# Artificial enzymes for artificial photosynthesis

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Artificial enzymes capable of catalysing significant transformations are highly desired but usually suffer from limitations in structural design and poor efficiency. Now, a monolayered metal–organic framework is reported as an editable biomimetic platform to achieve exceptional artificial photosynthesis performance.

Enzymes are essential to all living things, transforming indispensable substances under mild conditions with high specificity, selectivity, and efficiency. In particular, natural enzymes serve as efficient catalysts in various crucial fixation pathways including photosynthesis, nitrogen fixation and methane activation, to name just a few. The sophisticated structures of enzymes have greatly intrigued researchers and have led to the uncovering of their underlying reaction mechanisms. Thereafter, enzyme-mimicking structures that can help to tackle some challenging chemical transformations have become an ambitious target of research.

In particular, artificial enzymes for photocatalysis inspired by their natural counterparts in plants have gained widespread attention for their ability to convert light into chemical energy while consuming environmentally unbenign $CO_2$. So far, small molecules, nanoparticles, porous organic/hybrid frameworks and other systems have been investigated as mediators for synthetic photocatalysis. Nonetheless, due to the intrinsic complexity connected to creating an artificial enzyme, most of these photocatalysts can only realize relatively simple reactions, and their integration for multistep photocatalytic transformations remains difficult. Moreover, the total efficiency of most investigated systems is still far behind the demand of practical applications.

Now, writing in *Nature Catalysis*, Lin and co-workers reported monolayered metal–organic frameworks as a versatile enzyme-mimicking platform (metal–organic–zyme, MOZ) for highly efficient photocatalytic transformations, namely the $CO_2$ reduction reaction ($CO_2$RR), the $H_2O$ oxidation reaction (WOR), and even complete photosynthesis ($CO_2 + H_2O$) (ref. [1]).

Initially, the team constructed the basic framework as an adjustable platform. $Hf_{12}$ clusters $[Hf_{12}(\mu_3\text{-O})_8(\mu_3\text{-OH})_8(\mu_2\text{-OH})_6]$ (ref. [2]) vertically capped by trifluoroacetate (TFA) and laterally connected by photosensitizing Ir(4,4'-di(4-benzoato)-2,2'-bipyridine)[2-(2,4-difluorophenyl)-5-(trifluoromethyl)pyridine]$_2^+$ (Ir–PS) ligands are periodically expanded into a crystalline two-dimensional (2D) network with the formula $Hf_{12}(\mu_3\text{-O})_8(\mu_3\text{-OH})_8(\mu_2\text{-OH})_6(Ir\text{-PS})_6(TFA)_6$ (Hf–Ir) (Fig. 1). The monolayered 2D material, with a clearly determined structure, has a measured diameter of ~150 nm and a thickness of ~1.7 nm, which agrees well with the modelled structure. Importantly, the weakly coordinated TFAs can be readily exchanged by other more electron-rich carboxylate groups, thus facilitating the construction and diversification of biomimetic catalysts.

Next, a remarkable performance in photocatalytic $CO_2$RR was achieved by using an optimal catalyst selected from a diversified library of MOZs. The introduction of catalytically active ferric protoporphyrin hemin[3] to the basic framework was theorized to partially replace TFA, attaining MOZ-1 with an empirical formula of $Hf_{12}(\mu_3\text{-O})_8(\mu_3\text{-OH})_8(\mu_2\text{-OH})_6(Ir\text{-PS})_6(hemin)_{0.48}(TFA)_{5.52}$. Moreover, the screening of all 20 natural amino acids (AAs) to replace the remaining TFA not only modulated the environment surrounding the active site, but also diversified the catalysts. The prepared composites were implemented in $CO_2$RR tests showing different catalytic performances accordingly. Amongst these, MOZ-3 (with asparagine modification) showed a dramatically enhanced performance when compared with MOZ-1, which was ascribed to a hydrogen-bond stabilization effect, based on complementary calculations and experimental results. Furthermore, synthetically modified AAs with stronger hydrogen-bond stabilization capacity were predicted to further optimize MOZ's catalytic performance. Indeed, MOZ-4 – prepared by appending 4-(3-(3,5-bis(trifluoromethyl)phenyl)ureido)butanoic acid onto MOZ-1 – achieved the best performance, even under natural sunlight, showing results that were much better than other reported photocatalysts.

Following these results, another library of MOZ catalysts was established for photocatalytic WOR using the same approach as for photocatalytic $CO_2$RR. As a proof-of-concept, the researchers switched the active metal sites from hemin to [Ir(H–MBA)Cp*Cl] + MBA–Ir (where H–MBA = 2-(4'-methyl-[2,2'-bipyridin]-4-yl)acetic acid; Cp* = pentamethylcyclopentadienyl)[4] and again screened all natural AAs. MOZ-6 (with glutamine modification) with an empirical formula of $Hf_{12}(\mu_3\text{-O})_8(\mu_3\text{-OH})_8(\mu_2\text{-OH})_6(Ir\text{-PS})_6(MBA\text{–Ir})_{0.48}(Gln)_{5.52}$ was exceptional in the WOR thanks to a suitable oxidation potential and the stabilization of $H_2O$ through a hydrogen-bond interaction. Upon further optimization, MOZ-7 with the 6-((4-chlorophenyl)amino)-6-oxohexanoic acid modification showed the best performance.

Finally, the combination of the two optimal catalysts from the respective $CO_2$RR and WOR achieved an enhanced system for total artificial photosynthesis. In particular, MOZ-4 and MOZ-7 as catalysts in a ratio of 1:3 circumvented mutual quenching and performed the complete photosynthesis in the presence of the redox mediator $Co(bpy)_3^{2+}$ (bpy = 2,2'-bipyridine). With a turnover frequency number of 98.7 ± 3.7 per hour, this system surpasses previously reported photocatalysts[5].

This inspiring work by Lin et al. not only presented a general strategy to expand the broad class of artificial enzymes, but also demonstrated their significant applications in energy conversion schemes. Based on the foundations laid by this work, future developments can be anticipated in the areas of materials science, organic transformations and biological applications. From the perspective of materials design, there is still plenty of room for variations of arrangements in both ligand type and active-site spacing, which is key to tuning a catalyst's reactivity, selectivity, and efficiency. It is also predictable that MOZs will unlock more challenging reactions (for example, $N_2$ reduction, methane activation and chemo/regio/stereo-selective reactions) under mild conditions. In addition, the broad access to MOZ artificial enzymes will
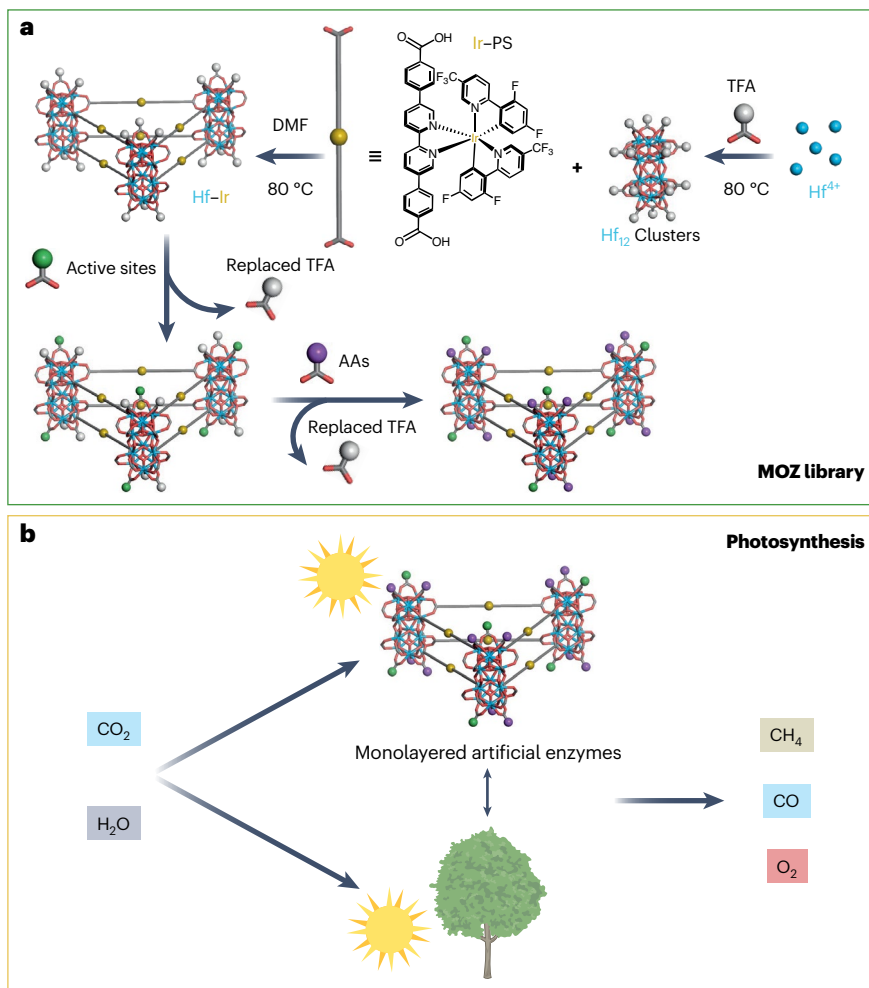
**Fig. 1 | Monolayered metal–organic framework as artificial enzymes for efficient photosynthesis. a**, Metal–organic framework monolayers as a platform for the constructions of artificial enzymes with precise integration of active centres, proximal amino acids (AAs), and cofactors. **b**, The obtained metal–organic–zymes (MOZs) show excellent performance in the photocatalytic $CO_2$ reduction reaction, the $H_2O$ oxidation reaction and integrated artificial photosynthesis. DMF, *N,N*-dimethylformamide; TFA, trifluoroacetate. Figure adapted with permission from ref. [1], Springer Nature Ltd.

expedite their exploitation for the latest biochemistry frontier, that is new-to-nature synthesis[6]. Furthermore, MOZs could presumably serve as nanomedicines for biological applications because of their good stability and high precision. In short, this elegant work creates a significant impact with 2D artificial enzymes by design at the molecular level, and builds up a bright blueprint for their cutting-edge applications.

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