Chemical and Biological Designs for Sustainability and Decarbonization

We have advanced a series of biorefining, algal bioproduction, and electro-biomanufacturing platforms to address the sustainability challenges of our generation. First, lignin utilization is crucial to modern biorefining and decarbonization. We have systemically advanced the understanding of the structure-property relationship to guide the chemical designs, empowering efficient conversion of biorefinery waste[1] and high-quality biomaterial manufacturing from lignin[2]. Second, algal carbon utilization represents another opportunity for decarbonization, yet is hindered by the low light penetration, and high harvesting and production costs. We have addressed the challenges by integrating machine learning modeling, synthetic biology design, and process design to simulate the optimal growth rate and develop a semi-continuous cultivation to substantially improve the algal productivity[3]. Furthermore, we have engineered a strain with high limonene productivity to create hydrophobic interactions among the cells, thereby leading to aggregation-based sedimentation (ABS) as a low-cost harvesting method. The ABS-empowered SAC has unleashed cyanobacterial growth potential to achieve 0.1g/L/hour biomass productivity in photobioreactor and the record 43.3 g/m^2/day outdoor biomass yield, empowering algal carbon capture and utilization[3]. Third, recent team breakthroughs highlighted a new concept to integrate electrocatalysis with bioconversion to achieve much higher efficiency than algae and plants[4]. We systemically designed the electrocatalysis, the chem-bio interface, and microorganisms to enable efficient electro-microbial conversion with C2 (EMC2) intermediates[5]. The EMC2 design have achieved 6 and 8 times increase of microbial biomass productivity compared to C1 intermediate and hydrogen-driven routes, respectively, and achieved 4.5% solar-energy-driven CO_2 conversion to biomass[5]. Furthermore, based on the breakthrough in electro-microbial conversion, we have advanced a new electro-biodiesel platform, where CO_2 was first converted into biocompatible C2 intermediates, including acetate and ethanol, by electrocatalysis. Systems biology has identified bioenergetic and metabolic limits of microbial conversion of these C2 intermediates, guiding the design of efficient bioconversion of ethanol and acetate into lipid. The engineered strain enabled a co-substrate effects, where ethanol can produce reductant and energy to drive more efficient acetate usage. Based on the co-substrate effects, we have designed catalysts to produce an optimal ratio of acetate and ethanol to achieve higher bioconversion efficiency. The synergistic microbial and catalyst design delivered electro-biodiesel with 4.5% solar-to-molecule efficiency for converting CO_2 into lipid, which is much more efficient than biodiesel and other competing platforms. Electro-biodiesel leverages the high efficiency of electrocatalysis and longer-carbon-chain products from microbial lipid synthesis, overcoming the limitations for both electrocatalysis and bioconversion, achieving 45 times less land usage than soybean biodiesel, competitive economics, and substantial carbon emission reduction.

1. Liu, et al., Nature Communications, 12, 3912.
2. Li, et al., Matter 5, 3513-3529.
3. Long, et al., Nature Communications 13, 541.
4. Zhang, et al., Chem 7, 3200-3202.
5. Zhang, et al., Chem 8, 3363-3381.
6. Chen, et al., Joule, 9, 101769.