin to renewable fuels and chemicals through biological funneling and chemical catalysis, Spring 2015 American Chemical Society Meeting, March 22, 2015
2. Adipic acid production from lignin, Spring 2015 American Chemical Society Meeting, March 22, 2015
3. Breaking down plant cell walls: A few short stories in improving biofuels production processes, West Virginia University, January 16, 2014
4. Lignin valorization via biological funneling and chemical catalysis, Iowa State University, December 16, 2014
5. Layered Double-Hydroxide Catalysts for Lignin Depolymerization, AIChE Fall meeting, November 17, 2014
6. Breaking down plant cell walls: A few short stories in improving biofuels production processes, West Virginia University, November 14, 2014
7. Breaking down plant cell walls: A few short stories in improving biofuels production processes, Northwestern University, October 30, 2014
8. Lignin valorization via biological funneling and chemical catalysis, Frontiers in Biorefining, October 23, 2014
9. Optimizing biological funneling of lignin and carbohydrate-derived species: substrate depolymerization, organism selection, and co-product generation, Frontiers in Biorefining, October 22, 2014
10. Breaking down plant cell walls: A few short stories in improving biofuels production processes, Colorado College, October 17, 2014
11. Breaking down plant cell walls: A few short stories in improving biofuels production processes, UC Denver, September 19, 2014
12. Revealing differences between free and complexed enzyme mechanisms and factors contributing to cell wall recalcitrance, 10th European Symposium on Biochemical Engineering Sciences and 6th International Forum on Industrial Bioprocesses, Lille, France, September, 12, 2014
13. Active site dynamics in metal/hydrotalcite-catalyzed lignin depolymerization. ACS Fall Meeting, August 14 2014
14. Integrated catalytic upgrading of muconic acid to adipic acid for renewable nylon precursor production, Fall 2014 American Chemical Society Meeting, August 12, 2014
15. Metal-hydrotalcite solid catalysts for base-catalyzed depolymerization of lignin, ACS Fall Meeting, August 12 2014
16. Conversion of lignin to fuels and chemicals using catalysis and biology, SIMB Annual Meeting, July 21, 2014
17. Directing carbon flow though catechol and protocatechuate pathways for increased yield in biological lignin upgrading, SIMB Annual Meeting, July 21, 2014
18. Understanding free and complexed enzyme mechanisms and factors contributing to cell wall recalcitrance, SIMB Annual Meeting, July 20, 2014
19. Integrated deconstruction, biological upgrading, and chemical catalysis for lignin valorization, Hybrid Processing for Biorenewable Fuels and Chemicals Production Symposium, Iowa State University, July 11, 2014
20. Clean fractionation of cell wall components in corn stover and their characterization for biorefinery processes, 36th SBFC , April 28, 2014
21. Understanding natural mechanisms of cellulose (and lignin) deconstruction, Joint BioEnergy Institute, April 23, 2014
22. Understanding natural mechanisms of cellulose (and lignin) deconstruction, Energy Biosciences Institute, UC Berkeley, April 22, 2014
23. Characterization of clean fractionated cell wall components in corn stover, 35th SBFC , April 29, 2013
24. Bench-scale process development for carbohydrate and lignin co-utilization, C2B2 Annual Meeting, April 5, 2013

Acronyms

- BCD: Base-Catalyzed Depolymerization
- CF: Clean Fractionation
- CHP: Combined Heat and Power
- DAP-EH: Dilute-Acid Pretreated, Enzymatically Hydrolyzed feedstock
- DDR-EH: Deacetylated, Disk-Refined, Enzymatically Hydrolyzed feedstock
- LCA: Life-Cycle Analysis
- MW: Molecular Weight
- TEA: Techno-Economic Analysis