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Board on Chemical Sciences and Technology

Final Technical/Scientific Report

DOE award number: DE-SC0010761
Recipient: National Academy of Sciences
Project Title: Industrialization of Biology: A Roadmap to Accelerate the Advanced Manufacturing of Chemicals
Project Director: Douglas Friedman

Executive Summary

A new report from the National Research Council lays out a 10-year roadmap to accelerate the use of biological synthesis and engineering in chemical manufacturing. Advances in synthetic biology -- the ability to read, write, and edit the DNA of microorganisms -- have enabled the design and construction of new and more efficient chemical reaction routes within cells, which opens the door for making chemicals that cannot presently be made at commercial scale through traditional chemical manufacturing processes. Biomanufacturing of chemicals could also help address global challenges related to energy, climate change, agriculture, and environmental sustainability by reducing toxic byproducts, greenhouse gas emissions, and fossil fuel consumption in chemical production, the report says.

In 2012, bio-based product markets represented more than 2.2 percent of the U.S. gross domestic product, or $353 billion in economic activity, and the markets for bio-based chemicals and industrial biotechnology for chemical manufacturing processes are growing roughly twice as fast as those in biomedicine or agriculture. Despite the industry's recent and projected growth, a number of technical and societal challenges must be overcome for biomanufacturing to be competitive with current chemical processes, the report says. The roadmap identifies the necessary advancements in basic science and engineering that would expand the role of biotechnology in chemical manufacturing.

Product and capital costs are critical considerations for biomanufacturing. Carbon in the form of fermentable sugars, derived from grains such as corn, is the primary raw material for the biological production of chemicals and often the largest single input cost -- up to as much as 65 percent -- of the total production cost, while fermentation itself represents the largest capital expense in bioprocessing. One of the roadmap's goals is increasing the widespread use of more abundant, more diverse, and less costly sources of carbon, such as from cellulosic biomass, natural gas, or biological methane. Developments such as continuous fermentation to replace small-volume batch production will help to mitigate some capital costs at manufacturing facilities.

The roadmap also calls for further research and development to facilitate chemical transformation via biological synthesis and engineering. Improvements in the ability to rapidly design enzymes and engineer their properties to carry out specific complex chemical transformations would significantly reduce the costs of scaling up biomanufacturing processes. In addition, the number and range of microorganisms engineered for industrial use will need to increase with the diversity of products manufactured.

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Manufacturing chemicals through biology might produce societal benefits while requiring fewer trade-offs between growth and sustainability than traditional chemical manufacturing, the committee said. Products based on biological sources such as plants, algae, bacteria, yeast, fungi, or other organisms could replace many chemicals now derived from petroleum or other fossil fuels, which are a limited resource. The specificity of biological synthesis could lead to high-purity products with fewer toxic byproducts and less waste. The report stresses the need for efforts to inform the public of the nature of industrial biotechnology and of its societal benefits, and to make sure that concerns are communicated effectively between the public and other stakeholders.

In addition to scientific advances, a number of governance and societal factors will influence the industrialization of biology. Industry norms and standards need to be established in areas such as read/write accuracy for DNA, data and machine technology specifications, and organism performance in terms of production rates and yields. An updated regulatory regime is also needed to accelerate the safe commercialization of new host organisms, metabolic pathways, and chemical products, and regulations should be coordinated across nations to enable rapid, safe, and global access to new technologies and products.

The committee recommends that relevant federal agencies support the scientific research and foundational technologies required to advance the areas identified in the report. To ensure that the roadmap goals are pursued and to adapt as needed, government agencies should consider establishing a mechanism to provide ongoing direction for technology development, translation, and commercialization at scale.

Goals, Objectives, and Accomplishments

Project Statement of Task

In order to realize the full benefit of research investments intended to enable the advanced manufacturing of chemicals using biological systems, an ad hoc committee will develop a roadmap of necessary advances in basic science and engineering capabilities, including knowledge, tools, and skills. Working at the interface of synthetic chemistry, metabolic engineering, molecular biology, and synthetic biology, the committee will identify key technical goals for this next-generation chemical manufacturing, then identify the gaps in knowledge, tools, techniques, and systems required to meet those goals, and targets and timelines for achieving them. It will also consider the skills necessary to accomplish the roadmap goals, and what training opportunities are required to produce the cadre of skilled scientists and engineers needed. While focused on industrial manufacturing of chemicals, the roadmap challenges identified here will also be relevant to applications in health, energy, environment and agriculture by advancing the tools and techniques required for new development in these areas.
Essential elements of the roadmap that the committee will consider in the study and in its report, include the following:

1. identification of the core scientific and technical challenges that must be overcome;
2. identification of and timeline for tools, measurement techniques, databases, and computational techniques needed to serve as the building blocks for research and applications;
3. how to develop, share, and diffuse common interoperable standards, languages, and measurements; and
4. when and how to integrate non-technological insights and societal concerns into the pursuit of the technical challenges.

The report will provide guidance to both the research and research funding communities regarding key challenges, knowledge, tools, and systems needed to advance the science and engineering required for advanced manufacturing of chemicals using biological systems and to develop the workforce required to realize these advances. The report will not include recommendations related to funding, government organization or policy issues.

The project's preliminary work schedule included 4 in-person meetings, committee teleconferences, and production and dissemination of the report. The project successfully completed these milestones.

The report resulting from this project, *A Roadmap to Accelerate the Advanced Manufacturing of Chemicals,* was published through the National Academies Press on March 13, 2015. It reflects the accomplishment of the goals and objectives in the statement of task. It is available for free download from the National Academies Press website at http://www.nap.edu/IndBio.

Since the report's release, it has been downloaded over 4,400 times, appeared as a feature in Chemical and Engineering News, and has received mention in several social media venues. The report has had a major impact on the international scene, being used as a tool at the OECD Science and Technology Committee and by China, the 2016 president of the G20, as a "key document" in planning its agenda for the G20 in 2016. The report will continue to be disseminated to the research community for at least the next 12 months.

The report was delivered to DOE in embargoed, pre-publication form on February 27, 2015 and briefings were provided on March 3, 2015.

Summary of Project Activities

The award was processed on September 1, 2013. An ad-hoc committee was appointed to address the statement of task and approved by the National Research Council Executive Office on January 31, 2014. The members are:

Thomas M. Connelly, Jr. (Chair), E.I. du Pont de Nemours & Company
Michelle Chang, University of California, Berkeley
Lionel Clarke, UK Synthetic Biology Leadership Council
Andrew D. Ellington, University of Texas at Austin
Nathan Hillson, Lawrence Berkeley National Laboratory
Richard A. Johnson, Global Helix LLC
Jay D. Keasling, University of California, Berkeley
Kristala Jones Prather, Massachusetts Institute of Technology
Stephen S. Laderman, Agilent Technologies, Inc.
Pilar Ossorio, University of Wisconsin Law School, Madison
Reshma Shetty, Gingko Bioworks, Inc.
Christopher A. Voigt, Massachusetts Institute of Technology
Huimin Zhao, University of Illinois, Urbana-Champaign

The committee held its first in-person information-gathering meeting on February 26-27, 2014 in Washington, DC.

The committee held a two-day workshop on May 28-29, 2014 in Washington, DC.

The committee held its third information-gathering meeting August 13-14, 2014 at the Joint BioEnergy Institute in Emeryville, CA.

The committee held its fourth and final meeting September 9-10, 2014 in Irvine, CA. This closed-session meeting contained no information-gathering sessions and was used by the committee to deliberate on findings and recommendations.

The committee produced a written report. The report went through the NRC's formal review and response process and was made publicly available through the National Academies Press website on March 13, 2015.

The committee briefed sponsors and other interested parties on March 3, 2015.

Products developed under the award

a. Publications

National Research Council. Industrialization of Biology: A Roadmap to Accelerate the Advanced Manufacturing of Chemicals. Washington, DC: The National Academies Press, 2015.

The report is available free of charge on the web at http://www.nap.edu/IndBio.

b. web site or other Internet sites that reflect the results of this project;

Report website: http://nas-sites.org/synbioroadmap/