MetalloMOFzymes – Heterogeneous Catalysis Inspired by Nature

Sudharsan Dwaraknath Literature Seminar October 4th, 2016

Metal-organic frameworks (MOFs) are atomically precise and permanently porous materials that self-assemble from metal ions or clusters and organic linkers. The variability of these building blocks has enabled tremendous structural and functional diversity among the thousands of MOFs that are prepared every year.[1] Indeed, the MOF field has become one of the fastest growing areas in chemistry[2,3] having shown use in a number of applications including gas storage, separations, light harvesting and energy conversion, drug delivery and catalysis.[4] The development of catalytic MOFs is motivated in part by the traditional advantages of heterogeneous catalysis – MOFs are chemically robust materials that can be easily separated from a liquid or gaseous reaction mixture and reused. At the same time, the three-dimensional pores of MOFs offer substrate selectivity and active site tunability that are characteristic of metalloenzymes (Figure 1).[5] Given that metalloenzymes perform challenging chemical transformations with excellent activity and selectivity under mild conditions, there is tremendous interest in exploiting MOF cavities for biomimetic catalysis.[6,7]

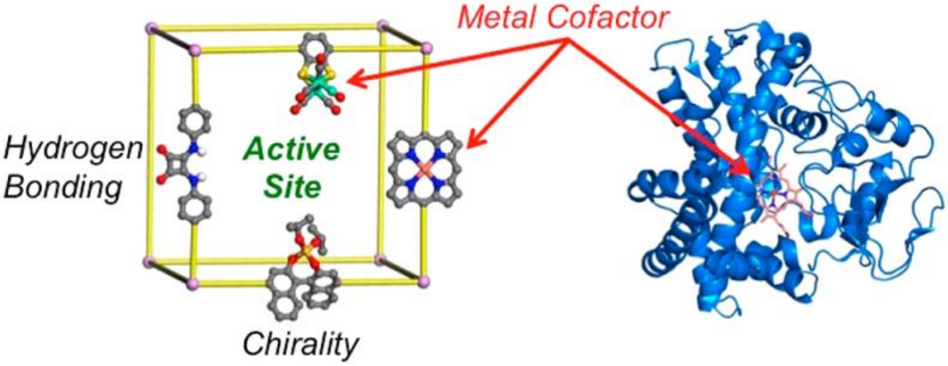

Figure 1. Schematic representation of a metalloMOFzyme; bioinspired features such as chirality, hydrogen-bonding groups and metal cofactors can be introduced into the pore of a MOF.

The activity and selectivity of enzymes stems from their use of non-covalent interactions to pre-organize substrate molecules and stabilize transition states. Following this, MOF pores have been decorated with functionalities such as hydrogen bonding, π-stacking and chiral donating groups.[8-10] Another desirable property of some metalloenzymes is their ability to carry out tandem reactions. These cascade processes ensure a fast reaction rate and prevent side product formation. Accordingly, two single-site molecular catalysts have been incorporated into the pores of MOFs to facilitate tandem chemistry.[9,10] For their biomimicry, these MOFs have been dubbed "metalloMOFzymes."[5] Their catalytic competency has been demonstrated in the tandem oxidation and functionalization of styrene to form cyclic carbonates and vicinal azidohydrins and the individual reactions therein (Figure 2).

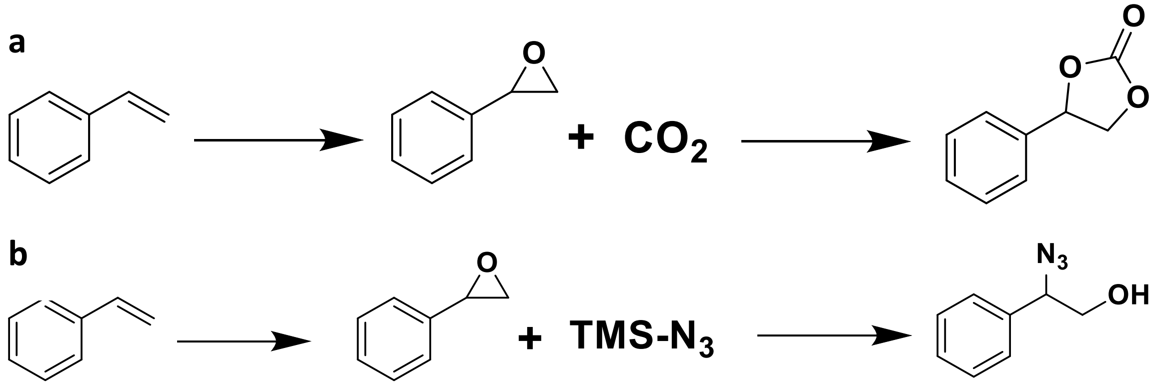

Figure 2. Tandem reactions for the conversion of styrene to a cyclic carbonate (a) and an azidohydrin (b)

The MOF, Hf-NU-1000, catalyzes the complete conversion of styrene oxide to a cyclic carbonate under mild conditions. In addition, it is proven useful in the complete and regioselective transformation of styrene oxide to azidohydrins. DFT calculations indicate that the MOF uses π-π interactions between the organic linker and substrate molecule to direct the regioselectivity.[8] In both reactions, an acidic Hf_6 node is the active catalyst and a pyrene-based organic linker is a spectator. Substitution of the pyrene linker for an Fe-porphyrin takes advantage of known porphyrin oxidation chemistry to facilitate tandem reactions that transform styrene to an azidohydrin.[9]

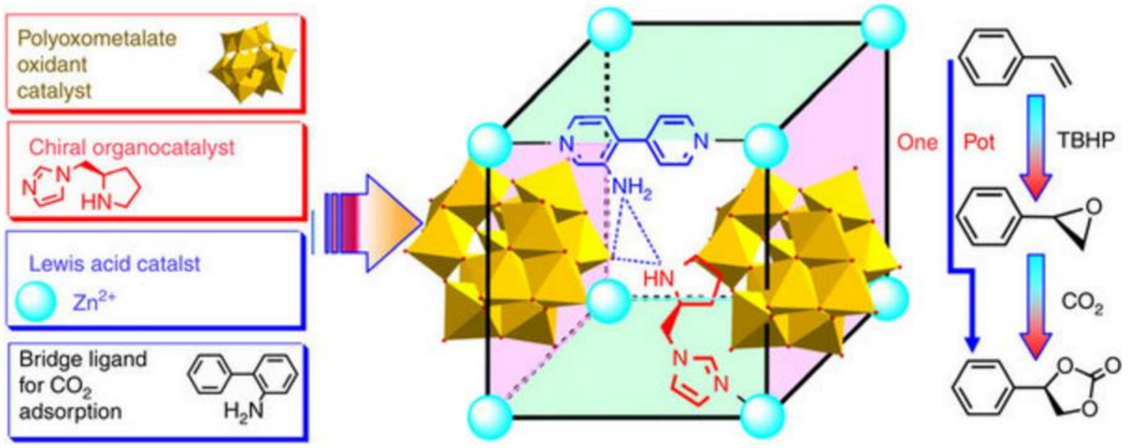

Figure 3. Schematic diagram of the building blocks of and non-covalent interactions in ZnW-PYI MOF and the tandem reactions for the asymmetric production of cyclic carbonates from olefins and CO_2.

A richly functionalized MOF, ZnW-PYI, leverages the oxidation chemistry of polyoxometalates and the acidity of Zn^{2+} ions for the conversion of styrene to a cyclic carbonate. In addition, this MOF features a chiral pyrrolidine moiety involved in critical non-covalent interactions. Specifically, a hydrogen bonding interaction between the tungsten-oxo oxidant and pyrrolidine amine provide steric orientation that drives asymmetric oxidation of styrene. The pyrrolidine also interacts with NH_2-bpy struts to enable the subsequent addition of CO_2 to styrene oxide under mild conditions (Figure 3). The overall transformation is achieved in $\geq$ 90% yield and good enantioselectivity.[10]

These examples are promising in their ability to drive selective catalysis in a biomimetic fashion inside of heterogeneous materials. Still, these emerging catalysts demonstrate only a small fraction of the turnover number exhibited by metalloenzymes and are used only to transform elementary small molecules. Future generations of MOFs must be designed for improved stability to highly basic and polar conditions to expand their reaction scope, faster diffusion to enhance catalytic rate, and more intricate selectivity to show promise for complex molecule transformations.[6,11]

References:

1. Furukawa, H.; Cordova, K.E.; O'Keeffe, M.; Yaghi, O.M. "The Chemistry and Application of Metal-Organic Frameworks," *Science* **2013,** *341,* 974.
2. Zhou, H.C.; Long, J.R.; Yaghi, O.M. "Introduction to Metal-Organic Frameworks," *Chem. Rev.* **2012,** *112,* 673-674.
3. Zhou, H.C; Kitagawa, S. "Metal-Organic Frameworks (MOFs)," *Chem. Soc. Rev.* **2014,** *43,* 5415-5418.
4. Howarth, A.J., et al. "Chemical, thermal and mechanical stabilities of metal-organic frameworks," *Nat. Mats.* **2016,** *1,* 1-15.
5. Cohen, S.M.; Zhang, Z.; Boissonnault, J.A. "Towards 'metalloMOFzymes': Metal-Organic Frameworks with Single-Site Metal Catalysts for Small-Molecule Transformations," *Inorg. Chem.* **2016,** *55,* 7281-7290.
6. Gu, Z.Y.; Park, J.; Raiff, A.; Wei, Z.; Zhou, H.C. "Metal-Organic Frameworks as Biomimetic Catalysts," *Chem. Cat. Chem.* **2014,** *6,* 67-75.
7. Nath, I.; Chakraborty, J.; Verpoor, F. "Metal organic frameworks mimicking natural enzymes: a structural and functional analogy," *Chem. Soc. Rev.* **2016,** *45,* 4127-4170.
8. Beyzavi, M.H., et al. "A Hafnium-Based Metal-Organic Framework as an Efficient and Multifunctional Catalyst for Facile CO_2 Fixation and Regioselective and Enantioretentive Epoxide Activation"
9. Beyzavi, M.H., et al. "A Hafnium-Based Metal-Organic Framework as a Nature-Inspired Tandem Reaction Catalyst," *J. Am. Chem. Soc.* **2015**, *137,* 13624-13631.
10. Han, Q.; Qi, B.; Ren, W.; He, C.; Niu, J.; Duan, C. "Polyoxometalate-based homochiral metal-organic frameworks for tandem asymmetric transformation of cyclic carbonates from olefins," *Nat. Commun.* **2015,** *6,* 1-8.
11. Chughtai, A.H.; Ahmad, N.; Younus, H.A.; Laypkov, A.; Verpoor, F. "Metal-organic frameworks: versatile heterogeneous catalysts for efficient catalytic organic transformations," *Chem. Soc. Rev.* **2015,** *44,* 6804-6849.