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Bioenergy research in 2017

2016 will be remembered as a year of global change both geopolitically and scientifically. From the point of view of bioenergy researchers, several events and continued economic trends will stand out. In July, the US Department of Energy (DOE) released the third 'billion-ton study'. The analysis updated the roadside availability of biomass (wastes, bioenergy crops, and algae) as a function of price and location. The report indicated the likely availability of 1.5 billion tons of biomass that could be used to produce biofuels or other chemical products [1]. Unfortunately, recent economic factors have prevented wider use of these potential renewable resources. Energy prices remained low for the third straight year, providing a substantial barrier to commercial deployment of bioenergy technologies. This challenge has driven 'biofuel' companies to rebrand and/or target new opportunities in producing higher-value compounds [2] and potentially slowed the pace of technology development [3]. Despite the economic hurdles, research to improve biotechnological routes for producing energy continues in both academic and industrial circles. Continued interest is motivated by the need to address the sustainability of current fossil fuels and by the potential to use living biocatalysts to convert low-cost natural gas to higher-value compounds [4,5]. In April, world leaders agreed to plans to address the growing threat of climate change [6]. Given the massive contributions of transportation fuels and flaring of natural gas to greenhouse gas emissions, development of more sustainable bioenergy technologies is justified and essential to meeting established goals [7]. In this compendium, we will reexamine established bioenergy topics, hear from prominent bioenergy research centers about the lessons learned and opportunities identified over the past 10-years, and discuss promising new technologies for applying biotechnology for generating bioenergy. While this issue covers a range of topics, it is not close to a comprehensive list of the advancements in energy biotechnology. We admit that the issue undercovers natural gas as a biotechnology feedstock [4,5], engineering of terrestrial plants [8], *in vitro* synthetic biology for synthesizing fuels [9], and perspectives from non-academic points of view.

Revisiting topics in energy biotechnology

There are many reoccurring themes in the Energy Biotechnology arena, and the opinions and reviews in this compendium provide a fresh look at some of these topics including: *Escherichia coli* as a platform chassis organism, engineering artificial photosynthesis systems, the advancement of systems biology techniques, and a review of the progress made to date on the bioproduction of adipic acid as an example of how biotechnology can be used to displace fossil fuels as feedstocks in chemical markets.

Moving away from petroleum resources will require the development of processes that efficiently utilize solar energy to convert CO_2 into chemical

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and fuels. Biotechnological routes leverage the power of photosynthesis to complete this task. A large fraction of the bioenergy sector works with terrestrial plants to produce energy rich extractives that microbes or chemical catalysts use as feedstocks. The alternative is directly couple photosynthesis with chemical production. In this issue, Woo provides a review of solar to chemical and solar to fuels processes [10]. Recent advances have focused on engineering photosynthetic microorganisms and on the development of hybrid photoelectrochemcial systems that enable the decoupling of carbon capture from solar energy harvesting.

The low cost and high volume of biofuels provide two difficult measures for novel biotechnologies to surpass. As mentioned above, many bioenergy companies have shifted focus to using their microbial technologies to produce higher value products in order to have a better chance at making a profit. Many of these efforts focused on the production of bifunctional molecules that could be incorporated into materials. In this issue, Kruyer and Peralta-Yahya provide an update on advances aimed at the bioproduction of adipic acid, an important industrial chemical currently produced from petroleum-derived benzene. Significant recent advances have been made in the development of new pathways for the production of adipic acid and related precursors from various feedstocks, as well as the development of alternative microbial chassis. As these advances continue, adipic acid will transition to a renewable, bio-based commodity.

The bioenergy community has long relied on natural or common model hosts, that is, *E. coli* and *Saccharomyces cerevisiae*, as platforms for performing microbial biotransformations and fermentations. The explosion of genomic sequence information and growth of genome engineering tools (*e.g.*, Cas9) has shifted focus to developing other non-model organisms (*e.g.*, cyanobacteria, methanotrophs, oleaginous yeasts) that possess advantageous traits. The rationale for this approach is our incomplete understanding of how these traits are genetically conferred and therefore our inability to transfer traits to existing hosts. In this issue, Wang et al. provide an update on *E. coli* as a platform organism for bioenergy and biochemical production as a counter-argument [11].

As advanced pathways and engineered organisms are created and deployed, it is becoming increasingly important to develop systems-level tools and techniques for evaluating successful designs, learning which elements are the most important to strain performance, and increasing the probability of successful design strategies. These tools are particularly important when working with new hosts that do not have the substantial literature base available for common model microbes. In this issue, Hansen et al., review the applications of systems biology approaches in the development of engineered organisms for biochemical and biofuel production [12]. These modeling approaches will continue to accelerate the development of new cellular factories.

Bioenergy research centers at 10 years

In 2007, the US Department of Energy established three cross-disciplinary research centers, the Joint Bioenergy Institute (JBEI), the Great Lakes Bioenergy Research Center (GLBRC), and the Bioenergy Sciences Center (BESC), to address the challenges in converting lignocellulosic biomass into liquid transportation fuels [13]. At the same time, British Petroleum supported the creation of an academic-industrial partnership, the Energy Biosciences Institute (EBI), to pursue research with similar goals. In 2016, the US DOE issued a renewed call for bioenergy research centers