

occurrence of the typical external quantum efficiency droop, albeit significantly less so than for the unoptimized device architecture as reference. An operating lifetime of 4 h, for which ASE could be demonstrated before device failure would result, would similarly be an important parameter to aim to improve further. The initially mentioned tunability of emission wavelength by changing the size of the QDs implemented should also be explored in practice. Lastly, the devices demonstrated in this study still lack lateral optical confinement and have not been optimized toward improved light out-coupling. As an exciting outlook, the authors therefore next want to work toward a nanocrystal-based laser oscillator, for example, using an in-plane distributed feedback grating or Fabry-

Pérot cavities through the addition of edge reflectors.

Overall, these results present a landmark study in the race for market-ready, solution-processable semiconductor lasers and predict a bright future ahead for QD-based optoelectronics.

DECLARATION OF INTERESTS

The author declares no competing interests.

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Expanding past ZIF-8: Biomimetic mineralization using other MOFs

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The development of protective metal-organic framework (MOF) coatings on the surface of natively folded proteins has emerged as a promising approach to enhance their stability. Zeolitic imidazolate frameworks have been the primary focus owing to their stability and ability to form in water. However, recent research has expanded the range of MOFs that can be synthesized under biocompatible conditions. This preview highlights the work of Yang, Giménez-Marqués, Ren, and others, showcasing novel efforts that provide a new direction for future research. These developments may lead to stable and robust biomolecules with broad applications in biomedicine and beyond.

Metal-organic frameworks (MOFs) are self-assembling, low-density coordination polymers with metal centers that coordinate organic linkers to produce extended solids. MOFs have found use in catalysis, gas separation, sensing, and other fields that make excellent

use of their surface-area-to-volume ratio. One of the more recent developments in MOF research has been the marriage between these classic materials and biomacromolecules. The thermal stability of MOFs is exploited as a protective coating for fragile biomate-

rials to preserve their structural and functional integrity. This result is achieved in two ways; one approach involves loading the biomaterials in an already-synthesized MOF with appropriately sized pores, referred to as “post-synthetic loading.” The other method—“biomimetic mineralization”—involves using the biomaterial as a nucleating surface for *in situ* MOF growth by adding a metal salt and an appropriate organic linker to the aqueous solution containing the biomolecule.¹ The biomolecules that have been coated are protected not only from heat but also from mechanical stressors, organic solvents, denaturing agents, and enzymatic degradation.

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BiOMImETIC MiNERALization oNLY WoRKs wITh ZIF-8

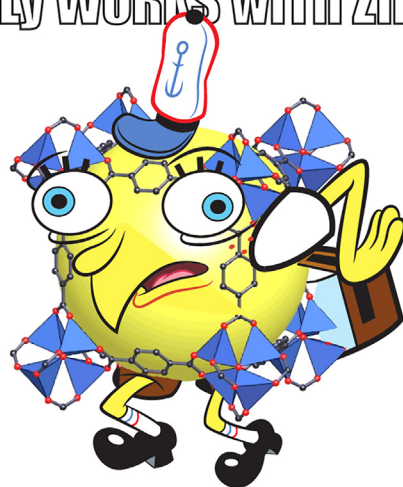


Figure 1. A narrow view of MOF-based biomimetic mineralization

These two approaches of biomaterial protection using MOFs each have their pros and cons. Because biomolecules are loaded after the MOF is made, post-synthetic loading has no limitations on the harshness of the MOF synthesis, meaning a wide variety of MOF chemistries exist to choose from. However, these MOFs are synthetically intensive as the pores must be bespoke for the biomolecule—large enough to allow it to enter the pores but tight enough that it would not easily escape again. In that regard, biomimetic mineralization is substantially more accessible synthetically than post-synthetic loading, as it is a one-pot process that can be applied to biomaterials of sizes ranging from small DNA fragments to liposomes.^{2,3} Biomimetic mineralization using MOFs has expanded rapidly over the last decade owing to the large scope of materials that can be encapsulated; however, the synthetic route to form these MOFs must be biorthogonal, which severely restricts the number of MOFs available for this process, as many MOFs do not form in water. As a result, ZIF-8—which readily forms in water—is the most commonly used MOF (Figure 1). Its facile, bio-friendly synthesis has also led to the

investigation of biomimetic mineralization using other Zeolitic imidazolate frameworks (ZIFs), such as ZIF-90 and MAF-7.⁴ While this body of work lays a solid foundation, its limited chemistry does not provide enough options for use in cases requiring a different metal, ligand, or their resulting biocompatibility, immune properties, and pharmacokinetics. Recognizing this gap in research, several groups have made excellent progress in moving away from ZIF-8, which this perspective highlights. Figure 2 illustrates the first instances of some already-published, existing MOFs whose synthetic schemes were adapted to make them biomineralization friendly.

Jordahl et al. took overcoming the “ZIF limit” to task by demonstrating the encapsulation of the enzymes lysozyme and lipase in a series of MOFs containing one of five metal ions Al^{3+} , Cu^{2+} , Ni^{2+} , Zn^{2+} , or Zr^{4+} .⁸ Each metal was reacted with the carboxylate-based ligands—1,4-benzenedicarboxylate (BDC) and biphenyl-4,4'-dicarboxylate (BPDC)—and eight out of the ten combinations yielded crystalline structures. A standardized synthesis is reported where the metal precursor, organic linker, and enzyme are com-

bined in water. The reactions were incubated overnight or until crystals precipitated. Enzyme immobilization in the MOF (or the amorphous construct) allowed for substrate interaction and maintained enzymatic activity while encapsulated. Moreover, the immobilized enzymes showed greater activity than the free enzyme. Such examples illustrate how various MOFs beyond ZIF-8 have the potential to mineralize, protect, and preserve biomaterials. The “one-pot” MOF synthesis described rids the use of organic solvents and makes this technique compatible with delicate biomacromolecules.

There is a piqued interest in developing MOF coatings from abundant metals in our bodies, resulting in a higher bracket of tolerance for fluctuation. Giménez-Marqués and coworkers recently published their strategy of encapsulating four different proteins—bovine serum albumin (pI 5.10), equine myoglobin (pI 7.20), subtilisin Carlsberg (SubC, pI 9.40), and bovine cytochrome C—in the iron MOF MIL-100.⁷ They introduced a metal precursor solution to a mixture of ligand and protein solution at a rate of 20 mL/h. Both solutions were degassed during the process. They noticed that higher protein concentrations resulted in larger protein@MOF composites. Additionally, they conducted protein-release studies using phosphate-buffered saline where it is likely that the phosphate anion degraded the MOF by binding to iron and out competing the ligand. They found that the MIL-100 coating was effective in preserving the activity of SubC against sodium dodecyl sulfate (SDS), but only somewhat effective against guanidine hydrochloride and dimethylformamide. Miao et al. also successfully optimized the encapsulation conditions for horseradish peroxidase in an iron MOF composed of Fe^{3+} and 2-amino terephthalic acid.⁵ The technique used here was ultrasonic synthesis, where the protein, metal, and linker were added to deionized (DI) water and reacted for 1 h at room temperature under

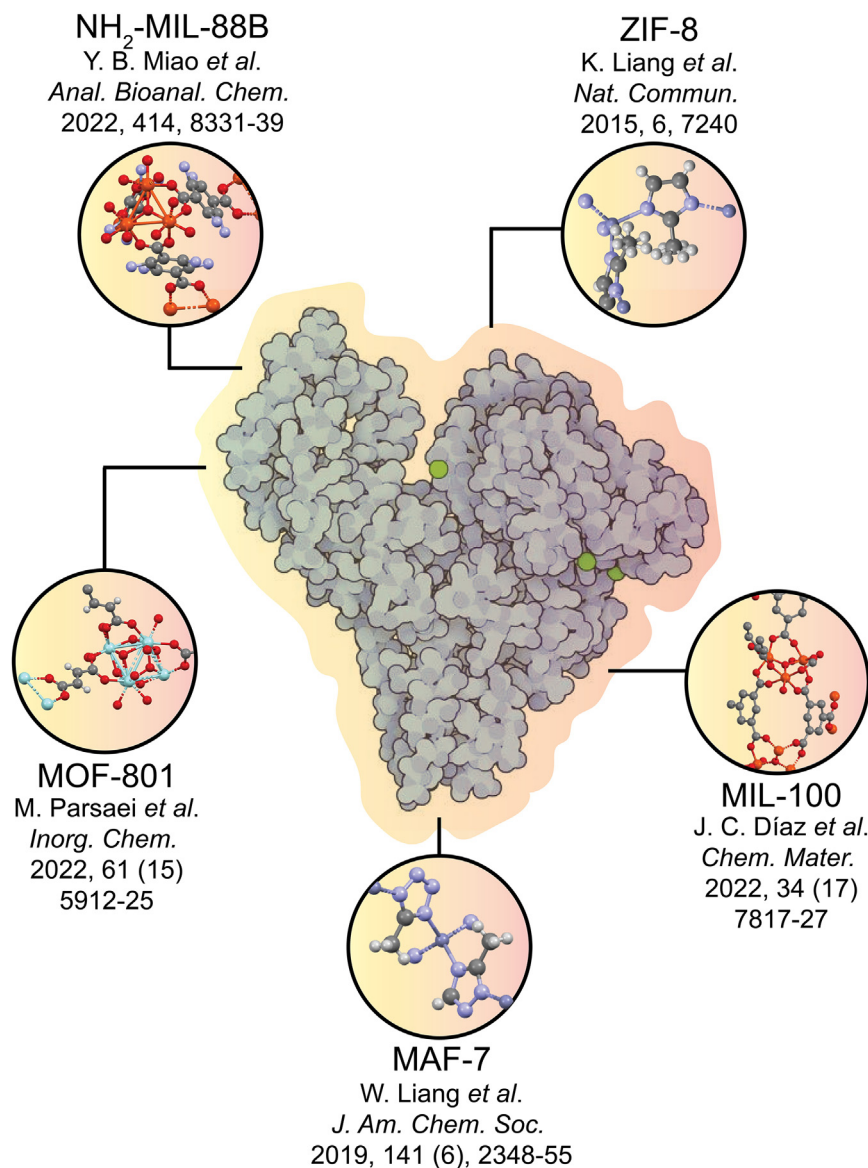


Figure 2. Foundational reports on biomimetic mineralization

First-known reports of biomimetic mineralization of NH₂-MIL-88B,⁵ ZIF-8,¹ MOF-801,⁶ MAF-7,⁴ and MIL-100.⁷

sonication. The encapsulation efficiency was determined by using EDTA as a chelating agent to remove the MOF coating, following which the released protein was quantified using a colorimetric assay. Even for protein-to-MOF mass ratios as high as 1:1, the encapsulation efficiency was over 90%.

Shen *et al.* recently published a method to biomimetically mineralize

glucose oxidase and β -galactosidase in a Fe/Co bimetallic MOF.⁹ While the authors intend to exploit the benefits of bimetallic MOFs for synergistic purposes, there is an increased interest in exploring the field to reduce the overall metal toxicity of the material, as each metal is metabolized in the body independently. In this paper, the encapsulation process was carried out by directly mixing the protein(s),

both metal salts, and the ligand in DI water and allowing the reaction to proceed for an hour under stirring conditions. The authors use polyvinylpyrrolidone (PVP) surface-adsorbent exchange and SDS immersion experiments to highlight how biomimetic mineralization can confer better protection than loading the pores of the MOF post-synthetically. In both cases, every subsequent wash removed a significant amount of protein from the post-synthetically loaded MOF, and only ~20% of the protein remained after five washes. In contrast, neither PVP nor SDS significantly impacted the biomimetically mineralized protein, and ~90% remained inside the MOF.

Although not a bioavailable metal (less than 1 mg in the human body), zirconium is well tolerated, with reported values of concentrations that induce 20% inhibition (IC₂₀) greater than 200 μ M *in vitro*.¹⁰ Parsaei *et al.* encapsulated 5-fluorouracil—a chemotherapeutic agent—in MOF-801, a Zr⁴⁺ MOF with a fumaric acid linker.⁶ The synthesis of the MOF-801 with 5-fluorouracil takes place at ambient temperature in water. Although this particular example encapsulates a small molecule drug, the biofriendly conditions suggest that this approach could also be applied to more sensitive biomacromolecules. To synthesize MOF-801 with 5-fluorouracil, Zr⁴⁺ salt is dissolved in water with formic acid. Subsequently, fumaric acid is added to the aqueous reaction mixture, followed by 5-fluorouracil, and is allowed to stir for one week at room temperature. The resulting crystals were then washed with water and ethanol. The authors reported the drug loading capacity and efficiency to be 88.5% and 70%, respectively.

Biomimetic mineralization strategies have been reported using MOFs made of copper, cobalt, iron, zinc, zirconium, aluminum, europium, nickel, and terbium. These results are exciting yet new, and their eventual validation with a broader scope of biomolecules is still

needed. We hope to see more in-depth studies and diversifications on such existing reports, as it will provide future researchers with the confidence to use other MOFs with comparable reliability and reproducibility as observed with ZIF-8.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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The magnet: With more power comes more annihilation

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Probing the underlying attributes of triplet-triplet annihilation-based upconversion systems is necessary to enable future practical applications. Through a combination of excitation power-dependent upconversion measurements under applied magnetic fields and molecular dynamics simulations, Schmidt and coworkers have recently demonstrated a quantitative approach for extracting critical parameters detailing the intricate upconversion process.

Since its initial discovery by Parker and Hatchard in 1962,¹ triplet-triplet annihilation upconversion (TTA-UC), also known as triplet fusion, has become an exciting area of research.^{2–4} The UC process combines multiple low-energy

photons into a single photon of higher energy, effectively shortening the wavelength of light emitted after illumination. In TTA-UC systems, the interaction between two spin-triplet states creates an excited spin-singlet state,

producing an apparent anti-Stokes shifted upconverted photon upon radiative relaxation. Due to the selection rules governing optical transitions, population of the triplet state is commonly achieved by means of triplet energy transfer from triplet sensitizers, as direct excitation from the ground state to the triplet excited state is spin-forbidden and only exhibits weak oscillator strength. This results in long triplet state lifetimes since the relaxation process to the ground state is also spin-forbidden, allowing spin-triplet states to be used as a form of long-lived energy storage. Therefore,

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