EFRC: CENTER FOR DIRECT CATALYTIC CONVERSION OF BIOMASS TO BIOFUELS (C3Bio)

UPDATED: AUGUST 2016

AWARDS: $20.0M (August 2009 – July 2014); $11.6M (August 2014 – July 2018)

WEBSITES: http://science.energy.gov/bes/efrc/centers/EFRC/c3bio; http://www.purdue.edu/discoverypark/c3bio/

TEAM: **PURDUE UNIVERSITY (Lead):** Maureen McCann (Director), Rakesh Agrawal, Nicholas Carpita, Clint Chapple, W. Nicholas Delgass, Hilkka Kenttämaa, Richard Meilan, Nathan Mosier, Fabio Ribeiro; **National Renewable Energy Laboratory**: Gregg Beckham, Michael Crowley, Bryon Donohoe, Michael Himmel, Melvin Tucker; **University of California-Santa Barbara**: Mahdi Abu-Omar; **University of Tennessee**: Joseph Bozell; **Northeastern University**: Lee Makowski

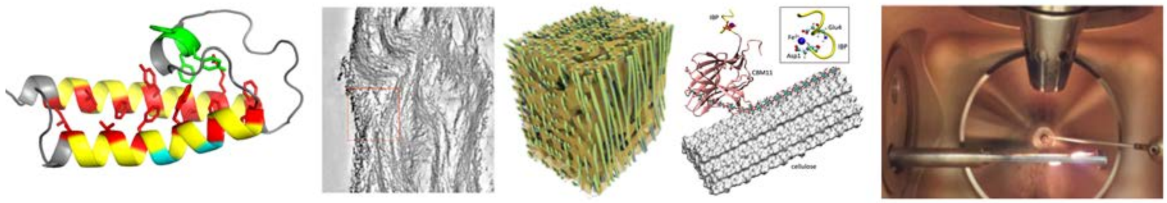
SCIENTIFIC MISSION AND APPROACH

C3Bio explores the potential of chemical catalysis and fast pyrolysis to transform the main components of lignocellulosic biomass (cellulose, xylan, and lignin) from grasses and trees directly to liquid hydrocarbons and aromatic co-products, the components of gasoline and jet fuels. The center aims to specify both the structures within and the reaction products from lignocellulosic biomass. C3Bio's vision is a future of "no carbon left behind"—the full utilization of carbon from plant cell walls in energy-dense fuels and high-value chemicals that are compatible with existing engines and transportation infrastructure. The team of plant biologists, chemists, and chemical engineers address three research goals:

1) **Robust catalyses**: Discover catalytic and pyrolytic processes specifically designed for the structural complexity of biomass.
2) **Redesigned biomass**: Tailor the structure of plant cell walls to optimize them for carbon- and energy-efficient catalytic and pyrolytic transformations.
3) **Biomass-catalyst interactions and systems**: Deliver innovative pathways for targeted product portfolios from tailored lignocellulosic biomass.

SELECTED SCIENTIFIC ACCOMPLISHMENTS

- Developed a powerful bimetallic catalytic system for the disassembly of lignin via β-O-4 ether bond cleavages from milled wood that produces high-value methoxypropylphenol products. Lignin is the major source of biomass recalcitrance in biochemical conversion processes. The new ability to first deconstruct lignin to useful products revolutionizes the conventional concept of the cellulosic biorefinery in which lignin is a waste stream or co-fired for power generation.
- Built a suite of hydropyrolysis and catalytic upgrading reactors coupled with in-house, cutting-edge mass-spectrometric analyses to develop a detailed understanding of how fast-hydropyrolysis and *in situ* hydrodeoxygenation in the presence of appropriate catalyst(s) can produce 100% drop-in hydrocarbon fuels starting from cellulose, methoxypropylphenols, or from delignified biomass. C3Bio found that the number of primary products of fast pyrolysis is greatly reduced, making hydrodeoxygenation in the vapor phase a viable technology.
- Gained genetic control of lignin synthesis within plants to produce poplar trees with high yield and selectivity for a single methoxypropylphenol product after catalytic depolymerization of lignin. This provides proof-of-concept that tailored biomass could reduce energy inputs in the biorefinery, for example, by facilitating product separations.
- New knowledge of the regulatory control of lignin biosynthesis by transcription factors is allowing bypass of a yield penalty commonly observed in plants with modified lignin structures. C3Bio can now simplify lignin structure in plants for downstream conversion without compromising growth.



C3Bio research, from left: crystal structure of a plant-specific domain in cellulose synthase; electron tomogram of a plant cell wall after catalytic treatment; model of secondary wall structure constructed from tomograms; model of a cellulose microfibril bound by a fusion protein delivering an iron catalyst in planta; fast-pyrolysis of cellulose at the inlet of the mass spectrometer.

IMPACT

- C3Bio has organized and/or co-hosted two Frontiers in Bioenergy symposia, three I-cubed workshops for STEM High School teachers, five Duke Energy Academy at Purdue programs, Purdue Bioenergy day, and the Purdue-France Biofuels Workshop together with the French US scientific attaché.
- Maureen McCann leads the Duke Energy Academy at Purdue program (DEAP), a one-week immersive program for High School students and teachers, which aims to inspire pre-college students both to enter STEM disciplines and to envision energy scholarship as part of their educational and career goals. C3Bio faculty contribute lectures, hands-on demonstrations, and research projects for student/teacher teams. Over 400 participants have been supported by a grant from the Duke Energy Foundation in the past five years, and funding is committed through 2019.
- Anchored by C3Bio research, the U.S. Department of the Navy and Purdue University, in 2014, signed a Statement of Cooperation agreeing to work together to convert up to half of the Navy and Marine Corps' energy consumption to alternative sources, including biofuels, by 2020.
- C3Bio's catalytic depolymerization of lignin is the technology basis of start-up company **Spero Energy Inc.**, founded by Mahdi Abu-Omar in 2013 (http://www.speroenergy.com). Presently manufactured from petroleum feedstock via a multi-step process, methoxypropylphenols are high-value fragrance and flavor compounds with an annual market value of $450 M.
- Follow-on funding for C3Bio has exceeded $6M, including $1.5M contribution of mass spectrometric equipment from industry partner Thermo Scientific.

PUBLICATIONS AND INTELLECTUAL PROPERTY

As of May 2016, C3Bio had published 119 peer-reviewed publications cited over 2,250 times and filed 18 disclosures, 9 US patent applications, and 3 international patent applications. 4 disclosures or patent applications have been licensed. The following is a selection of impactful papers:

- Bonawitz, N. D., Kim, Y. I., Tobimatsu, Y., Ciesielski, P., Anderson, N. A., Ximenes, E., Maeda, J., Ralph, J., Donohoe, B. S., Ladisch, M. & Chapple, C. Disruption of Mediator rescues the stunted growth of a lignin-deficient *Arabidopsis* mutant. *Nature* **509**, p376–p380, doi: 10.1038/nature13084 (2014). [**79 citations**]
- Parsell, T., Yohe, S., Degenstein, J., Jarrell, T., Klein, I., Gencer, E., Heweston, B., Hurt, M., Kim, J. I., Choudhari, H., Saha, B., Meilan, R., Mosier, N., Ribeiro, F., Delgass, W. N., Chapple, C., Kenttämaa, H. I., Agrawal, R,. & Abu-Omar, M. M. A synergistic biorefinery based on catalytic conversion of lignin prior to cellulose starting from lignocellulosic biomass. *Green Chemistry* **17**, p1492-p1499, doi**:** 10.1039/C4GC01911C (2015). [**54 citations**]
- Parsell, T. H., Owen, B.C., Klein, I., Jarrell, T. M., Marcum, C. L., Haupert, L. J., Amundson, L. M., Kenttämaa, H. I., Ribeiro, F. H., Miller, J. T. & Abu-Omar, M. M. Cleavage and hydrodeoxygenation (HDO) of C–O bonds relevant to lignin conversion using Pd/Zn synergistic catalysis. *Chemical Science* **4**, p806-p813, doi: 10.1039/C2SC21657D (2013). [**101 citations**]
- Ventakrishnan, V. K., Degenstein, J. C., Smeltz, A. D., Delgass, W. N., Agrawal, R. & Ribeiro, F. H. High-pressure fast-pyrolysis, fast-hydropyrolysis and catalytic hydrodeoxygenation of cellulose: production of liquid fuel from biomass. *Green Chemistry* **16**, p792-p802, doi**:** 10.1039/C3GC41558A (2014). [**25 citations**]