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Editorial Reflections on BioEnergy: Perspectives from 2024

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For millennia fermentations of grain and fruit — such as those used in beer and wine — provided valuable nutrition for communities worldwide. In 2024, this biobased energy has taken on a very different context: advancements in our ability to isolate organisms, manipulate DNA, and optimize bioproduction on different feedstocks have brought about more efficient fermentations; the energy derived from cultivating organisms not only fuels our food but also drives our cars and lifts our airplanes. This section of Current Opinion in Biotechnology: BioEnergy offers a snapshot of the global effort through collaborations across academia, government, and industry, to optimize microbial strains, expand feedstock variety, and streamline strain development time and cost.

Although historically focused on the production of bioethanol, the field as a whole is also exploring a host of advanced biofuels and small molecule products. Chainani et al. discuss how coupling chemistry and biology for the synthesis of advanced bioproducts integrates synthetic biology with chemical catalysis enabling the production of novel biofuels and valuable bioproducts. This multidisciplinary approach allows for precision in designing microbes that can produce a wider range of compounds, including advanced biofuels like isobutanol, higher alcohols, and alkanes. By leveraging both chemical and biological systems, it becomes possible to tap into new molecules and pathways that would have been out of reach using either system alone.

Meanwhile, nature has long been a source of inspiration and raw material for biotechnological innovation. Li et al. discuss how tapping into these natural resources holds enormous potential for biofuel production. Bioprospecting and metagenomics allow researchers to explore previously inaccessible microbial communities, such as those in extreme environments, for novel enzymes and metabolic pathways. These enzymes and pathways could lead to the production of new biofuels and bioproducts, potentially reducing the need for petroleum-derived materials and chemicals.

The tools for metabolic engineering have evolved rapidly, but modeling these complex systems remains a challenge. Han et al. discuss how advances in genome-scale metabolic models of industrially important fungi are helping address this challenge by offering powerful computational tools to optimize strain performance. Such models allow researchers to predict the effects of genetic modifications, optimize metabolic pathways, and ultimately improve the yield and efficiency of biofuel production. For fungi, which are crucial players in industrial biotechnology for their ability to produce bioethanol and other products from lignocellulosic biomass, these advances represent a significant step forward in accelerating research and reducing the trial-and-error approach that has historically dominated strain development. Designing and optimizing microbes at the genomic level require innovative approaches to enzyme engineering. Generative models, such as those using machine learning, allow researchers to design enzymes that are optimized for specific reactions, including those involved in biofuel production. Barghout et al. discuss how, by training these models on vast datasets of enzyme structures and functions, researchers can now create enzymes with higher specificity and activity, increasing the efficiency of biofuel production processes. This approach not only accelerates enzyme discovery but also opens the door to entirely new catalytic functions that might not exist in nature.

In the pursuit of biofuels, Hu et al. discuss how traditional model organisms like Saccharomyces cerevisiae and Escherichia coli are being joined by emerging oleaginous yeasts, algae, bacteria, and fungi each with unique metabolic capabilities that can be harnessed for next-generation biofuels. These organisms can often metabolize a wider range of feedstocks, including those that are less amenable to traditional microbial fermentation, and can produce biofuels that are more energy-dense than ethanol. Martinez-Garcia and Lorenzo offer an in-depth review of Psudomonas putida, while Zhang et al. discuss how extremophiles like Halomonas spp. offer opportunities in nonsterile bioproduction. Although the majority of this issue is focused on microbial bioproduction, Morgan et al. offer a review of plant synthetic biology and how it offers promise for sustainability and space exploration. As researchers continue to explore these nonmodel systems, they may uncover new opportunities to improve biofuel yields and expand the range of biofuels produced.

Another area of biofuel research is improving microbial bioproduction under low-oxygen conditions. Many industrial bioprocesses occur in conditions where oxygen is limited, such as in large-scale fermenters or in the production of biofuels from anaerobic digestion. Microbes that can function efficiently under low-oxygen conditions are therefore essential for these processes. Kulakowski et al. discuss how researchers are developing strains with enhanced tolerance to low oxygen and engineering metabolic pathways that can operate under these constraints, thereby improving the efficiency and robustness of biofuel production systems.

Finally, the issue of feedstock availability and suitability is central to the future of biofuels. As biofuel production expands, reliance on traditional feedstocks like corn and sugarcane becomes less sustainable. Scown et al. discuss the growing need to explore nontraditional feedstocks, including agricultural residues, municipal waste, and lignocellulosic biomass. Liu et al. offer a focus on bioproduction from lignin; Tan et al. discuss how methanotrophs are being used to harness methane for bioproduction. Matching these diverse feedstocks with the right microbial or chemical conversion processes is key to making biofuels more economically viable and environmentally sustainable. This approach not only diversifies the inputs into the biofuel production pipeline but also reduces competition with food crops, a crucial consideration as global populations and food demands rise.

This special issue has touched on some of the leading research on the frontiers of biofuel research, bringing together advances in microbial engineering, enzyme design, metabolic modeling, and feedstock conversion. As the world continues to shift towards renewable energy, the role of biofuels and bioproducts will become increasingly critical in mitigating climate change, reducing reliance on fossil fuels, and fostering sustainable economic growth. By exploring both established and emerging systems, as well as leveraging cutting-edge techniques in synthetic biology, machine learning, and bioprospecting, the biofuel field is well-positioned to continue advancing toward a more sustainable future.