Fundamental Catalytic Challenges to Design Improved Biomass Conversion Technologies

Theodore W. Walker[a], Ali Hussain Motagamwala[a,b], James A. Dumesic[a.b] and George W. Huber*[a]

a) Department of Chemical and Biological Engineering, University of Wisconsin – Madison, Madison, USA
b) DOE Great Lakes Bioenergy Research Center, University of Wisconsin-Madison, Madison, USA

*E-Mail: gwhuber@wisc.edu

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During the past ten years, there has been significant interest and investment in the study of catalytic conversion of biomass-derived feedstocks into renewable fuels and chemicals. In the United States, an estimated $25 billion has been spent by venture capitalists, industry, and government agencies during this period of time to commercialize "renewable technologies" including solar energy, wind power, batteries, and biofuels (*e.g.*, cellulosic ethanol).[1] Four societal factors are driving these investments including: (1) the increased price of crude oil; (2) concerns about global warming; (3) the desire to improve rural economies where biomass is produced, and; (4) national goals to become energy self-sufficient. Furthermore, underlying these efforts is the realization that lignocellulosic biomass is the only realistic, near-term and non-food-competitive source of renewable organic carbon.[2-5] To this end, legislative efforts, such as the US Renewable Fuel Standards, have been implemented to create subsidies, tax credits, mandates, and loan guarantees to help bring renewable fuel technologies to market.[6] However, the representative body of industrial efforts to this end has faced significant challenges, with several startup companies having commercialized biomass conversion technologies but having struggled to reach commercial scale; in fact, many of these companies have filed for bankruptcy.[1, 7] This situation is likely due to the challenges associated with scaling up unproven pioneer processes, as well as neophyte investors not understanding the decade-long time frames and the sheer amount of funding that is often required to bring chemical process technologies to market.[7] Nevertheless, several emerging catalytic technologies have either entered the market place, or are currently demonstrating their technologies in fully integrated pilot plants. Commercial and near commercial technologies for second generation biomass conversion technologies to-date include, among others: biomass-derived jet and diesel fuel from both waste vegetable oils and ethanol;[8] small scale production of renewable jet and diesel from landfill gases *via* Fischer-Tropsch synthesis;[9] catalytic conversion of carbohydrates into gasoline and aromatics;[10] hydropyrolysis of biomass into gasoline and diesel,[11] and; catalytic conversion of wood into aromatics.[12]

To be successful, biomass conversion technologies must ultimately be able to compete economically with petroleum technologies, which are already operating at large commercial scales and have been practiced for decades. To this end, various factors must be considered when evaluating the potential for new processes to compete with incumbent technologies; factors such as regional variations in feedstock quality and availability, government policy, subsidies and tax rates, and the proprietary positions of the ancillary technologies that might support the process. By

any measure, however, a critical metric of the economic potential of a process is its efficiency with respect to the yield of products from raw materials, and this metric of performance is directly related to atom efficiency of the underlying chemical reactions. Therefore, while promising biomass conversion technologies continue to demonstrate progress towards commercialization, there remains an important need for the catalysis community to aid in this effort by: (1) designing more active, selective and stable catalysts, and (2) elucidating a more detailed understanding of the catalytic chemistries underlying these processes. Indeed, the study of catalytic biomass conversion has grown tremendously during the past decade; and new or emerging technologies that are in the laboratory stage have allowed for biomass to be converted into a wider variety of commodity chemicals and the full range of liquid fuels that are produced from petroleum. The objective of this perspective is to highlight some of the ongoing, fundamental challenges with respect to the catalytic conversion of biomass into renewable products, and to provide insight as to how the catalysis community can overcome several of these challenges. It is our belief that, as an international academic community of catalysis researchers, we can (and must) work together to address these challenges, and to drive progress toward the production of next-generation renewable chemicals and fuels from biomass.

Challenge 1: Understanding the chemistry of realistic biomass feedstocks

Biomass is a complex and diverse feedstock, composed of a variety of oxygenated polymers, minerals, and extractives. In contrast to petroleum, lignocellulosic biomass is a solid, non-volatile material that contains up to 50 wt% oxygen, which must be removed *via* chemical transformations to afford higher-value products or fuels that are compatible with current infrastructure.[13] Furthermore, the minerals in biomass can be present in amounts up to 20 wt%, and strategies are required to utilize and/or remove them during biomass upgrading.[14] Biomass can be depolymerized into oxygenated molecules by a variety of techniques including hydrolysis, pyrolysis and liquefaction.[15] However, the oxygenated products derived from such processes, which involve multiple different reactions occurring both in series and in parallel, are as chemically diverse as biomass itself, and are therefore difficult to analyze and separate.[16, 17]

Whereas gas chromatography (GC) is the workhorse of most traditionally trained catalysis researchers,[18] this technique cannot typically be used to characterize most biomass-derived product mixtures, as they contain a preponderance of non-volatile compounds. Liquid-phase chromatographic techniques (HPLC) can be used to quantify some non-volatile analytes, but the large number of chemical species present in the product mixtures from biomass conversion processes makes it difficult to separate them effectively in many cases.[17, 19] Fully characterizing biomass conversion products thus requires more advanced analytical techniques which, taken alone, provide only partial information about biomass-derived molecules. However, a combination of such techniques can provide insights that allow for the structure and composition of biomass-derived products to be deduced. For example, nuclear magnetic resonance spectroscopy (NMR) can give information about the types of different chemical functionalities present in biomass, and the chemical linkages between these functionalities.[20] Gel permeation chromatography (GPC) can give information about molecular weight distributions.[21] High-resolution mass spectrometry (MS) techniques provide information about molecular weight, and even elemental composition.[22]

Much of the work in the past decade has focused on elucidating the chemistry underlying the conversion of biomass-analogous model compounds, or isolated and well-defined intermediates derived from biomass, such that traditional techniques like GC and HPLC analysis

can be employed.[23-28] However, developing expertise in the more sophisticated, aforementioned techniques (many of which fall outside the scope of traditional catalysis training) will be necessary for research groups to make progress in understanding the catalytic chemistry that occurs during *realistic biomass* conversion processes. To appreciate this point, consider that even minimally-processed biomass feedstocks can be mixtures of compounds whose structures are ill-defined, such as in the case of lignin-derived feedstocks. For example, the lignin-derived fraction of pyrolysis oil contains products with more than 1,100 distinct molecular weights.[29] Using a combination of solution-state NMR, GPC, and Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR MS), it is possible to propose a model lignin structure, represented in Figure 1 below. It is then possible to characterize the lignin structure after pyrolysis, and after catalytic hydrogenation of the pyrolysis products. Such analyses show that there are both catalytic *and homogeneous reactions* that are occurring during the lignin hydrogenation process, the former of which includes hydrogenation of aromatic, alkene and carbonyl functionalities that are preserved during the pyrolytic depolymerization process. The conclusions from this work are in contrast to the more limited insight that is garnered when simple, lignin-representative model compounds like phenols are studied.

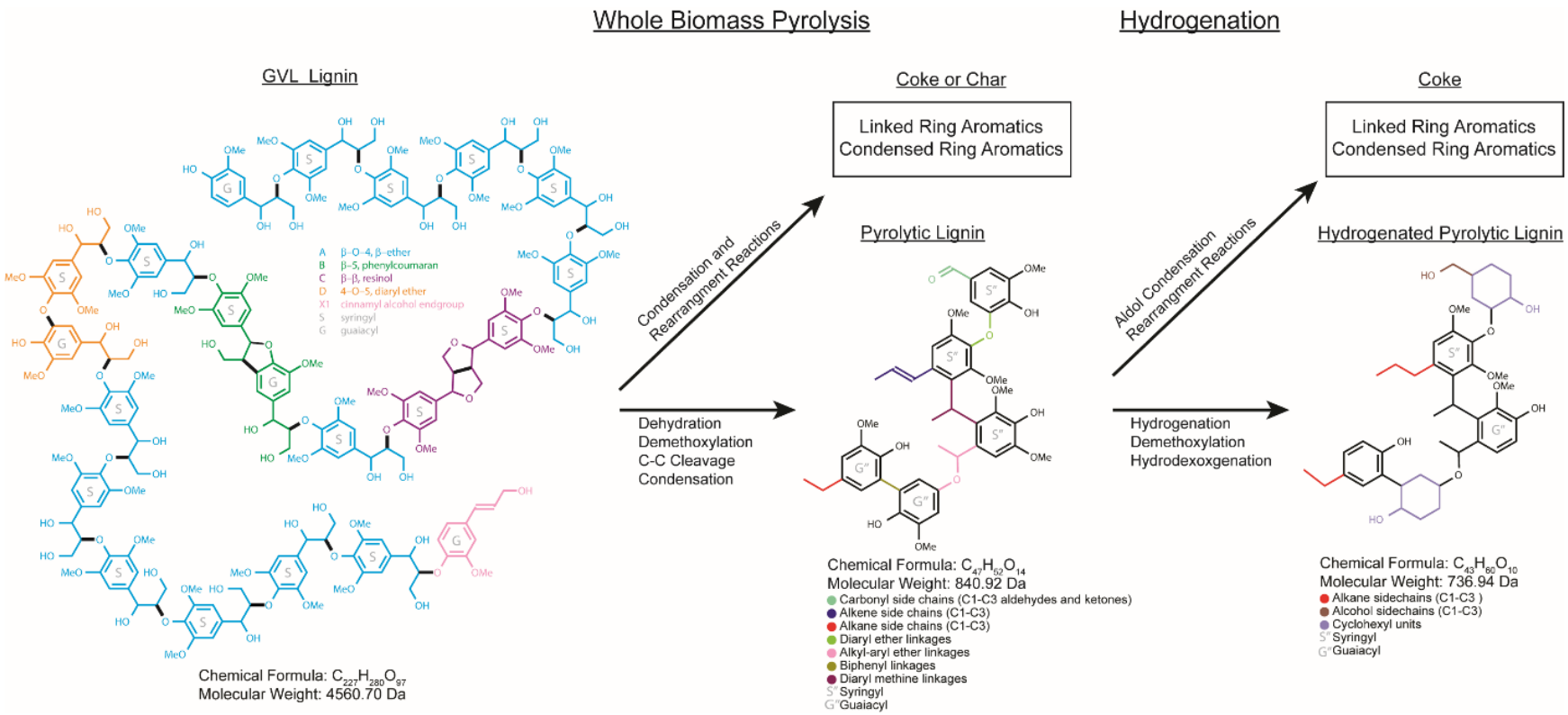

Figure 1. Proposed structure of lignin in biomass, pyrolytic lignin and hydrogenated pyrolytic lignin (adapted with permissions from [29])

While this example illustrates the complexity of lignin chemistry, it should be noted that biomass-derived feedstocks are typically complex mixtures of various compounds that are difficult to isolate and characterize. To this end, an emergent technique in biomass conversion research is *solid-state* ^{13}C NMR. Whereas the structure and chemical makeup of biomass can be altered by the pretreatment and fractionation techniques that allow for *ex situ* characterizations, solid state NMR enables the *in situ* characterization of biomass with respect to both structure and composition. For example, this technique has been used to study the structural differences between hydrothermal and pyrolytic carbon residues,[30] the lignin content of whole-plant energy crops,[31] and the crystallinity of cellulose in different biomass feedstocks.[32] Solid-state NMR represents a promising and sophisticated technique for characterizing realistic, whole biomass; and we expect this technique to gain further importance in the future.

The foregoing examples illustrate that the complexities underlying the structure and composition of real biomass have implications for catalysis research, and must therefore be more completely understood. One implication is that components present in biomass can catalyze homogeneous side-reactions, altering yields and selectivities as compared to the reactions of isolated, well-defined model compounds. For example, during the hydrotreating of pyrolysis oils, organic acids present in the oil can catalyze the enolization of hydroxyacetone.[33] The rate of hydrogenating a carbon-carbon double bond is often faster than the rate of hydrogenating a ketone, which in part explains the product distribution resulting from this process.

Another notable phenomenon with respect to realistic feedstocks is that components present in biomass can inhibit desired reactions by strongly binding to active sites. For example, the minerals in the biomass can poison zeolite catalysts.[34] Another example is that the organic acids in pyrolysis oil can inhibit the hydrogenation ability of common catalysts.[33] A ubiquitous complication in biomass conversion reactions is that acid- or base-catalyzed side reactions catalyze the formation of humins, which are complicated, non-volatile organic polymers.[35] Humins can be both soluble and insoluble in water, and the details of their structure are not completely known. The implication for catalysis is that formation of these ill-defined polymeric materials often makes it difficult to close the carbon balance in research, even in relatively simple catalytic reactions of biomass-derived intermediates.[23, 35] Moreover, the lack of general knowledge regarding the mechanisms of humin formation leaves the catalysis researcher with little insight as to how the formation of these species might be suppressed.

Another aspect of the complexity underlying realistic biomass feedstocks is that they often contain species that are present as structural- and/or stereoisomers. For example, glucose dissolved in water is present as five different equilibrated isomers/tautomers, whose speciation depends on factors such as the solvent composition and reaction temperature.[36] This speciation can affect their reactivity; for example, fructose is more readily dehydrated to 5-hydroxymethylfurfural (HMF) than the pyranose form (glucose), and as such the conditions under which fructose is predominantly in the furanose form leads to higher HMF selectivity. Thus, the presence of a Lewis acid catalyst (which facilitates the interconversion of these two isomers) can improve the yields of HMF from glucose. However, by some accounts, it is the open-chain aldohexose and ketohexose tautomers of fructose and glucose, respectively, that undergo isomerization, and so it is the equilibrium portion of the C6 sugars in the open-chain form that may ultimately control the rate of HMF formation. Thus, higher temperatures and aprotic solvents (such has dimethyl sulfoxide) better facilitate this reaction, with respect to the yield of HMF from glucose. [15]

A more general point is that the complexity of biomass-derived feedstocks has made it difficult for catalysis researchers to fully exploit modern spectroscopic and computational tools for catalyst design. One example where this elucidation has been attempted is with furfural hydrogenation.[37] It is difficult to identify the active surface species using current *in situ* spectroscopic techniques with biomass derived feedstocks, because large amounts of species are adsorbed on the inactive support compared to the amounts of species that are adsorbed on the catalytic sites.

The above complexities suggest that a more thorough understanding of the chemistry underlying the catalytic conversion *of realistic, whole biomass* is required to guide the judicious choice of simpler, representative model compounds, so that important insights are not lost simply for the sake of defining a more tractable problem. This way, the insights garnered from the study of well-defined model compounds can be translated into reliable design rules for improved biomass conversion catalysts.

Challenge 2: Obtaining process-relevant catalytic information

Unlike catalytic technologies for petroleum conversion, most catalytic technologies for biomass conversion are not at the commercial level. Thus, research in the early stage requires a better understanding of the potential processes that might result from the development of a new catalytic strategy, including the economics (or techno-economics) and the markets of the potential process. To this end, catalysis researchers should work with process engineers, and be trained to understand *process flow diagrams*, from which an understanding of how the reactor is integrated into the overall process can be developed, and the requirements of a catalyst can be understood.[38] The process flow diagram, represented schematically in Figure 2, contains several sections including feedstock handling, feedstock pretreatment, reactors, co-feeding of co-reactants, separations, recycling of co-feeds and by-products into the reactor, product purification and product storage.[39] One of the important functions of the process flow diagram is to facilitate a techno-economic analysis of the process, and therefore provide an estimate of the *profitability* of a potential process.[40] This economic model is based not only on the technical details of the process, but also on the price of the raw materials and products, and therefore requires knowledge of the market of the raw materials and products. Often times process heuristics are used in this early design stage.[41, 42] These heuristics are based on engineering principles, and are used in the conceptual design of processes. The catalysis researchers can use this knowledge to guide their fundamental research, and to ensure that their fundamental research can help to solve real industrial problems. Bridging this process engineer –catalysis researcher gap is critical to develop realistic catalytic technologies and decrease the time that is required to develop commercial processes.

For a sense of the various aspects constituting the gap between fundamental catalysis research and the development of actual processes, consider the following examples. First, in industrial processes, most catalytic technologies operate in continuous flow reactors, often at high pressure, and sometimes in complex configurations such as fluidized bed reactors.[38] In contrast, most fundamental research is carried out in batch reactors or low-pressure continuous flow reactors. However, batch reactor studies do not lend themselves well to studies of *catalyst stability*, which is a critical metric of catalyst performance in the context of processes economics.[43] A large number of reports in the last decade provide catalyst recycling data in batch reactors at high conversion, and these data are used as a demonstration of catalyst stability. However, catalyst deactivation behavior is masked in these types of studies; operating at high conversion means that there is an excess of active sites compared to the reactant, so that each site only participates in a

limited number of turnovers during the reaction.[44] Also, rather than *recyclability,* the relevant metric of catalyst stability for a continuous flow process is *time on stream* (or number of turnovers), meaning the length of time over which a catalyst can operate uninterrupted before it deactivates.[45] Furthermore, the hydrodynamic aspects of liquid-phase processes (such as mixing, phase equilibria and mass-transfer effects) change from batch to continuous flow reactors, and thus the *apparent* kinetics of the process may also change.[46] Therefore, the design rules developed for batch processes may not translate when the same reaction is carried out in a continuous flow configuration.

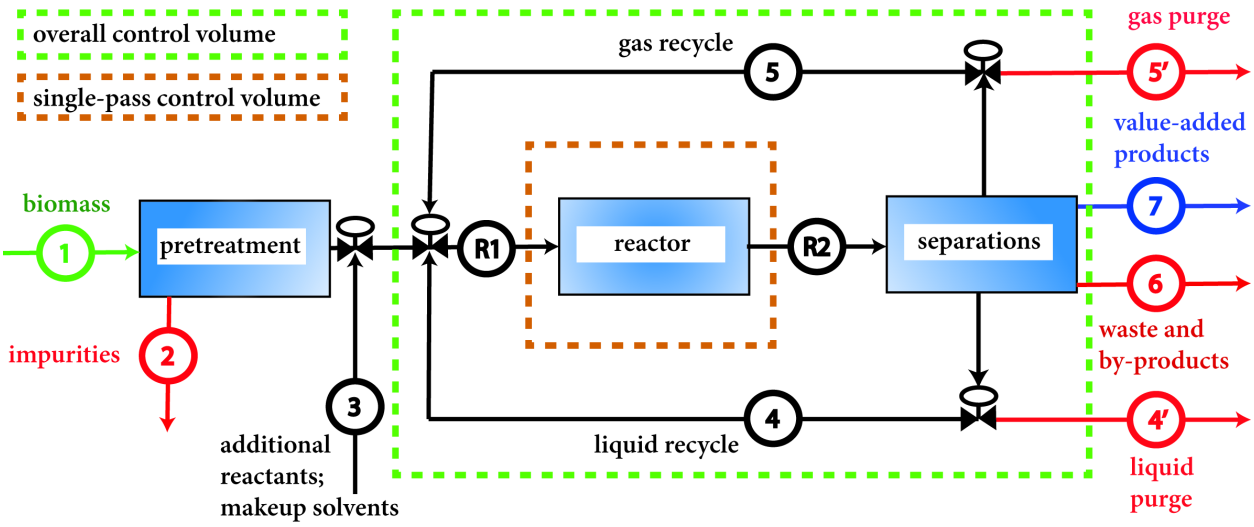

Figure 2. Schematic representation of an integrated biomass conversion process including pretreatment, catalytic conversion and separations steps. Many fundamental studies of catalytic processes focus on the single pass aspect of reactor performance (streams R1 and R2); with reactions being carried out at high conversion and no recycle loops. In practice, however, actual processes may be carried out at less than 100% conversion, with products and solvents being recycled to the reactor feed for multiple passes (the overall processes control volume; streams 1 and 7). This operation can introduce a number of complications that are not accounted for at the academic level, such as the accumulation of impurities or side-products (resulting in reactor plugging), or deactivation behavior that is not apparent at high conversion and shorter times on-stream.

Also, consider that the ultimate goal of an industrial process is to maximize the overall return on investment. To this end, it is often desirable to maximize the *overall process yield* with respect to the products and raw materials (streams 1 and 7 in Figure 2). This measure of processes efficiency is fundamentally different than the *single pass yield*, which is a measure of the efficiency of the reactor itself (streams R1 and R2 in Figure 2). At the lab scale, even reactions carried out in continuous flow systems are often operated at high conversion, so as to demonstrate a maximum single pass yield. The industrial process, in contrast, may contain recycle streams and the reactor may therefore *not* operate at the maximum single pass yield. Furthermore, industrial processes often involve recycling streams where the reactant *and some of the products or byproducts* may

be recycled back into the reactor. Thus, understanding the impact of the products *when cofed with the reactants* is often required.

Another point to consider it that the separation of the product from the solvent and other reaction media is often one of the most costly parts of the overall process.[47] The cost of these separation processes is typically driven by the concentration of the feed, and differences in the properties (like boiling points) of the products, solvents, and byproducts. For example, separating a 1 wt% product in water will be significantly more expensive than separating a 10 wt% product in water. It is typically easier, however, to carry out research using dilute conditions, where reactions are typically more selective and the kinetics are more easily measured, rather than using more realistic, concentrated conditions. Thus, fundamental research should also be carried out with *industrially relevant concentrations* of reactants, and consider the difficultly with which products and solvents are separated when choosing a reaction medium.

An important attribute of biomass as a raw feedstock is its potential to provide a *sustainable* source of organic carbon. However, the ultimate measure of the sustainability of a process includes more than just an estimate of the carbon, water and energy footprints associated with the process itself. Rather, a rigorous *life cycle analysis* (LCA) must be conducted to assess the footprint of the entire *supply chain* that facilitates the acquisition of raw materials, delivery of the utilities that support the process, the distribution of products, and the ultimate fate of the wastes generated by the end users.[48] While this exercise lies outside the scope of classical catalysis research, it is essential to note that the ultimate goal of research in biomass conversion is to develop *sustainable processes* for the production of chemicals and fuels. Therefore, research and development of catalytic technologies should at some point include rigorous LCA's, to ensure that new biomass conversion processes are capable of facilitating an overall carbon, water and energy-neutral economy.

Challenge 3: Improving catalytic stability

One of the most challenging factors related to the catalytic conversion of biomass, and even the upgrading of the derived chemical intermediates, is that biomass-derived feedstocks often contain impurities that can reduce the activity or lifetime of catalysts. Consider the hydrotreating of pyrolysis oils, which has been proposed as an economically viable route to produce liquid transportation fuels.[49] However, catalyst stability issues have been shown to occur because undesired coke forms in the reactor, due to the ash present in the pyrolysis oil.[50] Another promising strategy toward the production of bio-renewable chemicals is the upgrading of yeast fermentation products. For example, biologically-derived lactic acid and triacetic acid lactone can be hydrogenated to afford propylene glycol and succinic acid, respectively. However, liquid-phase hydrogenation catalysts such as nickel, platinum and palladium are inhibited by the impurities typically present in fermentation broths; namely, biogenic side-products such as methionine, biotin, tryptophan and niacin.[51] Organic compounds present in biomass can also chelate metal catalysts, resulting in a loss of active sites.[52] Minerals present in the biomass or biologically-derived feedstocks can poison zeolites during liquid phase processes as well, and even decrease the activity of homogeneous mineral acid catalysts by neutralizing excess protons. [34] For example, acid whey is an aqueous waste stream in dairy product manufacturing processes that contains lactose (a disaccharide), as well as amino acids, proteins, minerals, and metabolites such as urea. A promising strategy for upgrading these waste streams is to hydrolyze the lactose over an acid catalyst to produce sugar monomers. However, the urea and minerals present in acid whey

deactivate acid catalysts, and so any process to capture and upgrade the lactose in these waste streams will have to be integrated with separation steps to demineralize the whey.[53]

Two general approaches are typically followed to improve catalyst stability: (1) removal of the impurity poisoning the catalyst, and (2) design of catalysts that resist deactivation, while still facilitating the desired chemistry. In either approach, it is important to elucidate the underlying mechanism of deactivation. As mentioned above, this understanding is best facilitated by studying the catalyst under various conditions in continuous flow reactors, and monitoring the performance of the catalyst as a function of time on stream.[43, 45] In the last decade, a key insight garnered from such studies is that non-precious metal and metal-oxide catalysts often have higher rates of catalyst sintering than precious metals in condensed phase biomass reactions.[54-56] This behavior has serious implications for emerging catalytic technologies. For example, metal oxide nanoclusters sometimes exhibit activity comparable to their more expensive precious metal counterparts, but their tendency to undergo deactivation limits their feasibility in an industrial context.[55]

Another problem relating to the liquid-phase stability of non-precious metal catalysts is their tendency to undergo leaching.[56] The leaching processes can occur *via* direct solubilization of the catalyst or supporting framework, or *via* a chemical reaction with the solvent itself.[57] Leaching is a ubiquitous problem with metal oxides in aqueous phase processes, as most of the metal oxides are at least minimally soluble in water.[58] The latter mechanism is responsible for the poor hydrothermal stability of many acid zeolites: hydrolysis of the Si-O-Al bonds afford water-soluble aluminum hydrates, which leach out of the framework and into the liquid phase, destroying the zeolite.[59] Thus, an important and ongoing challenge with respect to catalytic biomass conversion is to develop water-stable, non-precious metal catalysts.

A promising strategy to stabilize metal oxides and other materials that undergo deactivation due to leaching is to protect them by overcoating the material with a stable, inert layer; for example, by methods such as atomic layer deposition (ALD).[60, 61] In this technique, the catalyst is treated with pulsed mono-layer quantities of metal-containing precursors bound up in ligands, which bind preferentially to under-coordinated sites on the metal oxide. In a second step, the ligands are removed *via* a chemical reaction, leaving behind a thin metal film covering the under-coordinated sites on the parent catalysts. It is these under-coordinated sites that are suspected of being most vulnerable to hydrolysis,[60] and the leaching process is therefore attenuated by the presence of the protective thin metal film. For example, it has been shown how ALD can also be used to stabilize Cu and Co catalysts against sintering under aqueous phase reactions.[62, 63]

The examples above illustrate that catalyst stability represents a complex and important challenge. Therefore, catalysis researchers should address this challenge toward bringing new biomass conversion technologies out of the lab and into the marketplace.

Challenge 4: Understanding the role of solvents

The composition of the liquid phase and the economics of solvent-mediated processes are intimately related. For example, the choice of solvent affects everything from the rates and selectivity of chemical reactions, to the stability of liquid phase-products and the solubility of raw materials.[25, 64-70] In the context of biomass conversion processes, the water content of the solvent system is of particular significance for two reasons. First, a minimum amount of water is often required to facilitate the solvation of biomass-derived materials, and secondly, biomass-derived feedstocks commonly contain a minimum fraction of entrained water that is costly and difficult to remove *via* drying or other methods.[71, 72]

It has been found that mixtures of water and organic cosolvents (*i.e.,* mixed solvent environments) not only facilitate, but also *improve* the performance of some important biomass conversion reactions, as compared to conversion in water alone. For example, mixtures of water with γ-valerolactone are able to solubilize all fractions of lignocellulosic biomass, affording high yields of water-soluble carbohydrates from raw biomass.[73] Also, the work of Sels, Rinadli and coworkers has demonstrated that semi-aqueous cosolvent mixtures lead to superior yields of soluble products from lignin hydrogenolysis.[74, 75] In another example, cellulose is dehydrated in pure tetrahydrofuran (THF) to afford levoglucosenone (LGO; a platform molecule of growing significance) in 50% carbon yield.[76] However, when a *small amount* of water is added to the THF solvent (<5% by weight), 5-hydroxymethylfurfural (HMF) gradually replaces LGO as the major product. This behavior is desirable from a process design standpoint, because the combined yield of HMF and LGO that can be achieved as *co-products* (65 carbon%) is greater in THF/water mixtures than can be achieved when either species is targeted at as a sole product.[77] The forgoing examples demonstrate how a fundamental base of knowledge with respect to solvent effects in biomass conversion reactions should empower the rational design of *tunable liquid phase processes* for the selective conversion of feedstocks with *diverse chemical compositions.[70]*

To this end, the effect of mixed solvent environments has been probed using both experimental[25, 65] and theoretical treatments[78-82] in the last ten years. However, the molecular nature of solvent effects in multi-component liquid-phase processes is not rigorously understood.[83-85] Therefore, toward the development of empowering, broadly applicable insights in this context, work in this area should aim to elucidate how the properties of the individual components of the liquid phase (water, organic cosolvents, modifiers, *etc*.) translate into critical metrics of performance for liquid-phase biomass conversion processes, such as information regarding how the composition of the liquid phase affects the intrinsic rates and selectivity of chemical reactions. With this information, factors relating to the ease of separating products from the solvent, as well the solubility limits of raw materials in the liquid phase can be incorporated into the necessary techno economic evaluations of conceived processes.

In recent work, experimental measurements and results from DFT calculations were used to explore how the formation of water-enriched or –deficient, semi-ordered solvent structures near hydrophilic reactant molecules affect the rates of acid-catalyzed dehydration reactions in mixed solvent environments.[86] These results were then generalized into a model-predictive framework that allows for the rates of acid-catalyzed reactions of biomass-derived oxygenates to be estimated *a priori* using computationally efficient molecular dynamics (MD) simulations, without requiring prior knowledge of the reaction mechanism.[87] This latter development was accomplished by recognizing that rates of liquid-phase chemical reactions are controlled by the thermodynamics of the solvated reactants, catalysts, and transition states in the underlying reaction mechanisms.[85] It was therefore postulated that the formation of water-enriched *local solvent domains* near reactants with a preponderance of vicinal hydroxyl groups creates a thermodynamic driving force for the transfer of a catalytic proton from the bulk solvent to the reactant, thus lowering the barrier for the reaction (Figure 3). Therefore, quantifying the extent of water enrichment about reactant molecules in mixed solvent environments using MD should provide a quantitative estimate of reactivity. This approach demonstrates how a fundamental understanding of solvent effects in biomass conversion chemistry can be elucidated using combined experimental and theoretical approaches, and how these insights can be successfully translated into design tools that facilitate the development of *improved liquid-phase processes*.

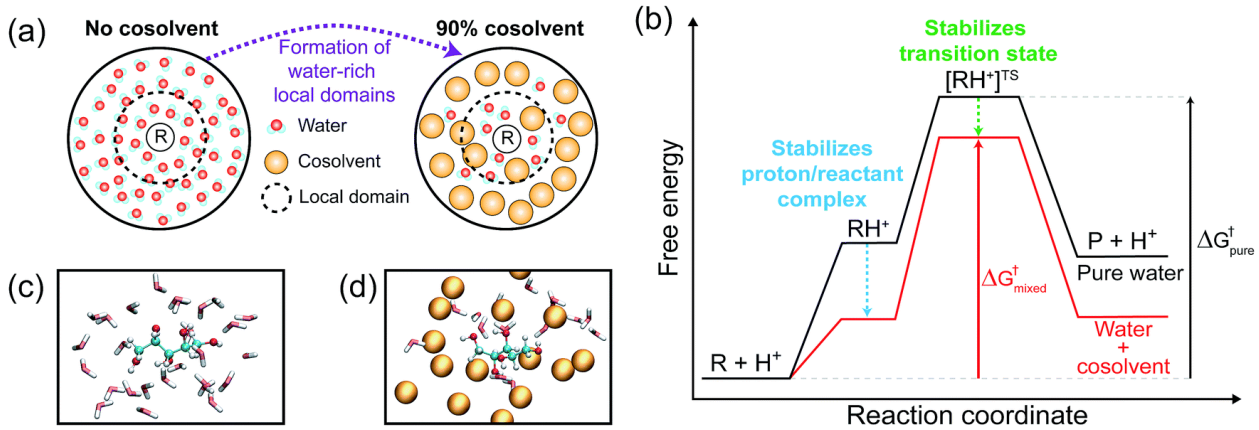

Figure 3. (a) Role of cosolvent molecules on the distribution of solvent molecules. Favorable interactions with hydrophilic reactants in mixed-solvent environments drive the formation of water-rich local domains around the reactant. While there are fewer water molecules in the local domain relative to pure water, the local water density is enriched relative to the bulk density in the solvent mixture. (b) Proposed effect of cosolvent molecules on a reaction free energy landscape. Stabilization of the proton and transition state in the water-rich local domain, relative to the bulk domain, lowers the apparent free energy barrier for the reaction in a mixed-solvent environment. (c, d) MD simulation snapshots of xylitol in (c) pure water and (d) 90 wt% 1,4-dioxane, which is drawn as a single representative bead to match the schematics in (a). Reproduced with permission from.[87]

Reaction networks underlying liquid phase biomass conversion processes are often complex, being comprised of multiple reactions occurring both *in series and in parallel*, where either afford a range of undesired (degradation) products, such as the prototypical humins that typically limit yields of liquid-phase biomass conversion reactions. Thus, in the future, it would be desirable to understand not just how the composition of the liquid phase affects the rates of chemical reactions, but the *selectivity* of reactions occurring in parallel as well. Importantly, researchers should also endeavor to translate these insights into *broadly applicable* design rules for new and improved liquid phase processes. In tandem with these efforts, researchers should investigate: (1) how the composition of the liquid phase affects the stability of biomass-derived products (classes of products such as furans, aldehydes and carbohydrates), (2) how the properties of mixed solvent environments can be tuned to improve the atom efficiency of biomass conversion reactions, and (3) how the choice of the solvent system can be integrated economically with downstream processes such as distillation and other purification steps.

A long-term research goal to consider in the near future is how the desirable aspects of solvent effects in biomass conversion processes can be engineered into chemically reacting systems without the need for large volumes of organic cosolvents. For example, recent work by Sun *et al.* has demonstrated that organic cosolvent moieties (such as dimethyl sulfoxide) can be integrated into heterogeneous solid frameworks alongside Brønsted-acidic species, resulting in immobilized solvation environments around the acid sites that effect high yields of HMF from the dehydration of fructose.[88] It should be noted that the reaction solvent in this study was

tetrahydrofuran (THF), rather than water. In future work, solid materials that mimic solvation effects for biomass conversion should be engineered to be hydrothermally stable, so that water can be used as a reaction solvent. In fact, due to their high cost, organic solvents must typically be recycled with near 100% efficiency for industrial-scale processes to be economically viable, which is seldom realistic. Therefore, despite their potential to improve the yields of biomass conversion reactions, it should be noted that not a single existing industrial process for biomass conversion uses non-aqueous solvents.

Final comments: Fundamental catalysis research and bringing new catalytic technologies to market

In closing, we suggest that catalysis researchers should carry out their fundamental studies with consideration of what the catalytic technology would look like in a large-scale industrial process. At some point, new technologies need to be scaled up from the laboratory to a pilot plant and then a larger demonstration plant, which introduces non-trivial engineering and scale up challenges; each step can involve anywhere from a 10 to 1,000 times increase in process scale. The degree of difficulty with scaling up new technologies often depends on the degree of project definition, the type of reactor system used, the number of recycle loops required, and the complexity of the process. This scale up process is also expensive, and can result in large amounts of money being lost if not done correctly. Therefore, it is critical that the scale up process is informed by laboratory data that are accurate, and that the material balances in the laboratory are correct.

One illustrative example of scaling up a new technology is the work of Liu and co-workers at the Dalian Institute of Chemical Physics (DICP), who scaled up the methanol to olefins process from the laboratory to a commercial scale, as reported in Table 1.[89] In 1982 they began working in the laboratory on this process at a scale of around 0.5 kg/day. In 1993 they then scaled up their process by 100 times, building a bubbling fluidized bed reactor that processed a feed of 50 kg/day. Thirteen years later, a demonstration facility (or small scale commercial facility) was built with a feed rate of 50,000 kg/day. The demonstration facility was in a different fluidization regime than the laboratory or pilot scale reactor, which likely caused changes to the material balance. In 2010 a larger scale 5.5 million kg/day was built which was a 100 times scale up from the demonstration facility. While this technology was first reported by the Mobil Oil Corp. in 1974[90], and was later worked on by Exxon in 1985[91] and by UOP in 1993,[92] the DICP led team was the first organization to build a commercial scale facility. This example shows that it typically takes decades of continual effort to bring a new chemical process technology to scale.

Table 1. Timeline for the scale up of the DICP Methanol to Olefin technology (adapted from[89])

	Laboratory	Pilot Scale	Demo Scale	Commercial Scale
Year Started	1982	1993	2006	2010
MeOH Feed (kg/day)	0.5	50	50,000	5,500,000
Catalyst Inventory (kg)	0.01	1	400	45,000
Superficial Velocity (m/s)	0.01-0.1	0.01-0.2	1-2	1-2
Fluidization Regime	Bubbling	Bubbling	Turbulent	Turbulent
Reactor Diameter (m)	0.01	0.1	1	10
Scale up from previous step		100	1,000	100

It should be noted that some insights about a catalytic process are only discovered during scale up. For example, it was recently discovered that new chemistry (as compared to the smaller lab-scale process) occurs during the production of a synthetic jet fuel blend from a biomass-derived stream. [93] Therefore, a key challenge with respect to the scale up process is understanding how factors such as reactor hydrodynamics change going from the lab scale to an industrial process, and how these changes affect the process and the underlying chemistries. To this end, new tools are being developed to understand the fundamental changes that occur when solid biomass decomposes. [94,95] The mechanical integrity of the catalyst also becomes an important issue in the larger facilities. Furthermore, poisons that were not anticipated in laboratory studies can introduce catalyst deactivation issues during scale up. This problem was encountered by Ineos when they attempted to scale up their ethanol production process, only to find that their catalyst was inhibited by ammonia. [96]

We note here that several limiting factors facing the development and scale up of new biomass conversion technologies extend well beyond the scope of the four challenges discussed herein. For instances, transport of diffuse biomass resources to processing facilities, handling of various components present in biomass (including mineral and ash content), and regional or seasonal feedstock variability are also important challenges that affect the sustainable production of value added fuels and chemicals from lignocellulosic biomass.

As a final thought, consider George Mitchell, who for decades put extensive time and energy into developing the technology to produce natural gas using hydraulic fracturing (or fracking) technologies. [97] His team knew that the natural gas was abundant in tight underground formations, but did not have the technology to extract it. Several skeptics criticized him for wasting too much time and money on this project. In the end, however, this technology turned into the most important energy advancement in the 21st century. Today, we find ourselves in a similar situation as George Mitchell was in during the 1990s: we know that biomass is available, abundant, and that it has energy content. What we are missing are the catalytic technologies to convert the biomass economically into fungible fuels and commodity chemicals. However, our society has no other short-term, realistic or economically viable options to produce sustainable liquid fuels and chemicals than from plant biomass. It is therefore our belief that, as an international catalysis research community, we can (and must) work together to overcome the long-term scientific challenges outlined herein, and develop catalysts and catalytic technologies that will reduce our society's dependence on fossil resources.

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