Lignin Utilization

Technology Session Review Area: Biochemical Conversion & Lignin Utilization
PI: Gregg T. Beckham, National Renewable Energy Laboratory

Project overview

Goal: Develop industrially-relevant processes and tools for viable lignin valorization – contribute $2-3/gge to MFSP

- Develop deconstruction catalysts for C–C bonds in lignin
- Provide deconstructed lignin to bioconversion efforts
- Develop lignin analytics and model compound syntheses
- Support lignin projects in the BETO/DOE portfolio (Biological Lignin Valorization (BLV), LigFirst, ORNL project, SepCon, Bioenergy Research Centers, etc.)

Heilmeier Catechism:

- **Aim**: develop lignin depolymerization catalysts and analytics for accurate process metrics
- **Today**: lignin combusted for heat, C–C bonds are major hurdle, analytics mostly monomers only
- **Important**: lignin key for biorefinery TEA and LCA
- **Risks**: C–C cleavage and quantitative lignin analytics are both challenging
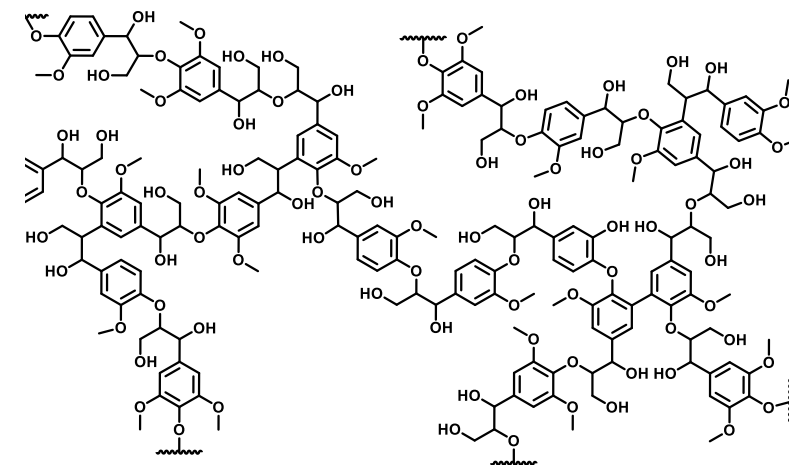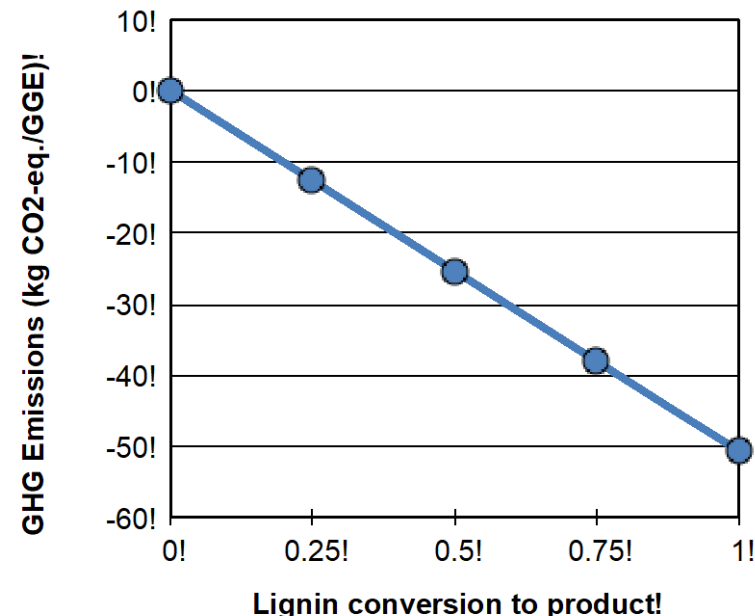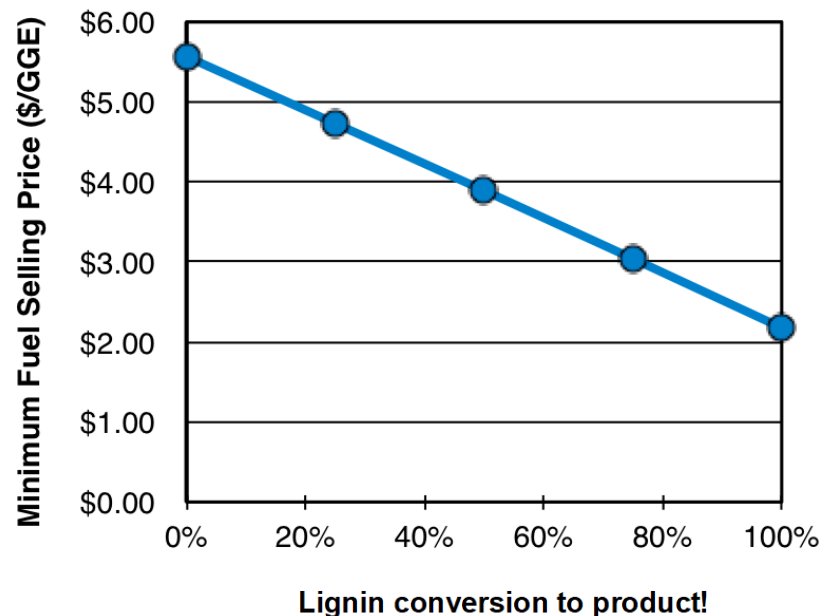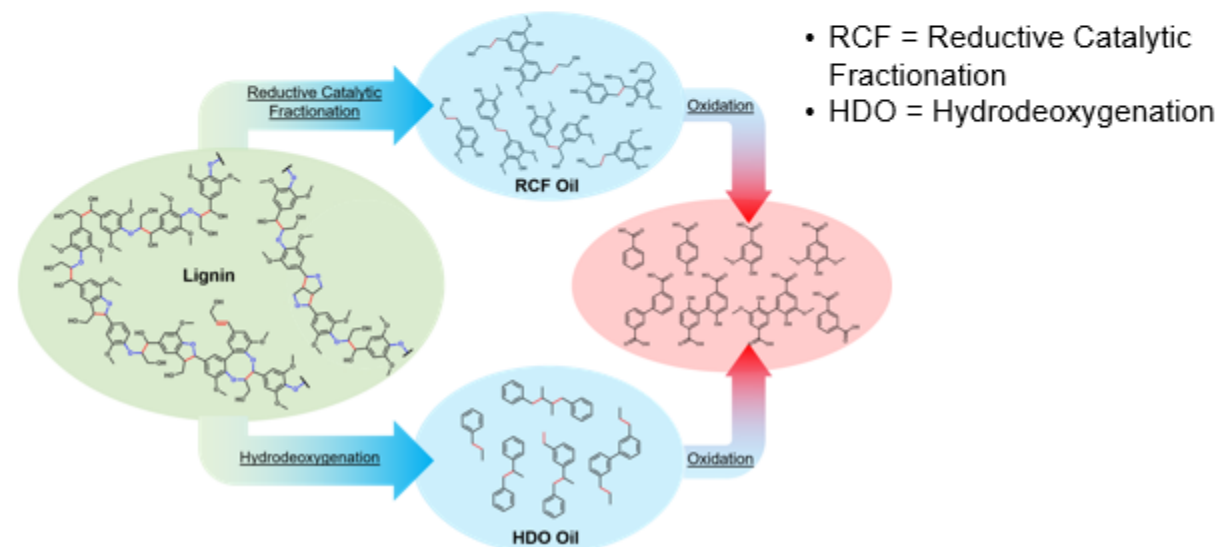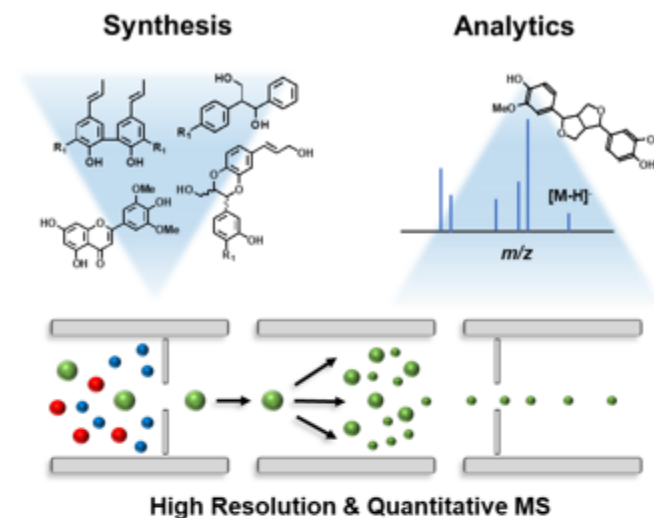
Management

Task 1: Analytics and Synthesis

- Experts in synthesis (R. Katahira) and analytics (B. Black)
- Milestones: **lignin characterization tool development, model compound synthesis**
- Collaborate with multiple projects – support BETO lignin portfolio for analytics and models
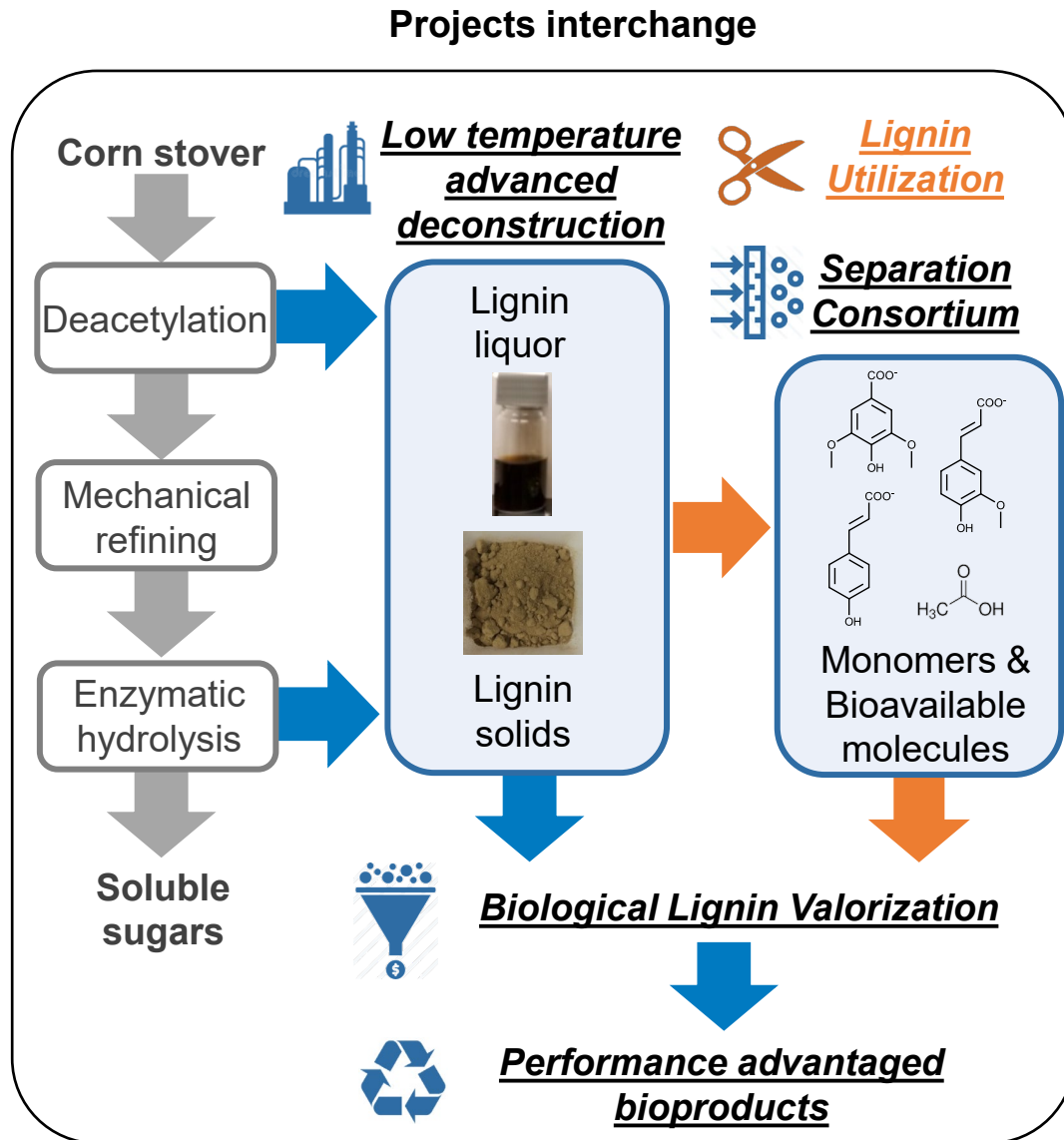
Task 2: Depolymerization

- Experts in oxidation catalysis (X. Du, C. Palumbo, K. Sullivan) and chemical engineering (J. Kruger)
- Milestones: **usable monomer yield** from **oxidative** catalytic deconstruction processes
- Milestones: **reaction/process engineering**, **TEA/LCA** with Biochem. Analysis, integration with BLV project

Project organization:

- Monthly meetings for catalysis and analytics
- Monthly 1-on-1 mtgs with PI, staff, postdocs
- *Ad hoc* meetings with Lignin-First Biorefinery Development, Biological Lignin Valorization, SepCon, Analysis, and other projects
- Ops and Project Managers – labs, equipment, reporting, and finances

Synthesis Analytics

[M-H]⁻

m/z

High Resolution & Quantitative MS

- RCF = Reductive Catalytic Fractionation
- HDO = Hydrodeoxygenation

Reductive Catalytic Fractionation

RCF Oil

Oxidation

Lignin

Hydrodeoxygenation

HDO Oil

Oxidation

Management: Project interactions

Projects interchange

We have established a network of lignin-related projects with Lignin Utilization as the central project

- Provide analytics development and support, model compound syntheses, and central lignin valorization platform for:
  - ○ Lignin-First Biorefinery Development
  - ○ Biological Lignin Valorization
  - ○ Low-Temperature Advanced Deconstruction, Feedstock-Conversion Interface Consortium
  - ○ Synthetic Metabolic Pathways for Bioconversion of Lignin Derivatives to Biofuels– ORNL
  - ○ Synthesis and Analysis of Performance-Advantaged Bioproducts
  - ○ Separations Consortium

Risks:

- Oxidative C–C bond cleavage is an inherently challenging reaction

- Oxidative reactions with lignin often lead to undesired side reactions

- Quantitative lignin analytics long pursued, not definitively/generally demonstrated
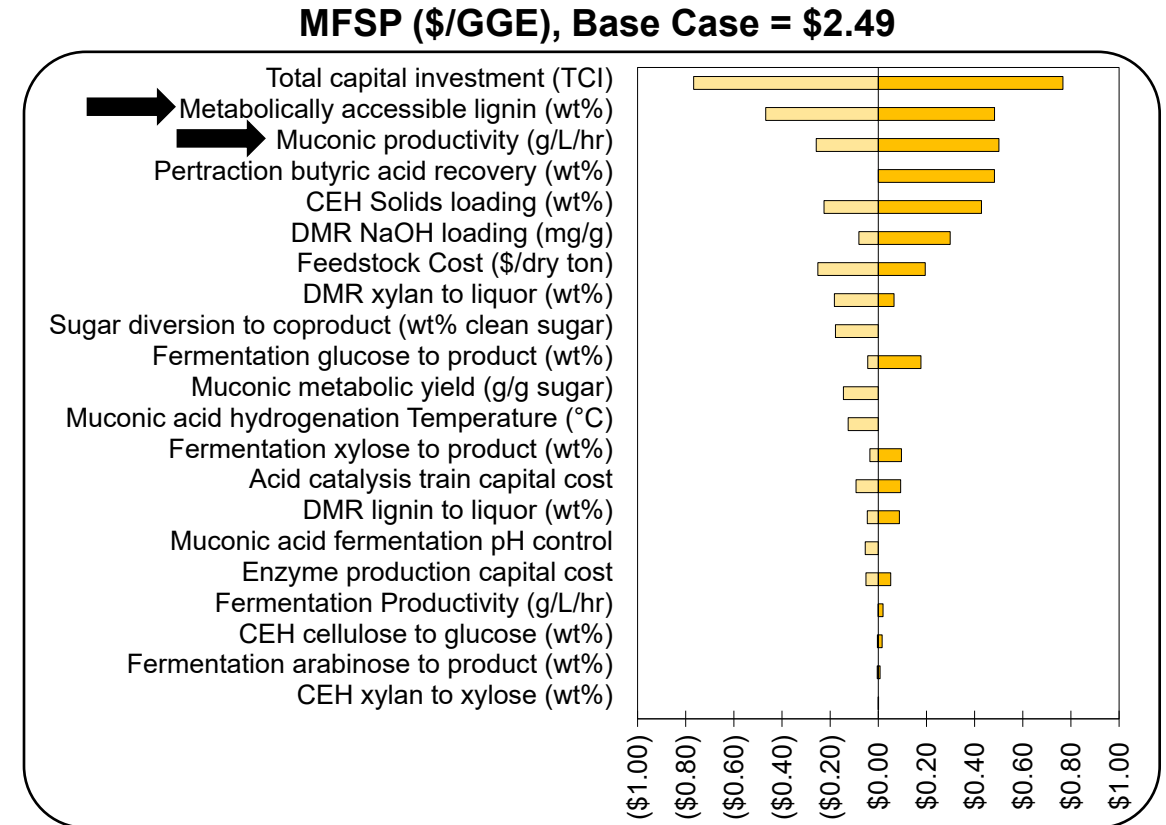
Approach

Overall approach:

- Catalyst development focuses on oxidative catalysis to cleave C–C bonds and produce bio-available aromatic compounds (SepCon, BLV)
- Analytics and synthesis disseminate methods via Laboratory Analytical Procedures
- Work with Biochem. Analysis project to develop TEA cases towards 2030 for lignin valorization

Major milestones, Go/No-Go Decisions:

- FY20: Screen 15 oxidation catalysts for C–C bond cleavage in model compounds
- FY21 G/NG: 20% above C–O bond cleavage baseline for a catalytic oxidation process
- FY22 (end of project): 60% monomer yield from lignin via C–O and C–C bond cleavage

MFSP ($/GGE), Base Case = $2.49

Tornado chart (top to bottom):
- Total capital investment (TCI)
- Metabolically accessible lignin (wt%) ←
- Muconic productivity (g/L/hr) ←
- Pertraction butyric acid recovery (wt%)
- CEH Solids loading (wt%)
- DMR NaOH loading (mg/g)
- Feedstock Cost ($/dry ton)
- DMR xylan to liquor (wt%)
- Sugar diversion to coproduct (wt% clean sugar)
- Fermentation glucose to product (wt%)
- Muconic metabolic yield (g/g sugar)
- Muconic acid hydrogenation Temperature (°C)
- Fermentation xylose to product (wt%)
- Acid catalysis train capital cost
- DMR lignin to liquor (wt%)
- Muconic acid fermentation pH control
- Enzyme production capital cost
- Fermentation Productivity (g/L/hr)
- CEH cellulose to glucose (wt%)
- Fermentation arabinose to product (wt%)
- CEH xylan to xylose (wt%)

X-axis: ($1.00) ($0.80) ($0.60) ($0.40) ($0.20) $0.00 $0.20 $0.40 $0.60 $0.80 $1.00

Approach: Analytics

B.A. Black, X. Dong, H.B. Mayes, *et al.* in preparation

Goal: Rapidly identify dimeric and oligomeric compounds in lignin samples

Challenges:

- Existing methods need standards to develop frag. patterns, limited for high-fidelity compound ID

- Existing MS analyses rely on compound libraries that do not include lignin-derived compounds
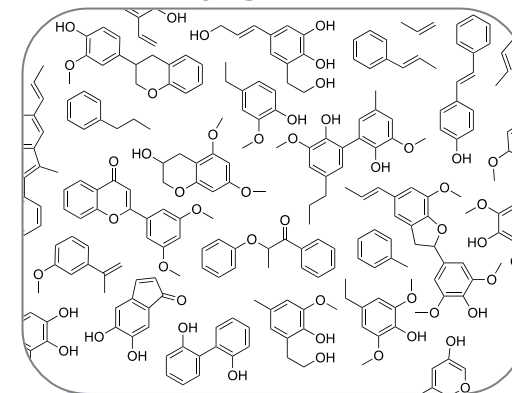
Approaches:

- Determine approaches that can differentiate lignin-derived molecules

- Build on previous modeling efforts[1-3] to generate a comprehensive lignin-based compound library

- Pattern match experimental fragmentation data with computational library to rapidly identify compounds
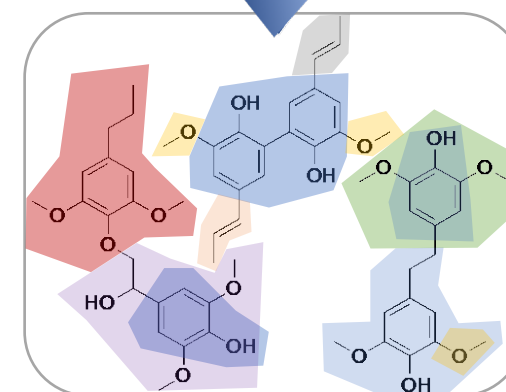
LC-MS optimization for rich data generation
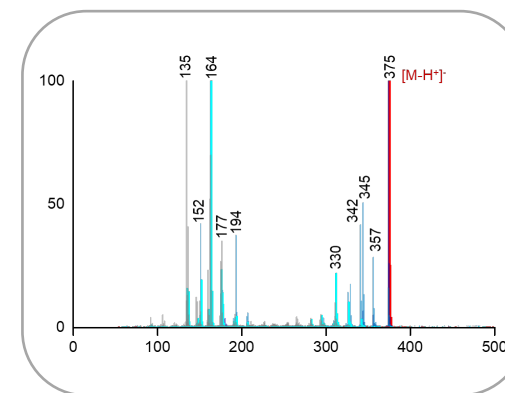
Experimental effort in LigU

Lignin-based compound library generation

Computational effort in Biochemical Process Modeling and Simulation (BPMS)

Identification by substructure matching

1. Orella *et al. ACS SusChemEng* 2019; 2. Gani *et al. ACS SusChemEng* 2019; 3. Vermaas *et al. ACS SusChemEng* 2018

# Approach: Metal-catalyzed oxidation of lignin

Goal: Develop C–C bond cleavage catalysis to depolymerize lignin oligomers

Challenges:

- C–C bonds difficult to cleave due to their stability

- Phenolic moieties of lignin deactivate catalysis

- Currently no selective methods to achieve high monomer yields through oxidation of lignin

Approaches:

- POM-mediated oxidative cleavage of C–C bonds

- Metal-mediated autoxidation for C–C bond cleavage

- Base-catalyzed depolymerization, with recovery and regeneration of salts
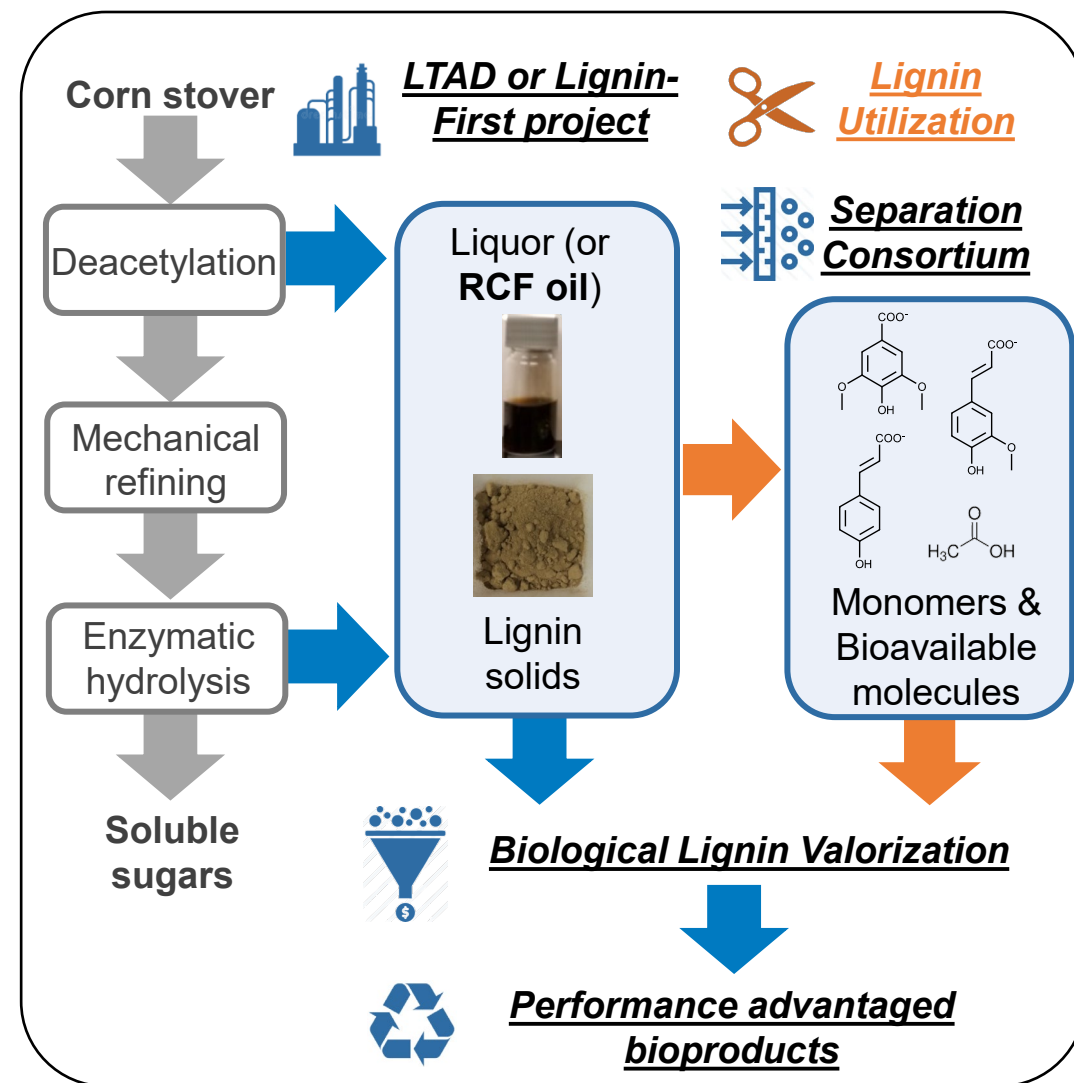
Impact

Scientific:

- Monomer yields are limited: C–C cleavage studies will be impactful
- Lignin-related computational pipelines published as open-source online via GitHub
- Developing quantitative methods for lignin analytics and process performance metrics

Industrial:

- Analytics is a common request – multiple Technical Services Agreements & CRADAs
- Partnership with oil major for advice on oxidation catalysis at scale, towards commercially relevant processes
- Focused on both DOE-relevant lignin substrates (DMR-EH) and pulp & paper lignins (Kraft)

Catalytic and Biological Valorization of Lignin to Chemicals

Biomass

Lignin Deconstruction

Microbial Conversion

Separations

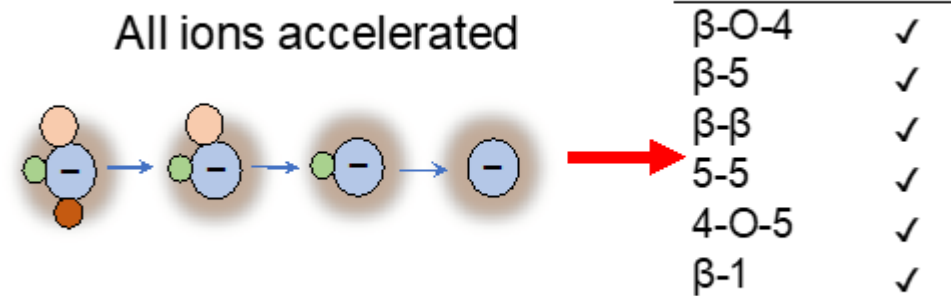Catalysis & Polymerization

Overall:

LigU aims to enable quantitative lignin characterization and achieve high-yield deconstruction chemistry for the biorefinery
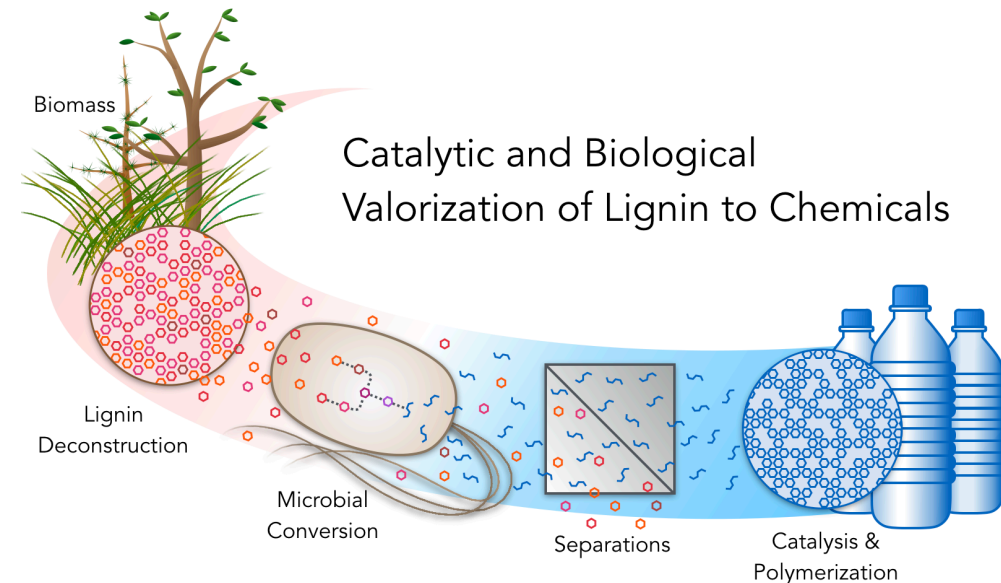
Progress and Outcomes

Outline of technical accomplishments and ongoing and future work

- Model compound syntheses

- MS method development for comprehensive lignin characterization

- Computational-experimental pipeline for rapid and quantitative lignin characterization

- Polyoxometalate-catalyzed lignin oxidation

- Metal-catalyzed lignin oxidation
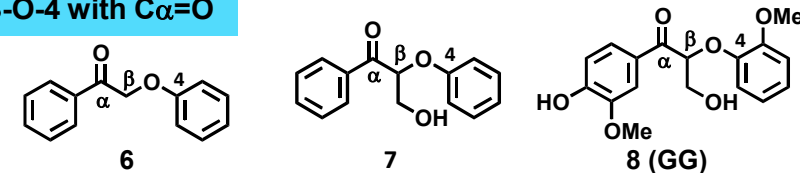
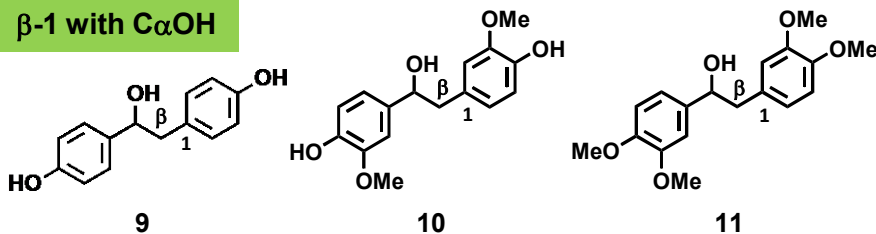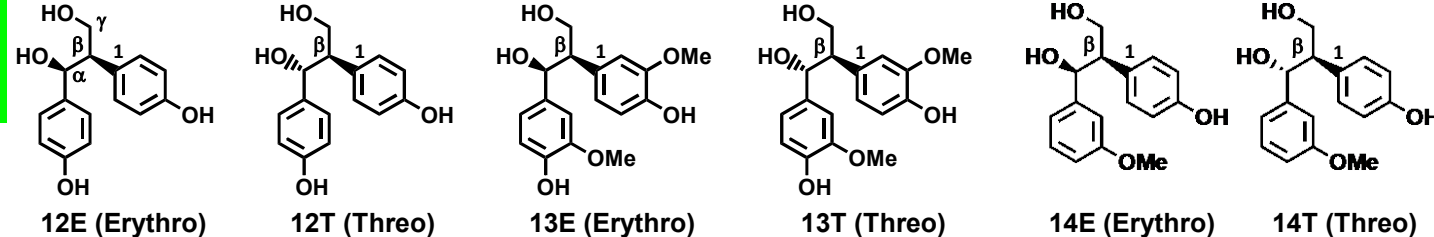- Base recovery in lignin depolymerization
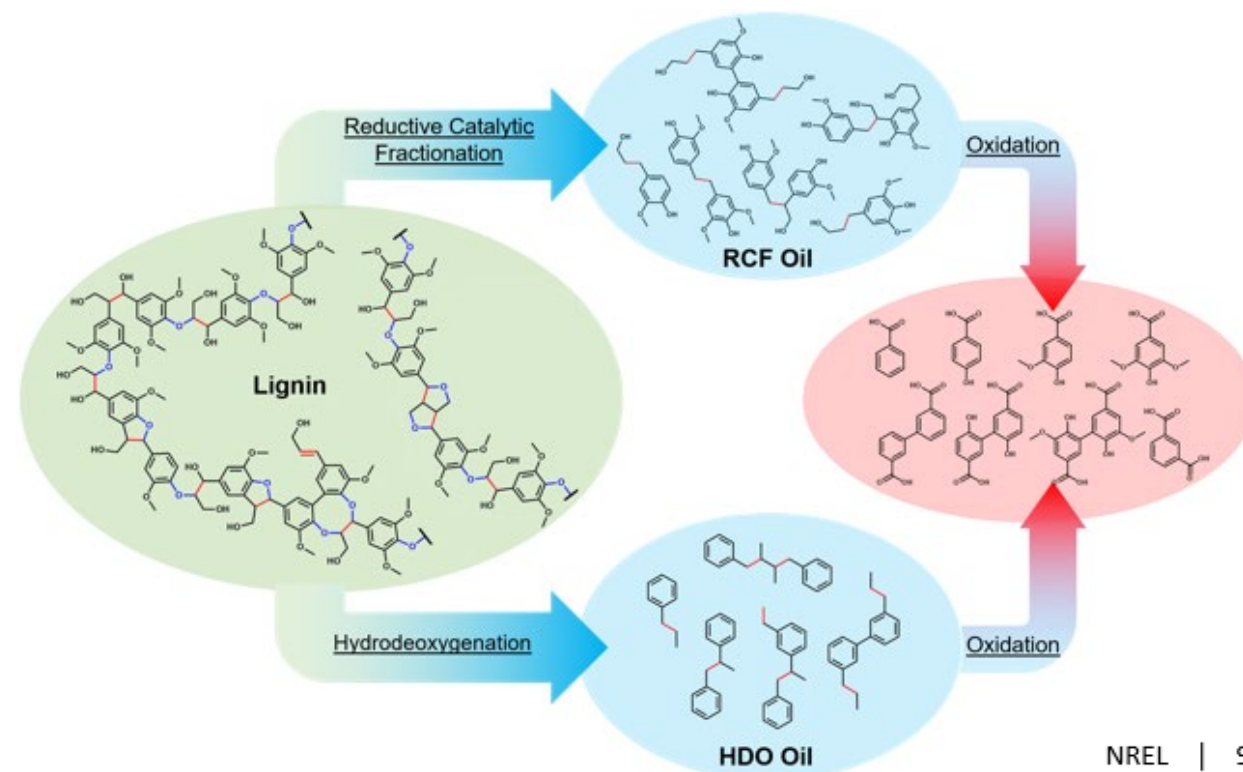
Model compound synthesis
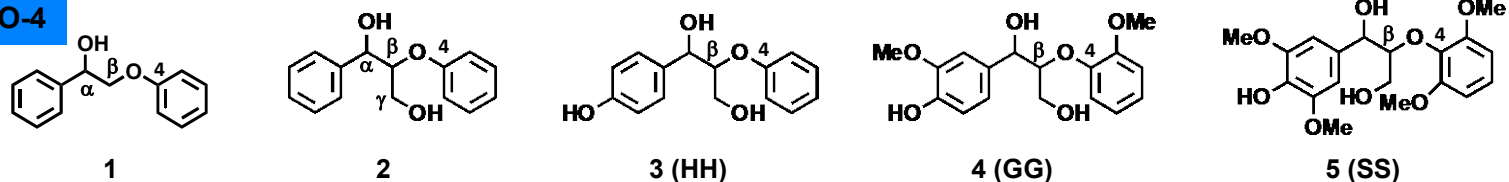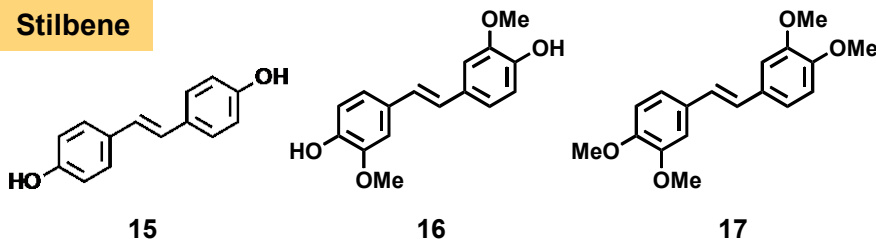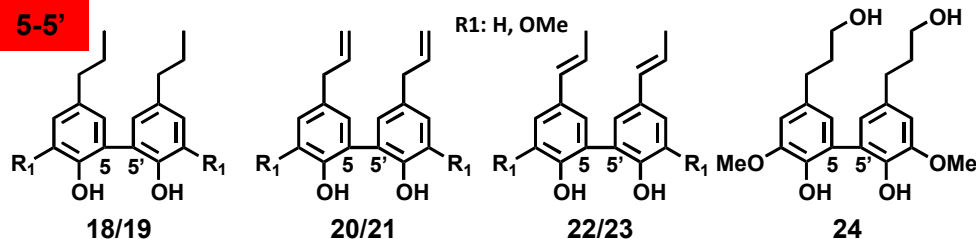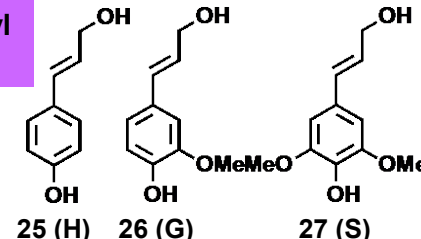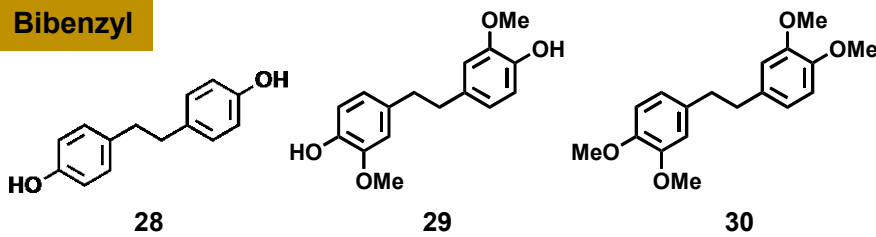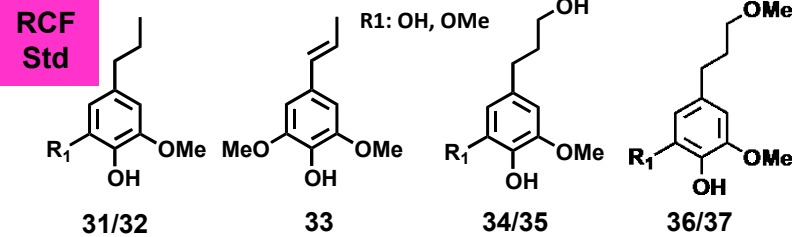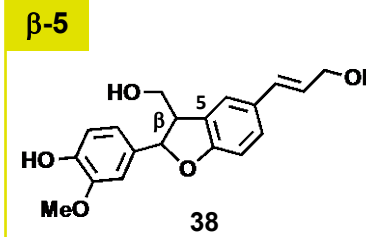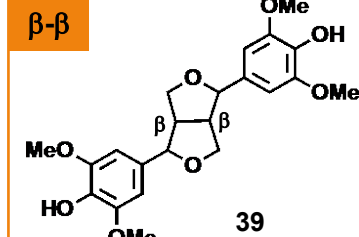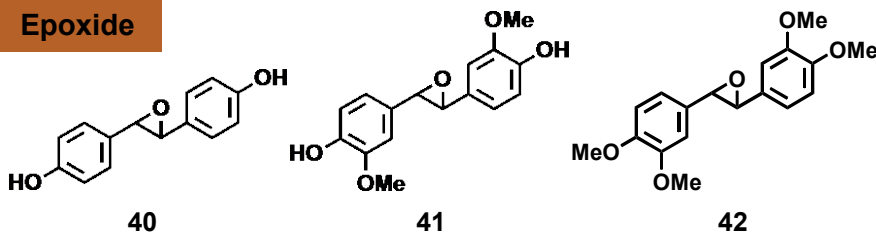
- **Prepared 42 models** as substrates for catalytic, biological, and stereo-chemically specific lignin depolymerization testing and as analytical standards
- **Enabled multiple biological and catalytic studies for lignin valorization across the DOE lignin project portfolio and for many collaborators**

Lignin analytics: new MS methods for lignin characterization

Goal: Develop methods that provide improved data for confident lignin oligomer identification

X. Dong, B.A. Black *et al.* in review at *Green Chem.*

Conventional MS^2 methods are limited for lignin identification

Tandem MS at a single collision energy

- Results in limited structural information for e.g. 5-5, 4-O-5, and β-1 linkages


resonance-MS^2

Parent ions accelerated

Product ions not accelerated

β-O-4	✓
β-5	✓
β-β	✓
5-5	x
4-O-5	x
β-1	x

one optimal collision energy (0.8 V)
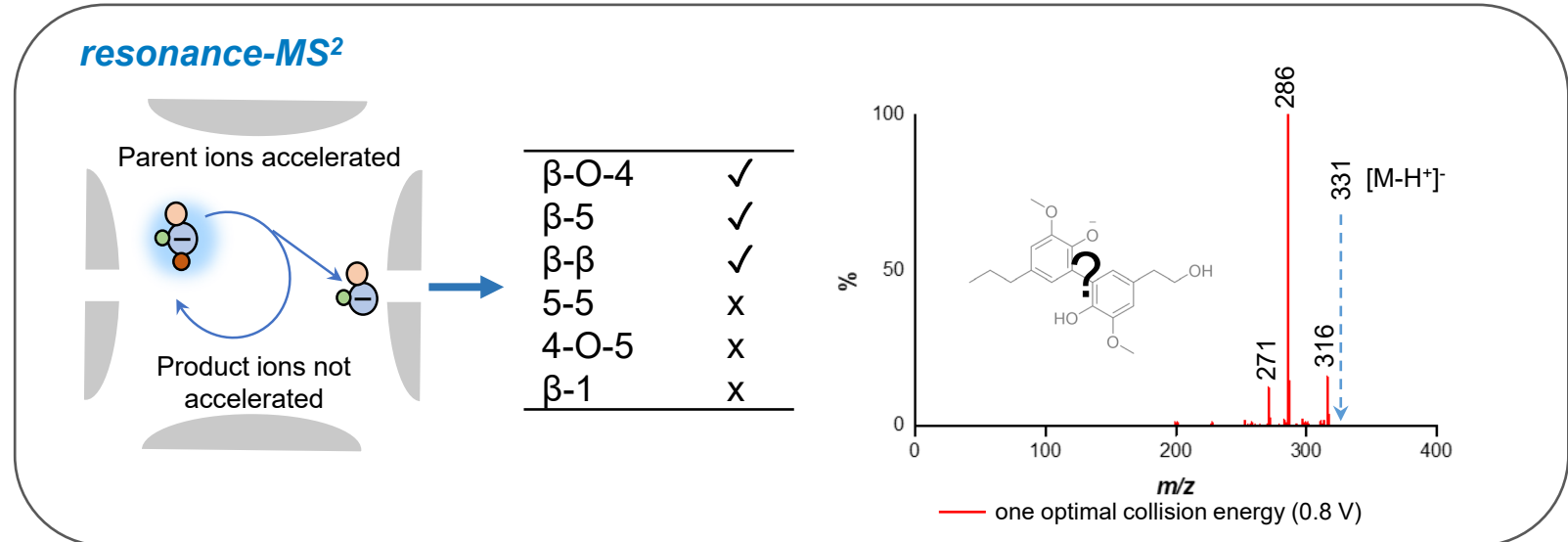
Energy resolved MS (ERMS) methods

Tandem MS at multiple collision energies

- Increase in fragmentation with beam-configured instruments for maximum structural info
- Allows for ID of lignin oligomers from 6 major linkages
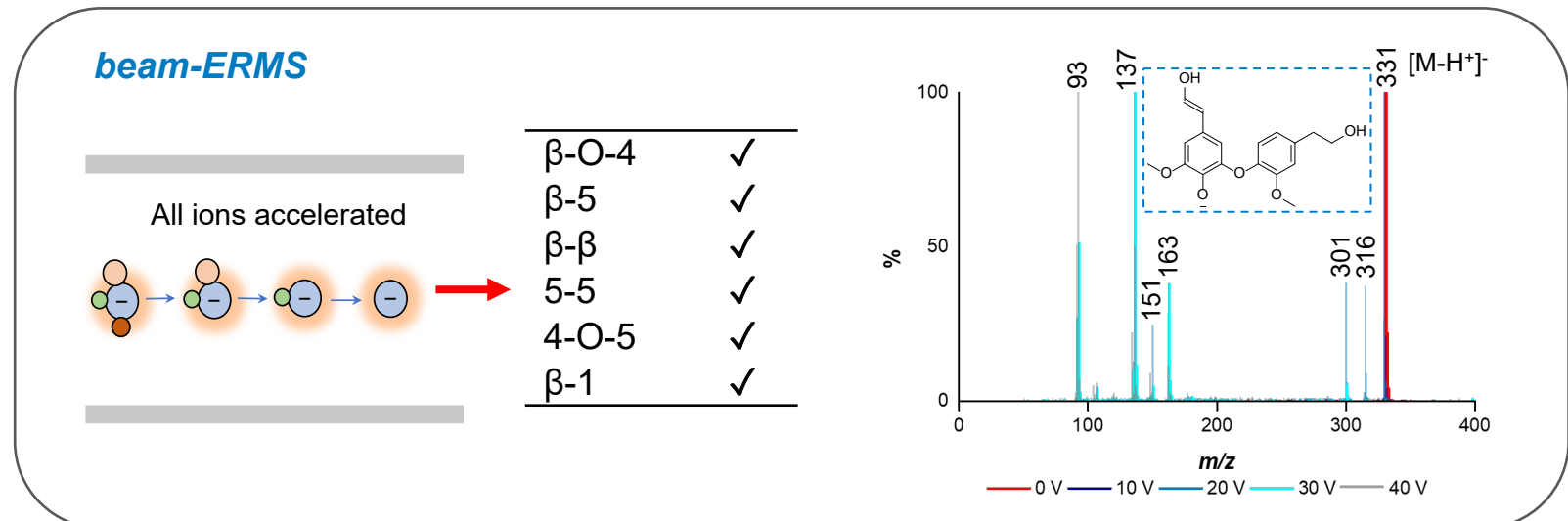
Beam-ERMS methods allow for identification of all lignin oligomers

beam-ERMS

All ions accelerated

β-O-4	✓
β-5	✓
β-β	✓
5-5	✓
4-O-5	✓
β-1	✓

0 V — 10 V — 20 V — 30 V — 40 V

Lignin analytics: library development and matching algorithm

Experiment
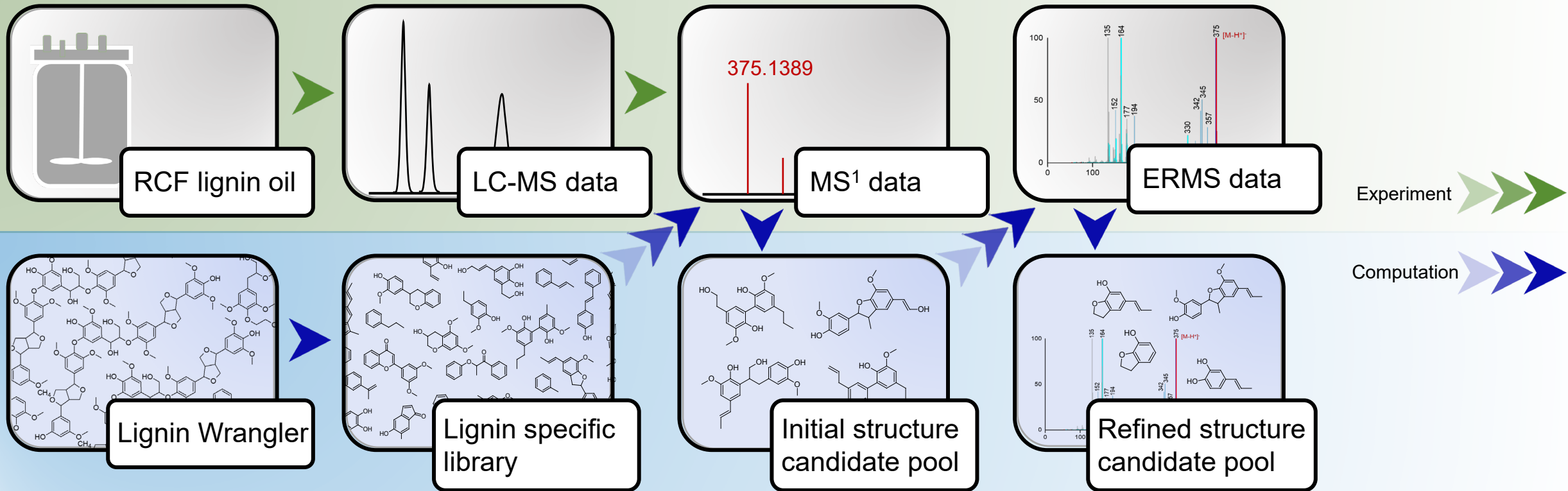
Computation

LigninWrangler: new modular computational-experiment pipeline for lignin analytics

MakeLignin builds on our efforts[1,2] to generate libraries of lignin structures based on kinetics or experimental data

BreakLignin applies chemistry to lignin structures to create a library of thousands of lignin-derived molecules

MS2Molecules matches lignin library compounds to MS^2 data, identifying likely compound structures based on fragmentation

H.B. Mayes, *et al.* in preparation

1. Orella *et al. ACS SusChemEng.* 2019
2. Vermaas *et al. Green Chem* 2019

Polyoxometalate-based oxidation of Kraft lignin model compounds

Kraft pulping process[1]

Dominated lignin production process
(50 million tons/year)

98-99% of KL incineration
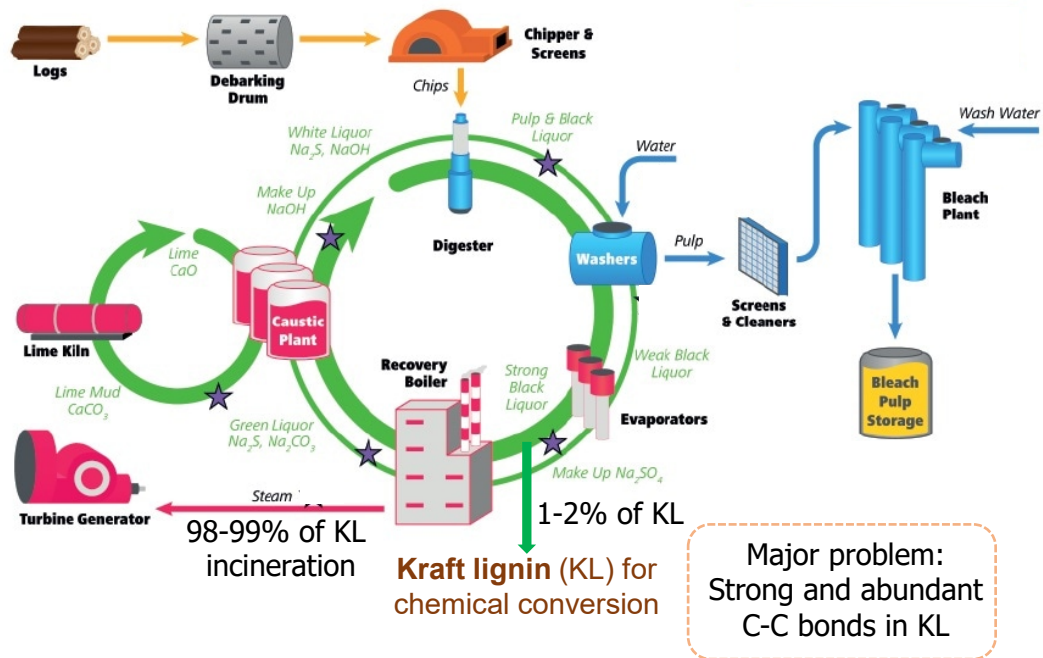
1-2% of KL

Kraft lignin (KL) for chemical conversion

Major problem:
Strong and abundant
C-C bonds in KL

POM catalyzed C-C cleavage of KL model compounds

C-C bond

POM, O$_2$, 180°C, 3h
HOAc
(Conv. 87.8%)

1.9%   0.2%   8.0%   11.4%   BP: 6.27%

C(OH)-C bond

POM, O$_2$, 180°C, 3h
HOAc
(Conv. 100%)

4.1%   12.1%   BP: 78.0%

C(O)-C bond

POM, O$_2$, 180°C, 3h
HOAc
(Conv. 100%)

1.4%   41.7%
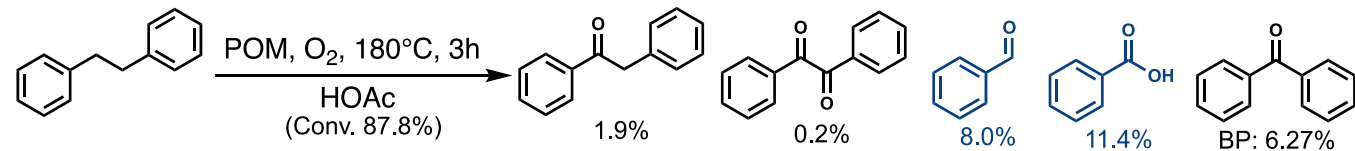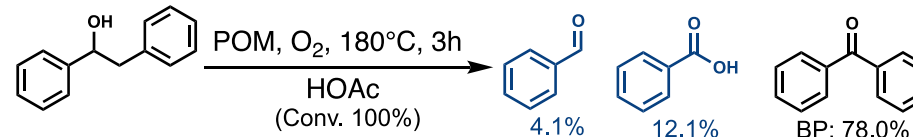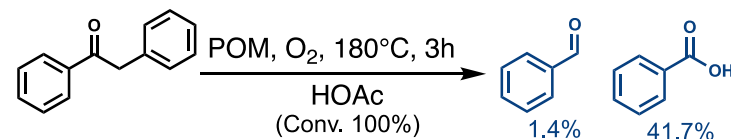
Polyoxometalate (POM) catalyzed C-C cleavage in lignin model compounds

- Both oxidative C-H activation and C(OH)-C cleavage can be achieved by POMs via known mechanisms[2,3]

- POM catalytic systems have potential to be applied for depolymerization of C–C linkages in lignin

- In acetic acid (HOAc), POM can cleave all types of C-C bonds

1. Metrohm process analytics.
2. Neumann et al. JACS. 2001
3. Neumann et al. JACS. 2008

GPC

GC

	Mn	Mw	PD
KL	1200	8400	7.2
KL-w/o POM	440	940	2.2
KL-POM	280	370	1.3

180℃ 3h

KL-w/o POM   KL-POM

120℃ 3h

180℃ 3h
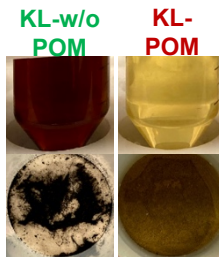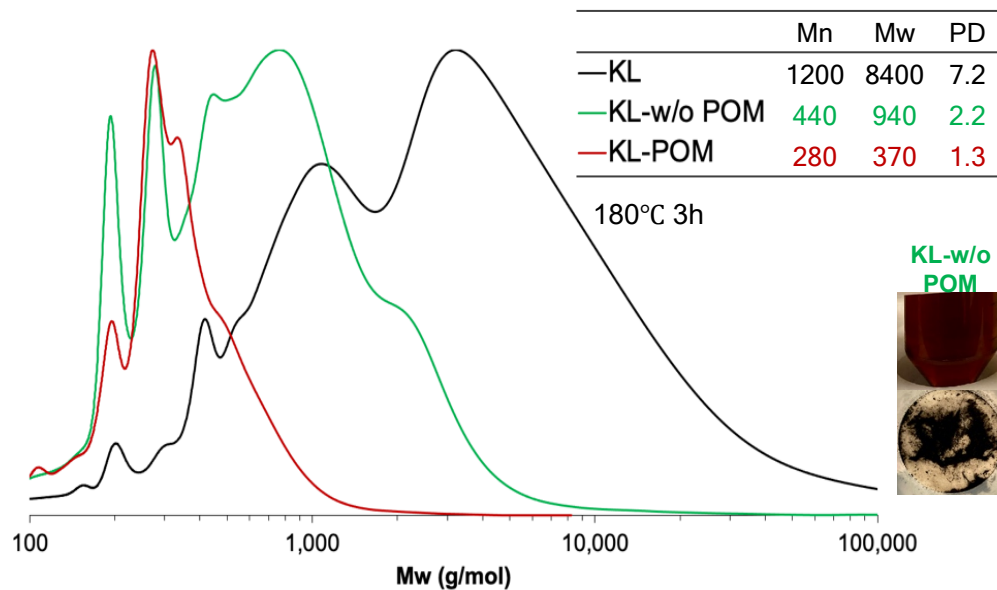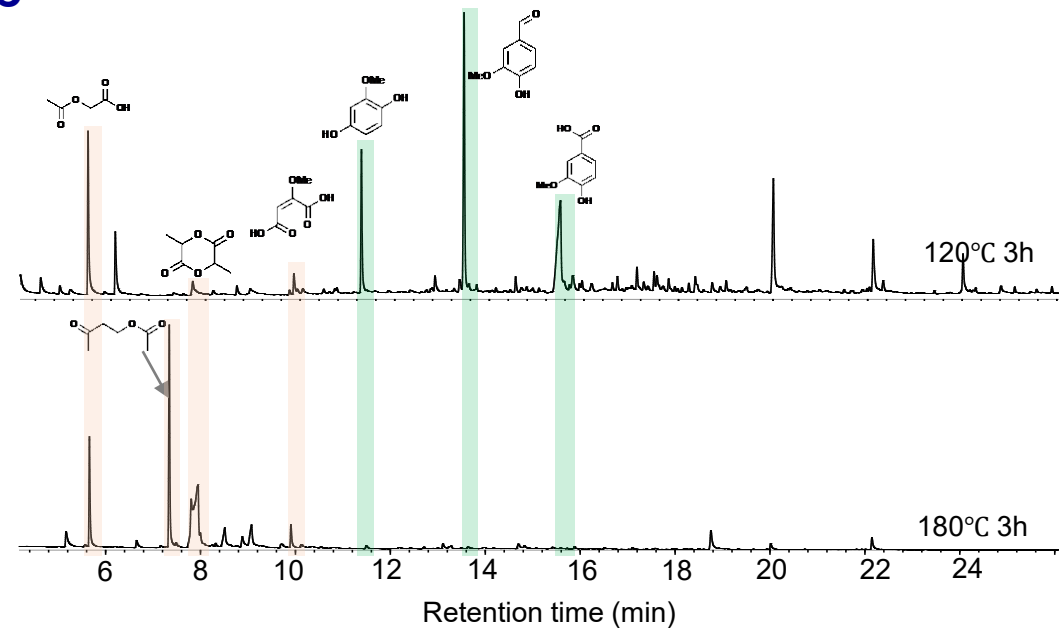
POM-catalyzed Kraft lignin depolymerization

- In HOAc, KL depolymerization extent is considerable – strong effect of temperature on aromatic monomer yields

Current directions:

- Optimizing reaction conditions for model compounds and KL to maximize aromatic products
- Applying advanced MS-based analytics and emerging NMR methods to identify C-C cleavage products in KL

Developing basis for catalytic chemistry with model compounds

- Autoxidation used at scale in petrochemical industry

- **Goal:** apply autoxidation for C–C bond cleavage

- Achieved C–C cleavage product yields up to 85% with propylbenzene and *p*-propylanisole

- Products nearly exclusively benzoic acids (which are readily bio-available compounds)

- Successfully protected phenols through O-methylation, enabling oxidation
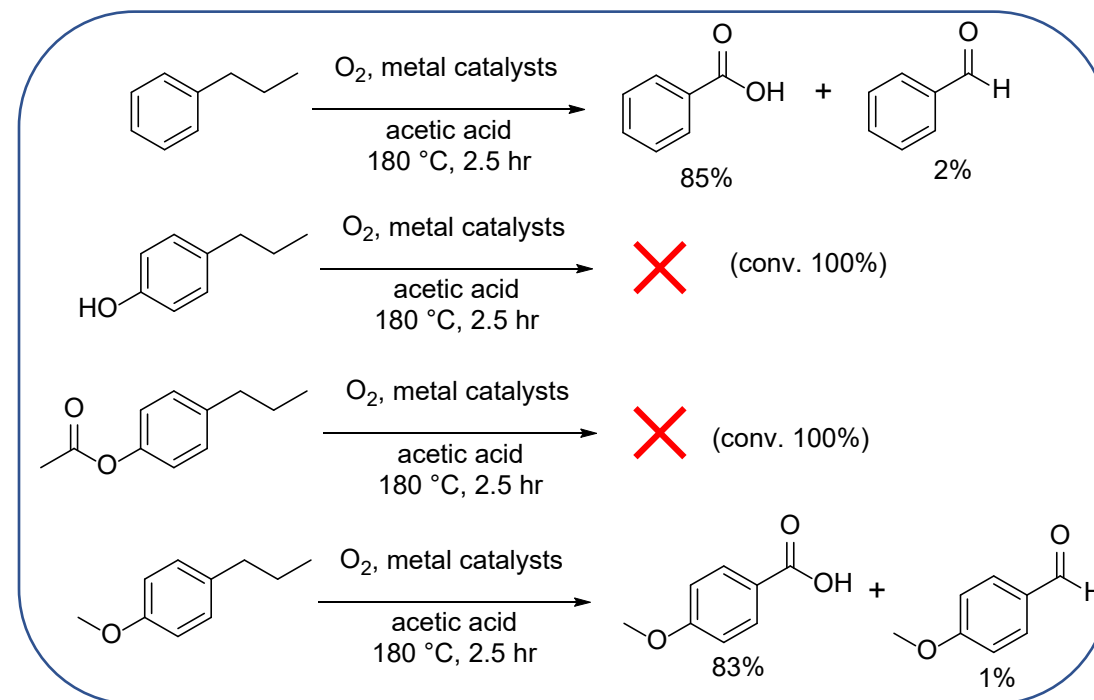
Current directions:

- More realistic model compounds, including G- and S-type monomers, as well as dimers

- Developing detailed mechanistic understanding

Metal-catalyzed oxidation of lignin
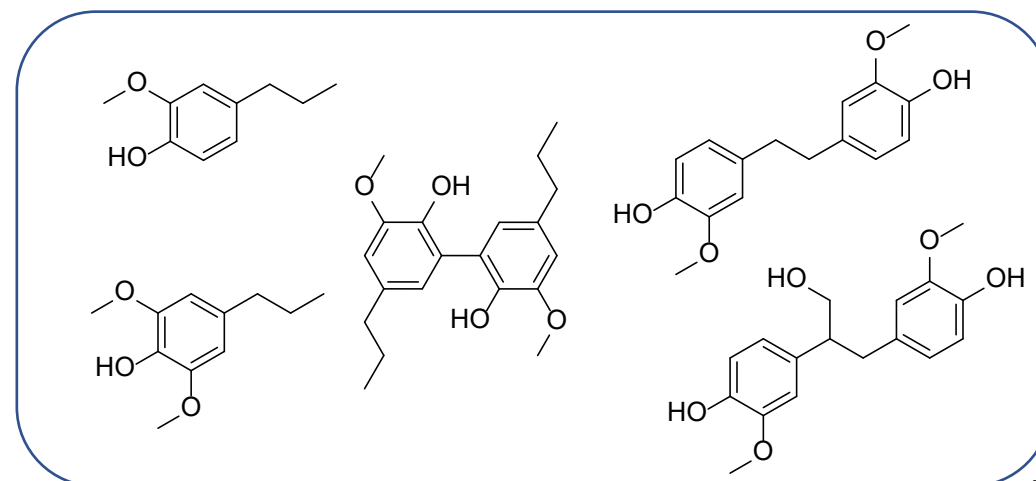
K.P. Sullivan *et al.* in preparation
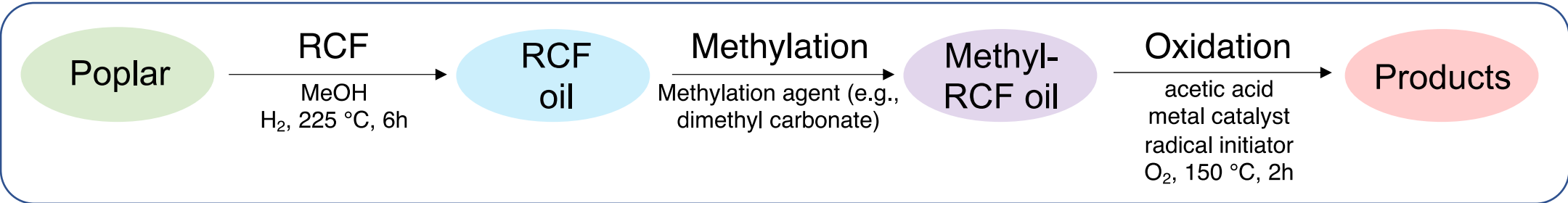
Lignin substrates for oxidation catalysis

- Lignin from Lignin-First Biorefinery Development project
- Treat with RCF to obtain C-C dimer- and oligomer-rich substrates

Current directions:

- Optimize depolymerization of RCF oil from pine and poplar lignin
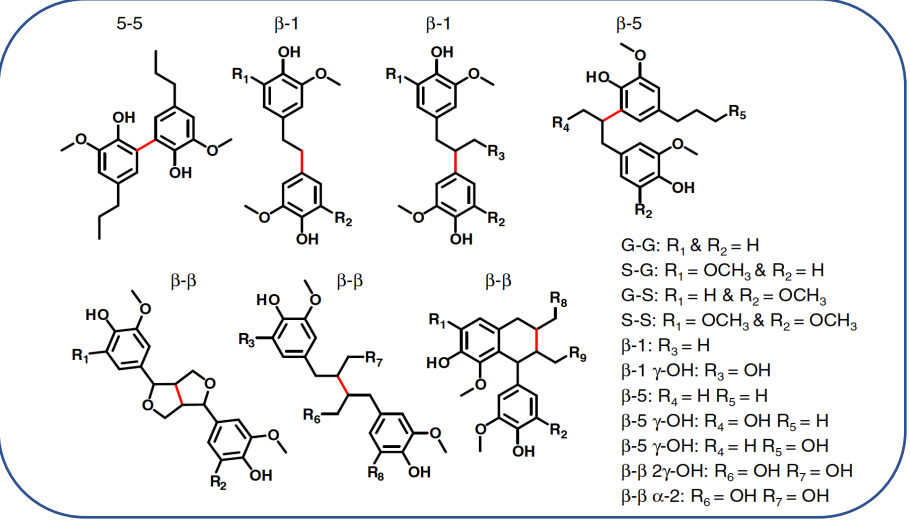
Image from EM Anderson, ML Stone *et al. Nature Comm.* 2019
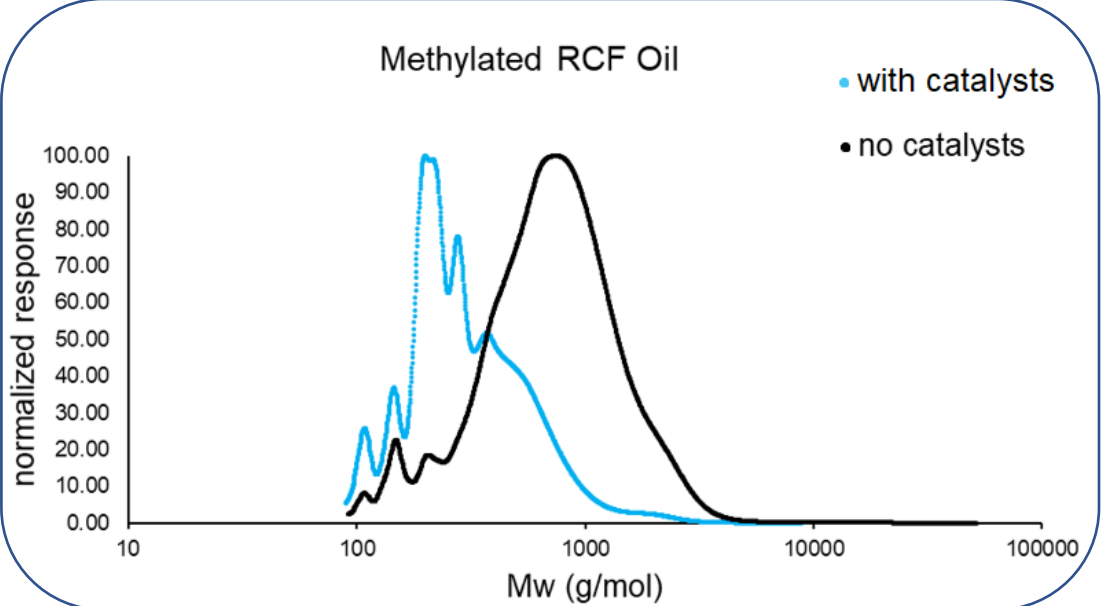
Base recovery and regeneration in lignin depolymerization
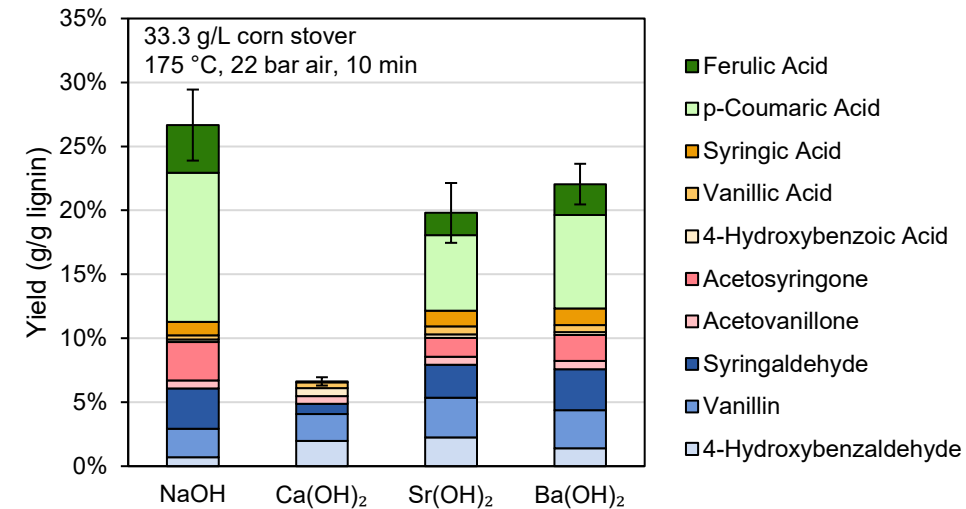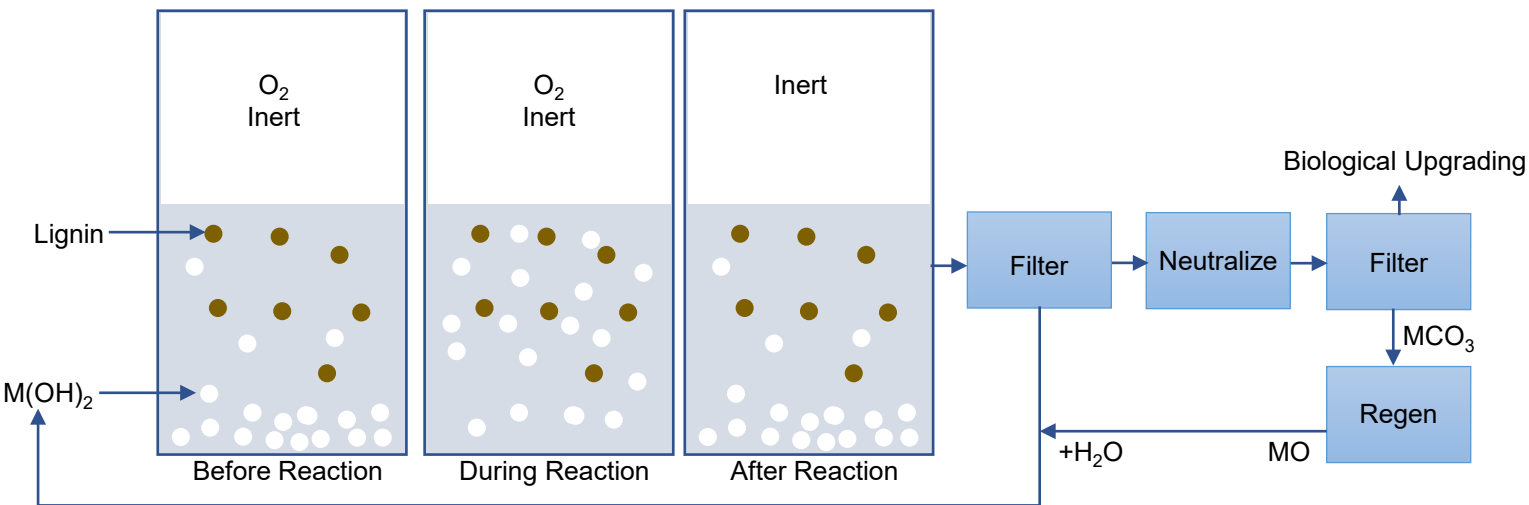
Temperature-reversible solubility of Sr(OH)$_2$ allows high monomer yields and easy recycle of base by filtration and regeneration

- Estimated monomer yields nearing 50 wt%, including deacetylation and alkaline oxidation steps

- Neutralization with CO$_2$ produces low-salt pH 6 solution, allowing bio-upgrading

- Integrates with ongoing research targeting C-C bond cleavage in base

- **May be able to replace NaOH in deacetylation, BCD, and/or alkaline oxidation**

Base recovery and regeneration in lignin depolymerization

TEA and LCA show that $Sr(OH)_2$ is more economical and sustainable than NaOH

- Recycle equipment and more expensive base offset by near-elimination of ongoing base purchase and disposal

- Solids loading is major factor

- May enable sequential cleavage of specific lignin bonds to maximize monomer yields within DMR-EH framework

  - Higher base ($Sr(OH)_2$) loading in deacetylation = release all ester-linked monomers, which degrade under oxidation conditions

  - Aqueous alkaline oxidation or RCF = cleave β-O-4 bonds

  - Non-aqueous oxidation = cleave C—C-linked oligomers

- Global warming potential: 30% improvement with Sr

- Cumulative energy demand and ecotoxicity: 15-20% improvement with Sr
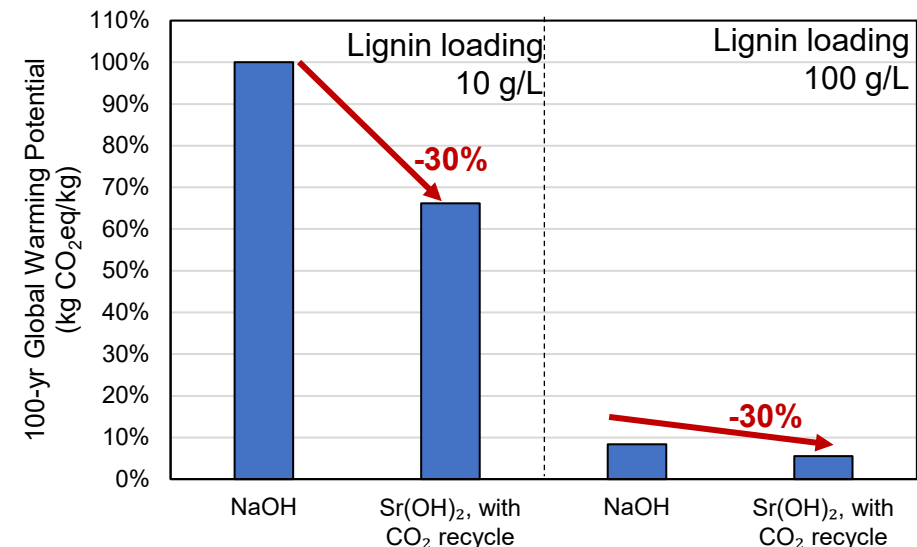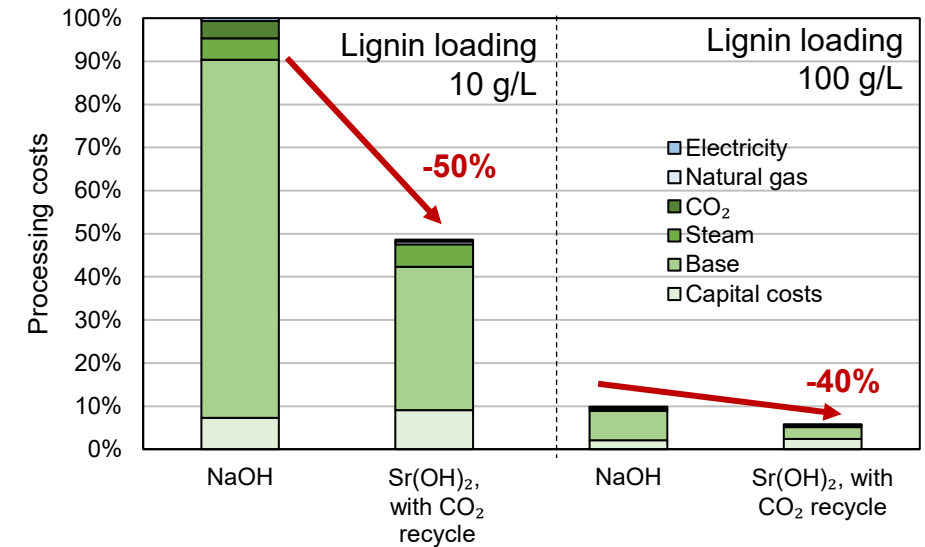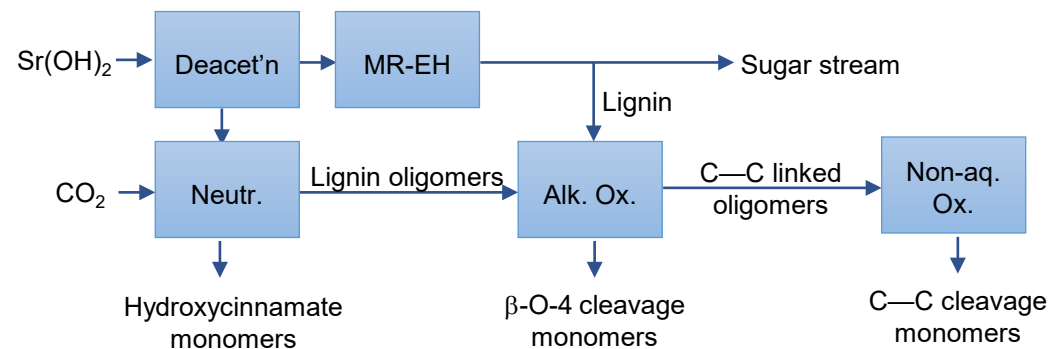
Summary

- **Overview:** Focus on 1) increasing the theoretical monomer yield for lignin deconstruction via C-C bond cleavage, 2) developing quantitative lignin analytics, and 3) supporting BETO lignin portfolio

- **Management:** LigU serves as a central hub for lignin valorization projects in the BETO portfolio

- **Approach:** Focus on parallel tracks for lignin deconstruction, employ analysis to identify metrics and milestone targets

- **Impact:** Strategies for technical lignins and DOE-relevant biorefinery lignins

- **Progress and Outcomes:** New computational-experimental pipeline developed for lignin MS-based analytics, two new oxidation methods for lignin deconstruction, recoverable bases demonstrated
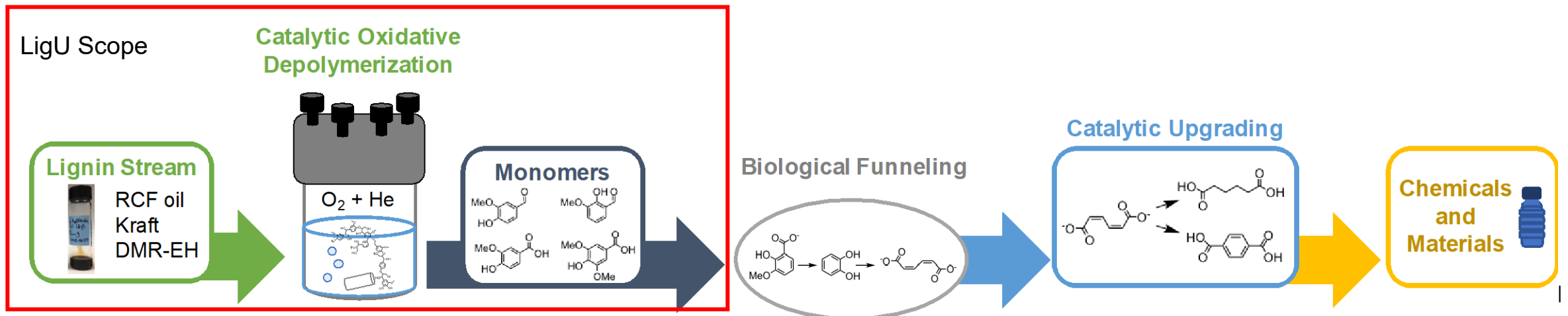
Quad charts

Timeline
- Active Project Duration: 10/1/2019 – 9/30/2022
- Total Project Duration: 10/1/2016 – 9/30/2022

	FY20	Active Project (FY20-22)
DOE Funding	$1,450,000	$4,350,000

Project Partners

BETO projects: Lignin-First Biorefinery Development (2.2.3.106), Biological Lignin Valorization (2.3.2.100), Separations Consortium (2.5.5.502) , Biochemical Platform Analysis (2.1.0.100)

Nat'l labs: Oak Ridge National Laboratory

University collaborators: Northwestern University, University of North Texas, University of British Columbia, Massachusetts Institute of Technology, University of Wisconsin Madison

Barriers addressed
- Ct-C Process development for conversion of lignin
- Ct-F Increasing the yield from catalytic Processes

Project Goal
Develop industrially-relevant processes and tools for lignin valorization

End of Project Milestone
Deliver an oxidation catalyst that can achieve ≥75% monomer yield from a realistic lignin stream via C-O and C-C bond cleavage with molecular oxygen as the oxidant in a batch or flow-through system.

Funding Mechanism
Bioenergy Technologies Office FY20 AOP Lab Call (DE-LC-000L071) – 2019

Acknowledgements

DOE Technology Managers Jay Fitzgerald, Sonia Hammache, and Beau Hoffman

NREL Contributors:

Brenna Black, David Brandner, Megan Browning, Nicholas Cleveland, Ryan Davis, Xueming Dong, Xu Du, Rick Elander, Renee Happs, Stefan Haugen, Rui Katahira, Kelsey Kinley, Bruno Klein, Jacob Kruger, Megan Krysiak, Heather Mayes, Joel Miscall, Chad Palumbo, Michelle Reed, Allison Robinson, Wouter Schutyser, Lisa Stanley, Kevin Sullivan, Todd Vinzant

Collaborators:

Linda Broadbelt (Northwestern), Rick Dixon (UNT), Thomas Elder (USDA), Lindsay Eltis (UBC), Adam Guss, Robert Hettich, Josh Michener (ORNL), Yuriy Román-Leshkov, Eric Anderson, Michael Stone (MIT), John Ralph, Shannon Stahl (University of Wisconsin Madison)

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BIOENERGY TECHNOLOGIES OFFICE

Q&A

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Additional Slides

Responses to previous reviewer comments

- The Lignin Utilization project is tasked with a wide breadth of work that is actually three projects (described as tasks: characterization, deconstruction, and upgrading). Ultimately, the goal is to recover the highest possible yield of usable monomers from lignin, to be upgraded either chemically or biologically to value-added compounds (e.g., muconic acid, adipic acid, terephthalic acid), all to be done from an economically attractive process. Each of these tasks performed to date have demonstrated progress on track with expectations. A new catalyst for C-C bond cleavage has been identified, a more recoverable base to replace sodium hydroxide (NaOH), better understanding of structure, analytical development, and synthesis of model compounds, and pathways to adipic acid and terephthalic acid have been demonstrated. There is still a long way to go in terms of yields, such as additional catalyst identification and development, process integration (chemical and biological), and, importantly, proving out the economics. The project appears very well managed and integrated with other projects such as Biological Lignin Valorization, which will continue to be essential to keep on track.

- This is a well-thought-out and organized team effort with a solid technical approach. Model compound synthesis upfront to evaluate and define the approach is a great first principle approach for the project. There are excellent project results to date, and the team is on track to assist the fuel dollars-per-GGE longer term and help other teams by excellent characterization of products formed for use by the bioupgrading team. Excellent progress on the recovery of monomers from multiple feed materials with the easier-to-recover oxidative bases versus sodium hydroxide. There are minor questions around processes to convert muconate to dimethyl terephthalate (DMT), including iodine, which can be a challenge to remove from wastestreams and any traces could carry through causing issues with processes downstream. Has the team considered other isomerization approaches that might be easier to separate, such as solid isomerization catalysts for fixed-bed operations? Also is there a reason why nickel, which is cheaper than palladium (Pd), is not used in dehydrogenation to DMT? Or is it just for initial proof of concept?

  - The question about use of iodine is a good one. Iodine catalysis is used industrially today, but we are working towards other options for the muconate isomerization in parallel as well, including heterogeneous catalysis strategies, as the reviewer suggests. In terms of the dehydrogenation chemistry to produce DMT, Pd is an initial starting point for this reaction to demonstrate proof of concept, as the reviewer notes.

- This project tackles a key challenge to higher biological utilization of lignin-enriched streams, namely presence of condensed C-C linkages. The approach builds on NaOH-catalyzed lignin depolymerization, now using bases that can be readily recovered and recycled. To facilitate the analysis of lignin products, the team created a library of model lignin compounds, which represents a unique resource that has been made available to other BETO projects. To further demonstrate the applied significance of a basecatalyzed lignin depolymerization process, it will be helpful to report yields of products from the downstream bioconversion step in terms of amount of product per amount of total lignin consumed. The stability of lignin-derived compounds produced by the base-catalyzed process will also be important to verify.

- This appears to have been a broad, effective program that has made significant progress toward its goals while enabling other projects through expansion of the lignin analysis toolbox. The application of analytics and development of a range of model compounds should be leveraged across multiple BETO lignin-related projects.

- The PIs present an important project with direct relevance to the biorefinery. Their effort to generate a reasonable yield of monomers from lignin depolymerization processes that can be used for further biological processing is valuable and addresses a crosscutting challenge to biorefinery development. Improving the clarity regarding certain process steps and the current status of the model versus real lignin work would be helpful.

  - We agree on how to report yields. This is indeed a challenge in many lignin conversion processes, but as discussed at the peer review during the questions, we are attempting to achieve comprehensive mass closures to be able to provide these yield data to the TEA teams in a rigorous fashion.

Publications

In preparation:

Jacob S. Kruger, Reagan J. Dreiling, Daniel Wilcox, Katherine Krouse, Camille Amador, David G. Brandner, Kelsey J. Ramirez, Stefan J. Haugen, Bruno Klein, Ryan E. Davis, Rebecca Hanes, Gregg T. Beckham, Lignin Alkaline Oxidation Using Reversibly Soluble Bases.

In review or revision:

Xueming Dong, Rui Katahira, Yanding Li, David G. Brandner, Reagan J. Dreiling, John Ralph, Brenna A. Black*, Gregg T. Beckham*, Energy-Resolved Mass Spectrometry as an Identification Tool for Lignin. In review at *Green Chem*.

Eugene Kuatsjah, Anson C. K. Chan, Rui Katahira, Gregg T. Beckham, Michael E. P. Murphy, and Lindsay D. Eltis*, Elucidating the repertoire of lignostilbene dioxygenases of *Sphingomonas* sp. SYK-6 and their role in the catabolism of lignin-derived aromatic compounds, in revision at *J. Biol. Chem.*

Gerald N. Presley‡, Allison Z. Werner‡, David C. Garcia, Stefan J. Haugen, Caroline B. Hoyt, Rui Katahira, Kelsey J. Ramirez, Richard J. Giannone, Gregg T. Beckham*, and Joshua K. Michener*, Pathway discovery and engineering for cleavage of a ß-1 lignin-derived biaryl compound, in revision at *Metabolic Eng.*

Sandra Notonier‡, Allison Z. Werner‡, Eugene Kuatsjah, Linda Dumalo, Paul E. Abraham, E. Anne Hatmaker, Caroline B. Hoyt, Antonella Amore, Kelsey J. Ramirez, Sean P. Woodworth, Dawn M. Klingeman, Richard J. Giannone, Adam M. Guss, Robert L. Hettich, Lindsay D. Eltis*, Christopher W. Johnson*, and Gregg T. Beckham*, Metabolism of syringyl lignin-derived compounds in *Pseudomonas putida* enables convergent production of 2-pyrone-4,6-dicarboxylic acid, in revision at *Metabolic Eng*.

In print:

Laura Berstis, Thomas Elder, Richard A. Dixon, Michael F. Crowley*, Gregg T. Beckham*, Coupling of flavonoid nucleation sites with monolignols studied by density functional theory, in press at *ACS SusChemEng (*2021)

Josh V. Vermaas, Michael F. Crowley*, Gregg T. Beckham*, Molecular lignin solubility and structure in organic solvents, in press at *ACS SusChemEng* (2020).

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Nicholas E. Thornburg, M. Brennan Pecha, David G. Brandner, Michelle L. Reed, Josh V. Vermaas, William E. Michener, Rui Katahira, Todd B. Vinzant, Thomas D. Foust, Bryon S. Donohoe, Yuriy Román-Leshkov, Peter N. Ciesielski,* Gregg T. Beckham*, Mesoscale reaction-diffusion phenomena governing lignin-first biomass fractionation, *ChemSusChem* (2020), 13, 4495-4509.

In print, continued

Erica Teixeira Prates, Michael F. Crowley, Munir S. Skaf, Gregg T. Beckham*, The catalytic mechanism of aryl-ether bond cleavage in lignin by LigF and LigG, J. Phys. Chem. B. (2019) 123, 10142-10151.

Josh V. Vermaas, Michael F. Crowley*, Gregg T. Beckham*, A quantitative molecular atlas for interactions between lignin and cellulose, *ACS SusChemEng.* (2019) 7, 19570-19583.

Josh V. Vermaas, Richard A. Dixon, Fang Chen, Shawn D. Mansfield, Wout Boerjan, John Ralph, Michael F. Crowley*, Gregg T. Beckham*, Passive membrane transport of lignin-related compounds, *PNAS* (2019), 116, 23117-23123.

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Thomas J. Elder*, Jose Carlos del Rio, John Ralph, Jorge Rencoret, Gregg T. Beckham, Radical coupling reactions of piceatannol and monolignols: A density functional theory study, *Phytochemistry* (2019) 164, 12-23.

Josh V. Vermaas, Lauren D. Dellon, Linda J. Broadbelt, Gregg T. Beckham*, Michael F. Crowley*, Automated transformation of lignin topologies into atomic structures with LigninBuilder, *ACS Sust. Chem. Eng.* (2018) 7, 3443-345.

Andrea Corona, Mary J. Biddy, Derek R. Vardon, Morten Birkved, Michael Hauschild, and Gregg T. Beckham*, Life cycle assessment of adipic acid production from lignin, *Green Chem.* (2018) 20, 3857-3866.

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Publications, patents, presentation, awards, and commercialization

Presentations (2019-2021)

Performance-advantaged bioproducts from lignin, BioEnergy Society of Singapore (via webinar), December 14th, 2020

Efforts towards sustainable performance-advantaged bioproducts and plastics upcycling, Materials Life-Cycle Management Mini-Symposium, University of Delaware (via webinar), October 1st, 2020

Bacterial aromatic catabolism for lignin and plastics conversion, University of Minnesota BioTechnology Institute, March 5th, 2020

Using selective chemical and biological catalysis to upcycle lignin and plastics, ExxonMobil Research and Engineering, October 25th, 2019

Enzymes for lignin and plastics conversion, Enzymes, Coenzymes and Metabolic Pathways, July 23rd, 2019

Engineering non-model cell factories to produce novel polymer precursors, Biomass to Biobased Chemicals and Materials, July 17th, 2019

Challenges and opportunities in plastics upcycling, Plenary Invited Lecture, 26th BioEnvironmental Polymers Meeting, June 5th, 2019

New progresses on biological and catalytic lignin valorization, Great Lakes Bioenergy Research Center and University of Wisconsin Madison, May 13th, 2019

Catalytic valorization of lignin in the biorefinery, 4th Ibero-American Congress on Biorefineries, Plenary Invited Lecture, October 24, 2018

Patent applications (cumulative)

Polyoxometalate catalyzed reductive catalytic fractionation (RCF) oil and Kraft lignin depolymerization: ROI-20-129, pending

Process for Converting CO2 into Conductive Carbons via Flash Joule Heating: ROI-21-40, pending

Issued patents (cumulative)

Chimeric Enzyme For Conversion of Guaiacol: ROI-16-21

Integrated biological and catalytic conversion for the production of renewable polymer precursors derived from aromatic β-ketoadipate pathways: ROI-15-24

Muconate Addition to Industrial Polymers: ROI-15-88

Muconate Separations and Catalytic Upgrading to Adipic Acid: ROI-15-89

Renewable Unsaturated Polyesters and Resins: ROI-16-54