Designing a Bifunctional Brønsted Acid–Base Heterogeneous Catalyst Through Precise Installation of Ligands on Metal–Organic Frameworks

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A Brønsted acid–base bifunctional metal–organic framework (MOF) catalyst, PCN-700-AB [A = Brønsted acid site, TPDC–(COOH)₂ [(1,1′:4,1″-terphenyl)-2,2′,4,4″-tetracarboxylic acid] and B = Brønsted basic site, BDC-NH₂], was designed precisely and synthesized successfully through sequential installation of Brønsted acid and base functionalities in a crystalline zirconium (Zr)-MOF. The installation underwent single-crystal-to-single-crystal transformation throughout the process; hence, the structure of the bifunctional catalyst could be characterized accurately via single-crystal X-ray crystallography. The bifunctional MOF catalyst obtained exhibited excellent acid–base catalytic activity for a cascade of one-pot deacetalization–Knoevenagel condensation reaction. The work presented here could be considered as a promising solution to incorporate multifunctional components readily, especially the hostile aspects, into one MOF structure.

Keywords: Brønsted acid–base catalyst, linker installation, single-crystal transformation, metal–organic frameworks

Introduction

Currently, a hot topic of catalysis is to design and synthesize multivariate heterogeneous catalysts for tandem or cascade reactions, due to their obvious advantages such as easy recovery from solution and simplifying procedures of multicomponent or multistep reactions.¹³ These types of catalysts could have multiple catalytic sites, as well as great tolerance of various organic solvents, yet one of the challenges encountered in their
fabrication is the introduction of acidic and basic sites in the same heterogeneous catalyst for tandem acid-base reactions. The reason is that it is very difficult to find a facile route able to prevent neutralization of acid-base active sites during the synthesis process. In recent years, some catalysts that contain these hostile catalytic sites within a single mesoporous silica or polymer resin have been prepared, but due to complications in the preparation procedure or the unsustainable acid-base sites, there is a hindrance in the subsequent steps toward their application.

Metal–organic frameworks (MOFs), an emerging crystalline hybrid material, are famous for their porous structures and diverse compositions. Over the past 20 years, MOFs generation has been one of the important branches in the area of heterogeneous catalysis, owing to their tailored pore size and diverse catalytic centers. Especially, the design of acid–base bifunctional MOF catalysts is an attractive but difficult work, and the formation of most catalytic sites of the existing MOF catalysts has focused on the use of open metal sites as Lewis acid, and basic organic groups of ligands as Lewis bases. However, the application of Brønsted acid–base MOF catalysts for tandem or cascade reactions has rarely been reported due to the sluggish Brønsted acid/base chemistry in MOFs.

As far as we know, two main problems hamper the development of Brønsted acid–base MOF catalysts: (1) it is very difficult to integrate hostile catalytic sites within one framework by either one-pot synthesis or post-synthetic modification. (2) MOFs, used for anchoring Brønsted acid and basic sites, have to withstand both acid and basic environment; however, only a small number of candidate compounds are qualified. One of the successful examples is synthesis of a Brønsted acid-base bifunctional catalyst, MIL-101-SO3H-NH2, based on a post-synthetic modification, this method is short of the direct evidence of a combination of Brønsted acid and base active sites in MOFs. Recently, Zhou’s group and Su’s group succeeded in the construction of Zr-MOFs through a sequential linker installation or dynamic spacer installation processes. These methods provided plausible alternative ways to solve the issues mentioned above, and involved resorting to a responsive Zr-MOF system, namely PCN-700, as the prototype, assembled using the organic linkers, H2Me2-BPDC (H2Me2-BPDC = 2,2′-dimethylbibenyl-4,4′-dicarboxylic acid) and eight-connected Zr clusters, Zr6O4(OH)8(H2O)4. Peculiarly, two specific types of “pockets” with different lengths (16.4 Å for pocket A and 7.0 Å for pocket B) in PCN-700 were created, which matched linkers with different lengths, as well as different functional groups (see Figure 1).

Herein, inspired by this new unique structure, we attempt to introduce Brønsted acid and base sites in the MOF PCN-700-pockets A and B, respectively, characterize the newly modified structure by single-crystal X-ray diffraction analysis (SCXRD), Fourier-transform infrared (FT-IR) spectrometry, 1H NMR and temperature-programmed desorption (TPD) experiments, as well as study the catalysis performance of the new fabrication by performing one-pot deacetalization–Knoevenagel condensation reaction.

**Results and Discussion**

We introduced the Brønsted acid site into MOF PCN-700 by installing H2TPDC-(COOH)2 [[(1,1′:4,1′-terphenyl)-2,2′,4,4′-tetracarboxylic acid] into the pockets A and created the Brønsted base site by installing H2BDC-NH2 (2-aminothrephalic acid) into pocket B (see Figure 1). Owing to the mild synthetic conditions and the spatial isolation of the acid and the base sites, we fabricated successfully, a Brønsted acid-base bifunctional MOF PCN-700-AB [PCN-700-BDC-NH2-TPDC-(COOH)2] by a precise, sequential, two-step installation of linkers. Since the newly created structure underwent single-crystal-to-single-crystal transformation throughout the procedure, it was possible to confirm undoubtedly, the coexistence of the acid (A) and the base (B) sites by SCXRC. The PCN-700-AB obtained exhibited excellent acid-base catalytic activity for the tandem one-pot deacetalization–Knoevenagel condensation reaction, with the Brønsted acid groups, −COOH, catalyzing the deacetalization reaction, and the Brønsted base groups, −NH2, catalyzing the Knoevenagel condensation reaction.

As depicted in Figure 1, the as-synthesized PCN-700 crystals were immersed in DMF solutions of H2BDC-NH2 for 24 h under solvothermal conditions to get the crystal PCN-700-B (B = Brønsted basic site, BDC-NH2). Then, PCN-700-B was soaked in dimethylformamide (DMF) solution of H2TPDC-(COOH)2 and reacted for 36 h under the solvothermal condition to harvest the crystal, PCN-700-AB. In order to verify the cooperative
catalytic activity of –NH₂ and –COOH for the one-pot deacetalization–Knoevenagel condensation reaction, we prepared another MOF, PCN-700-MB (M = H₂TPDC-Me₂, 2',5'-dimethylterphenyl-4,4'-dicarboxylate) as a control, in which the Brønsted acid site (–COOH) of pocket A was substituted with methyl (–CH₃) groups, following a parallel synthetic procedure (see Supporting Information 3); thus this modified control MOF possessed the Brønsted base integrated in its structure but lacked the Brønsted acid pocket moiety (see Figure 2). The structures of the prototype MOF (PCN-700), and the newly modified MOFs (PCN-700-B, PCN-700-AB, and PCN-700-MB) were confirmed by SCXRC (see Figures 1 and 2, and Supporting Information Table S1).

Considering that the three MOFs were constructed by installing linkers into the void space of PCN-700, their frameworks were very similar to the parent MOF. PCN-700-B showed the same space group and unit cell as PCN-700, except for the extra H₂BDC-NH₂ linkers in pocket B (see Supporting Information Table S1). However, PCN-700-AB and PCN-700-MB crystallized in the axis of the fourth-order (P4₂/mnm) space group, and showed a doubled-size unit cell, compared with the prototype, PCN-700; since H₂TPDC-(COOH)₂ or H₂TPDC-Me₂ linkers occupied one of every two adjacent pockets A, it led to asymmetric assignment of these linkers in PCN-700-AB or PCN-700-MB, as viewed along the c axis (see Supporting Information Figure S1). In addition, the coexistence of the acid and the base sites were also confirmed by ¹H NMR (see Supporting Information Figure S20) and confirmed further by powder X-ray diffraction technique (see Supporting Information Figure S4). The powder X-ray diffraction patterns of the modified MOFs agreed well with simulated results obtained from Mercury software (see Supporting Information Figures S2–S5), which specified that the phase purity of our newly fabricated MOFs.

The FT-IR spectra (see Figure 3a) were also acquired to confirm the existence of Brønsted basic sites –NH₂ in PCN-700-B, PCN-700-AB, and PCN-700-MB; beside, we have shown here the spectra of the Brønsted base moiety, H₂BDC-NH₂, for comparison. Compared with PCN-700, the FT-IR spectra of PCN-700-B and PCN-700-MB displayed two apparent peaks at 3503 cm⁻¹ and 3389 cm⁻¹ in the high wavenumber area, resembling the bands of H₂BDC-NH₂ at 3509 cm⁻¹ and 3395 cm⁻¹, which could be ascribed to the asymmetric and symmetric stretching of the amine moieties in the complexes. In contrast, for PCN-700-AB, the υ(N–H) characteristic peaks appeared at 3499 cm⁻¹, 3385 cm⁻¹, which was a slight shift, compared with H₂BDC-NH₂, and it was due to the additional electron-withdrawing groups, –COOH, of H₂TPDC-(COOH)₂, which occurred after the second step of the installation. In addition, the free carboxylic acid, –COOH, in PCN-700-AB has also been observed at ~3170 cm⁻¹ in the FT-IR spectra (see Supporting Information Figure S11). Overall, the FT-IR spectra confirmed the successful incorporation of Brønsted basic sites –NH₂ and Brønsted acid sites –COOH in PCN-700-AB after two-step linker installation.

Moreover, TPD experiments were conducted to evaluate the surface strengths, as well as the concentrations...
of basic (CO$_2$–TPD) and acidic (NH$_3$–TPD) sites of PCN-700-AB, as shown in Supporting Information Figure S13 and S14. The results showed that, in contrast to the single peak at ~430 K in the CO$_2$–TPD curve of PCN-700, three visible TPD signals at ~473, 530, and 610 K were observed with PCN-700-AB, which indicated that the latter displayed higher affinity toward CO$_2$ and –NH$_2$ groups in structure, and thus, could be classified as medium to strong base sites. Subsequently, the acidity of PCN-700-AB was verified by NH$_3$–TPD measurement (see Supporting Information Figure S14), and although both PCN-700 and PCN-700-AB showed one prominent peak around 440 K, classified as medium strength acidity, PCN-700-AB, on the other hand, had higher concentration of acid sites than PCN-700, which could be attributable to the existence of free surface carboxylic acid in PCN-700-AB. Besides, the acid and base contents in PCN-700-AB were calculated according to the peak area integration and calibration curve (see Supporting Information Figure S13–S16, Table S2 and S3) to be 0.36 mmol/g and 1.11 mmol/g, respectively, revealing enhanced acid-base concentration of the surface PCN-700-AB.

The permanent porosities of the post-modified MOFs were verified by N$_2$ adsorption-desorption isotherms at 77 K, using an automated gas adsorption manometer (ASAP 2460 from Micromeritics Co. Ltd, USA). The N$_2$ adsorption–desorption isotherms revealed that these three new MOFs (PCN-700-B, PCN-700-AB, and PCN-700-MB) displayed reversible type I isotherms (see Figure 3b). The Brunauer–Emmett–Teller (BET) surface area and the total pore volumes were 1289 m$^2$ g$^{-1}$ and 0.598 cm$^3$ g$^{-1}$ for PCN-700-B, 1171 m$^2$ g$^{-1}$ and 0.539 cm$^3$ g$^{-1}$ for PCN-700-AB, and 1145 m$^2$ g$^{-1}$ and 0.519 cm$^3$ g$^{-1}$ for PCN-700-MB, respectively. The slightly lower values of BET surface area and total pore volumes of bifunctional MOFs could be ascribed to the decrease in void space occupied by –COOH or –CH$_3$ groups, compared with PCN-700-B. However, our BET surface area analysis demonstrated that these materials maintained a high BET surface area with large pore volumes, beneficial for the diffusion of reactants and products in the subsequent catalytic reaction.

Further, we investigated the acid-base catalytic activity of PCN-700-AB in a one-pot tandem conversion reaction of benzaldehyde dimethyl acetal into benzylidene malononitrile. The substrate conversions and the product yields were determined by monitoring the benzylic protons of the benzaldehyde dimethyl acetal (the substrate), benzaldehyde (product 1), and benzylidene malononitrile (product 2) by $^1$H NMR spectra (see Supporting Information Figure S22–S29). The protons involved are labeled with different colors for clarity (Figure 4a). Figure 4b is a histogram display, summarizing the percent yield of the catalytic conversion products 1 and 2, which are also summarized in Supporting Information Table S5.

Additionally, Figure 4b display a line graph of the catalytic selectivity. As shown in Figure 4b and Supporting Information Table S4 and S5, both high conversion and selectivity were obtained when the tandem reaction was conducted with the presence of PCN-700-AB. Furthermore, the robustness of the Zr–O bonds endowed PCN-700-AB with high stability, and hence, could be reused at least three times with negligible reduction in the catalytic activity (conversions: first = 91.03%; second = 89.57%; third = 87.26%). The powder X-ray diffraction pattern after three cycles was also in full agreement with the as-synthesized one (see Supporting Information Figure S6), which verified the sustainability of the bifunctional MOF PCN-700-AB catalyst. In contrast, PCN-700 could only convert as low as ~32% of the substrates to products. Regarding PCN-700-B, with an incorporation of only the Brønsted base sites, the substrate conversion yield rose to a moderate of 56.14%, but surprisingly the selectivity of product 2 was as high as 99.22%, which suggested that the Brønsted base sites, –NH$_2$ groups could promote the second step of the tandem reaction. However, the absence of the Brønsted acid sites in the structure caused a low catalytic activity. Therefore, we inferred that the coexistence of Brønsted acid sites, –COOH, and Brønsted base sites, –NH$_2$, endowed PCN-700-AB with both high...
conversion and high catalytic selectivity of the cascade reaction.

In order to confirm this hypothesis further, our MOF PCN-700-MB containing –NH2 and methyl groups control also resort to 56.71% yield in the catalytic conversion of the substrates to products, which was very close to the performance of 56.14% in yield of PCN-700-B. Collectively, these results indicated that the incorporation of –NH2 and –COOH into PCN-700-AB indeed exhibited cooperative Brønsted acid–base catalytic effect in the cascade reaction. Beside, it is worth mentioning that the 92.80% selectivity achieved for PCN-700-AB was slightly lower than that of PCN-700-B (99.22%), which might be due to the slight protonation of some NH2 groups during the second step of the installation of TPDC–(COOH)2. However, PCN-700-AB gave rise to an overall best performance, in terms of conversion and selectivity, for the one-pot deacetalization–Knoevenagel condensation reaction.

According to previous reports, the deacetalization step is catalyzed typically by an acid, and the Knoevenagel condensation step usually catalyzed by a base in the tandem reaction.25,32,33 Although both Lewis acids and Brønsted acids could catalyze the first step, most previous reports on MOFs have focused on the former method, owing to the inevitable existence of metal sites in Lewis acids.32,33 However, our findings have led us to propose the following: (1) The free carboxylic acid, –COOH, as Brønsted acid sites in PCN-700-AB plays a dominant role for the first deacetalization step, based on the observation that PCN-700-AB showed high conversion rate of ~90% than PCN-700-MB (56.71%) and PCN-700-B (56.14%), in which the structures contained only Brønsted base without any carboxylic acid, –COOH, group. (2) The second step of the cascade reaction is catalyzed by the amine groups anchoring in MOF skeleton,4,32,39 which is evident from the conversion yield of ~32% obtained for the MOF PCN-700 prototype, showing the lowest catalytic activity, compared with the other modified three MOFs, which all have amine groups decoration inside of the pore (see Figure 4 and Supporting Information Table S5), and we and others have demonstrated that an imine intermediate is formed during the catalytic process (see Supporting Information Figure S29).29,48,49 Based on the mechanism proposed by previous investigators and our present catalytic data analyses, we also propose that benzaldehyde was formed initially during the Brønsted acid-catalyzed deacetalization, and then reacted with the malononitrile, promoted by the Brønsted base sites, –NH2 groups (see Figure 5).

**Conclusions**

We have successfully constructed a dual-functional Brønsted acid–base MOF catalyst, PCN-700-AB, based on the strategy of precise installation of Brønsted acidic and basic linear linkers in a crystalline Zr-MOF. The installation underwent single-crystal-to-single-crystal transformation throughout the process, and therefore, the acid and base sites could be characterized precisely via single-crystal X-ray diffraction analysis. In addition, the dramatic acid–base catalytic activity of the bifunctional MOF catalyst obtained was confirmed through a one-pot deacetalization–Knoevenagel condensation reaction. Our present approach represents a novel route for constructing catalysts with incompatible, dual-functional catalytic sites, possessing enhanced active surface areas for effective catalysis, and efforts are underway to explore other facile methods to design efficient Brønsted acid–base MOF catalysts for tandem chemical reactions.

**Supporting Information**

Supporting Information is available.

**Conflicts of Interest**

The authors declare no conflict of interest.

**Acknowledgment**

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