

Designing Mixed-Solvent Environments for Acid-Catalyzed Biomass Conversion Processes

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Project Goals:

The objective of this project is to develop biomass deconstruction and separation strategies that optimize C yields.

Abstract:

Lignocellulosic biomass is a promising renewable resource that can be converted into transportation fuels or commodity chemicals. Biomass conversion is facilitated by liquid-phase, acid-catalyzed dehydration and hydrolysis reactions that are hindered in aqueous solution by low reactivity and poor selectivity. One approach to improve biomass conversion efficiency is to modify the solvent composition by mixing water with *organic, polar aprotic cosolvents* (e.g. dioxane, tetrahydrofuran, etc.) to form mixed-solvent environments. Mixed-solvent environments have been shown to improve the reactivity of biomass conversion reactions by *100-fold* compared to the same reactions in pure water.¹ However, identifying an optimal solvent composition experimentally by trial-and-error is cost-prohibitive and lends little physical insight into how these mixtures will perform in new processes. Instead, *in silico* techniques can understand and predict the influence of solvent composition on experimental reaction rates and selectivities to guide solvent selection.

We developed classical molecular dynamics (MD) simulation methods to understand the effects of mixed-solvent environments on seven acid-catalyzed reactions involving biomass-derived reactants.¹ We found that inclusion of polar aprotic cosolvents leads to the formation of *water-enriched local domains* around *hydrophilic* reactants, which draws the acid catalyst to these regions due to preferred catalyst-water interactions² and results in improved reaction rates. By quantifying the extent of water-enrichment around the reactant, we found that MD measurables can accurately predict experimental reaction rates for dioxane-water mixtures, showing that classical simulation techniques can inform reaction rates without modeling the reaction mechanism or the catalyst.¹ We improved the predictive model by analyzing MD trajectories using three-dimensional convolutional neural networks (CNNs), which can capture complex spatial features that are related to reaction rates but are difficult to quantify by human experts. MD simulations in conjunction with CNNs were used to screen solvent compositions for the same seven reactions in

three water-cosolvent mixtures of varying composition (a total of 84 mixed-solvent environments).³ Our results show that the CNN methodology accurately predicts experimental reaction rates for these and additional reactants/solvents not present in the initial training data, enabling reaction rate predictions for a design space that is too large to study with conventional quantum mechanical methods. Finally, we used MD simulations to understand the influence of solvent composition on experimentally determined product selectivities for representative acid-catalyzed reactions.⁴ We synthesized these computationally efficient methods into a workflow for the selection of mixed-solvent environments by analyzing relevant biomass conversion reactions, such as the dehydration of fructose to 5-hydroxymethylfurfural (HMF).⁵ We confirmed that the solvent system identified with this approach led to high HMF production experimentally. These computational models thus enable the rational design of new liquid-phase acid-catalyzed biomass conversion processes by guiding solvent selection.

References:

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