Rapid Preparation of *β*-Ketoenamine-based Covalent Organic Frameworks (COFs) via Amino-yne Click Polymerization

Wei Bai[a,b], Qi Tian[a,b], Xinyao Fu[a,b], Anjun Qin[*,a,b], and Ben Zhong Tang[b,c,d]

[a] State Key Laboratory of Luminescent Materials and Devices, Guangdong Provincial Key Laboratory of Luminescence from Molecular Aggregates, South China University of Technology, Guangzhou 510640, China

[b] Center for Aggregation-Induced Emission, AIE Institute, South China University of Technology, Guangzhou 510640, China

[c] School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen (CUHK-Shenzhen), Guangdong, 518172, China

[d] Hong Kong Branch of Chinese National Engineering Research Centre for Tissue Restoration and Reconstruction, The Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong 999077, China.

KEYWORDS: Amino-yne Click Polymerization; Dynamic bond; Atom Economy; *β*-Ketoenamine; Covalent Organic Frameworks

ABSTRACT: As a new class of crystalline porous organic polymer materials, covalent organic frameworks (COFs) have permanent porosity and broad application prospects. The synthesis of COFs has strict requirements for both the reaction equations and the reaction conditions. Therefore, it is critical for researchers to develop new, scalable synthetic reactions. In this work, for the first time, we report an in-situ synthetic strategy toward COFs via the amino-yne click polymerization by taking advantage of its produced dynamic β-ketoenamine bond. This strategry also enjoys the advantages of high efficiency and atomic economy. The crystallinity and BET measurements indicated that the resultant COFs have excellent crystallinity and high porosity. Thus, this work not only provides a new strategy for the rapid preparation of COFs with excellent atom economy, but also enriches their family.

INTRODUCTION

Covalent organic frameworks (COFs) are a class of crystalline porous organic polymers with highly ordered structures and controllable pores, which have diverse applications in the areas such as gas separation[1-3], catalyst[4,5], sensing[6,7] and drug delivery[8,9]. The synthesis of COFs typically relies on reversible covalent bond formation reactions, such as boric acid condensation[10,11] or Schiff base condensation [12,13]. The reversibility of the reactions allows for the dynamic formation and cutting of covalent bonds during the reaction, which is crucial in COFs preparation because it can be dynamically controlled during the formation of the crystal structure. Recently, less reversible bonds have been used for the construction of COFs. For example, Zhang et al. synthesized a series of vinylene-bridged COFs via Knoevenagel condensation.[14,15] Perepichka et al. prepared a two-dimensional (2D) COF with β-ketoenamine by means of a Mickel addition-elimination reaction.[16] Jiang et al. also reported the preparation of COFs by nucleophilic addition-elimination reaction between arylamine and enaminone monomers on the basis of traditional solvothermal method (Figure 1a).[17] Notably, most the reactions for the preparation of COFs generate by-products, such as water and amine. Thus, the reactions without producing by-products are highly desirable for their atom economic feature.

One of the ideal reaction for the preparation of COFs is the click polymerization, which exhibits remarkable features such as excellent selectivity, atom economy, high efficiency, and mild reaction conditions. Very recently, the alkyne-based click polymerizations have made remarkable progress. For example, besides the well-developed Cu(I)-catalyzed azide-alkyne click polymerization, the thiol-yne, hydroxyl-yne, and amino-yne click polymerizations have also been well-developed, but they have not been applied in preparation of COFs.[18-21] During our research on the spontaneous amino-yne click polymerization of aroylacetylene and amine monomers, we found that the formed β-ketoenamine is a dynamic bond and could perform the dynamic exchange reaction.[22-27] Moreover, when the primary amine monomers were used, the spontaneous amino-yne click polymerization readily generates products with sole Z-configuration due to intramolecular hydrogen bonding interactions.[24] These features make it a promising strategy for preparing COFs. In addition, by design of different aroylacetylene and amine monomers, the formation and properties of COFs might be regulated.

Furthermore, our established amino-yne click polymerization enjoys many advantages, including atom economy and high efficiency, and it usually produces no by-product, which might improve the purity and crystallinity of COFs when applied in this area. Therefore, the preparation of COFs by the amino-yne click polymerization might be a promising direction, which is expected to make important progress in the field of COFs preparation.

In this work, by designing and synthesizing trifunctional carbonyl-activated ethynyl monomers and reacting them with trifunctional primary aromatic amines (Figure 1b), COFs namely BTTP-TAPT COF and the BTTP-TTTBA COF were readily generated by the amino-yne click polymerization. Afterward, systematic characterizations of these two COFs were carried out, and the results indicated that the COFs have excellent crystallinity and good porosity. This design approach allows us to control the topology and pore properties of the COFs, providing greater flexibility and customization for subsequent applications.

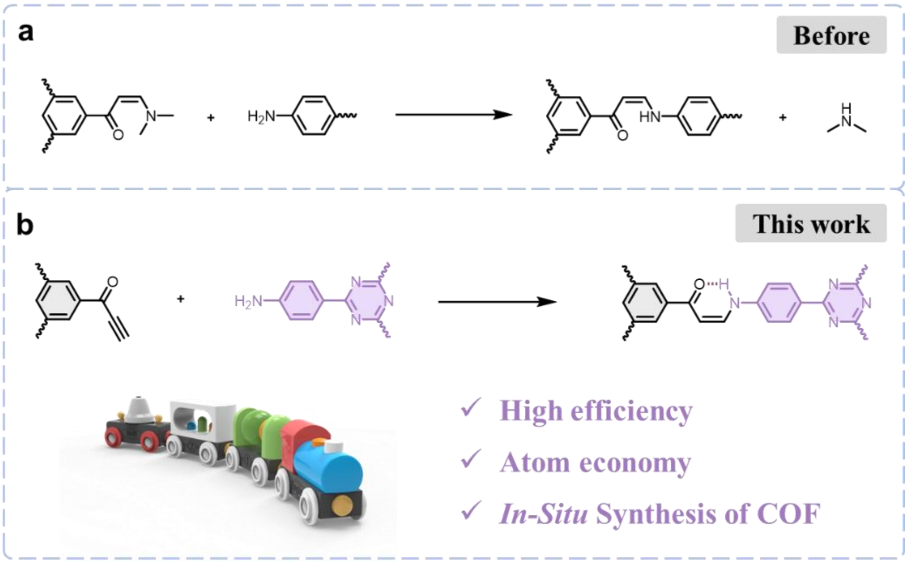

Figure 1. Strategy for synthesis of COFs by amino-yne click polymerization. (a) Previously reported work on the synthesis of *β*-ketoenamine-based COFs. (b) Current work on the synthesis of COF by amino-yne click polymerization and its enjoyed advantages.

RESULTS AND DISCUSSION

Characterization of prepared COFs. We designed and synthesized trifunctional carbonyl-activated ethynyl monomers BTTP, and then used them to react with two different triamine monomers 4,4',4''-(1,3,5-triazine-2,4,6-triyl)trianiline (TAPT) and 4',4''',4'''''-(1,3,5-triazine-2,4,6-triyl) tris(([1,1'-biphenyl]-4-amine)) (TTTBA) via amino-yne click polymerization, and BTTP-TAPT (Figure 2a), and BTTP-TTTBA COFs were obtained (Figure 2b), respectively.

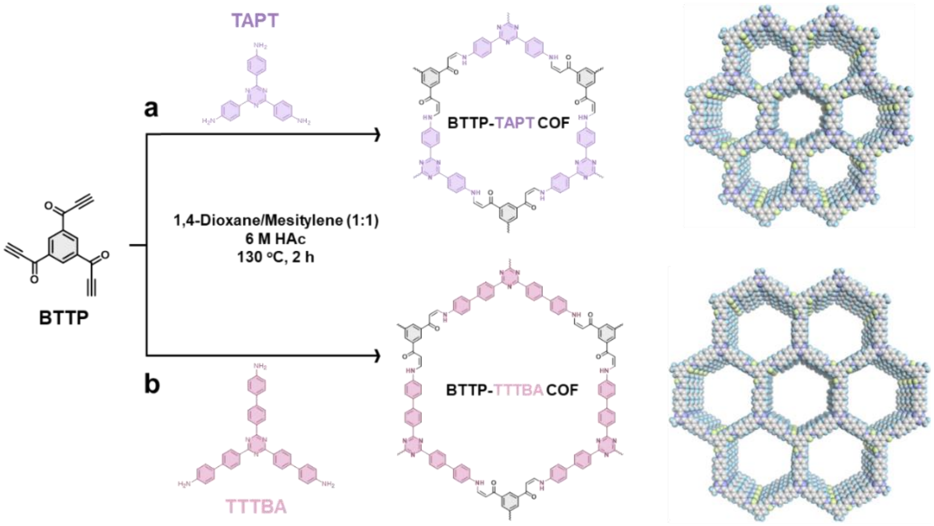

Figure 2. Schematic representation of BTTP-TAPT COF and BTTP-TTTBA COF. (a) The scheme of the preparation of BTTP-TAPT COF. (b) The scheme of the preparation of BTTP-TTTBA COF.

Afterward, the structures of the BTTP-TAPT COF and the BTTP-TTTBA COF were first characterized by Fourier-transform infrared spectroscopy (FT-IR). It can be seen from Figures 3a and 2b, both COFs showed that the characteristic N−H stretching vibrations of the primary amine TAPT (3317 cm^{-1}) and TTTBA (3356 cm^{-1}) completely disappeared. The characteristic C≡C−H and C≡C stretching vibrations of TAPT (3210 and 2093 cm^{-1}) and TTTBA (3221 and 2095 cm^{-1}) also disappear on both COFs. At the same time, the C=O stretching vibration of the TAPT (1630 cm^{-1}) and TTTBA (1631 cm^{-1}) remained, and the C=C stretching vibrations appeared at 1598 and 1596 cm^{-1} respectively. These results confirm the formation of the desired COFs.

To better determine the information of chemical bonds, we also performed solid-state cross-polarization magic-angle-spinning ^{13}C nuclear magnetic resonance (ssNMR) spectra of COFs. The characteristic chemical shifts in ssNMR spectra at 188 ppm (C=O) and 94 ppm (α-C) of BTTP-TAPT COF confirms the presence of enaminone moieties

(Figure 3c). And the characteristic chemical shifts at 188 ppm (C=O) and 93 ppm (α-C) also confirm the presence of enaminone moieties in the BTTP-TTTBA COF (Figure 3d). These results consistent with literature reports,[29] confirming the correction of the structure of BTTP-TAPT and BTTP-TTTBA COFs.

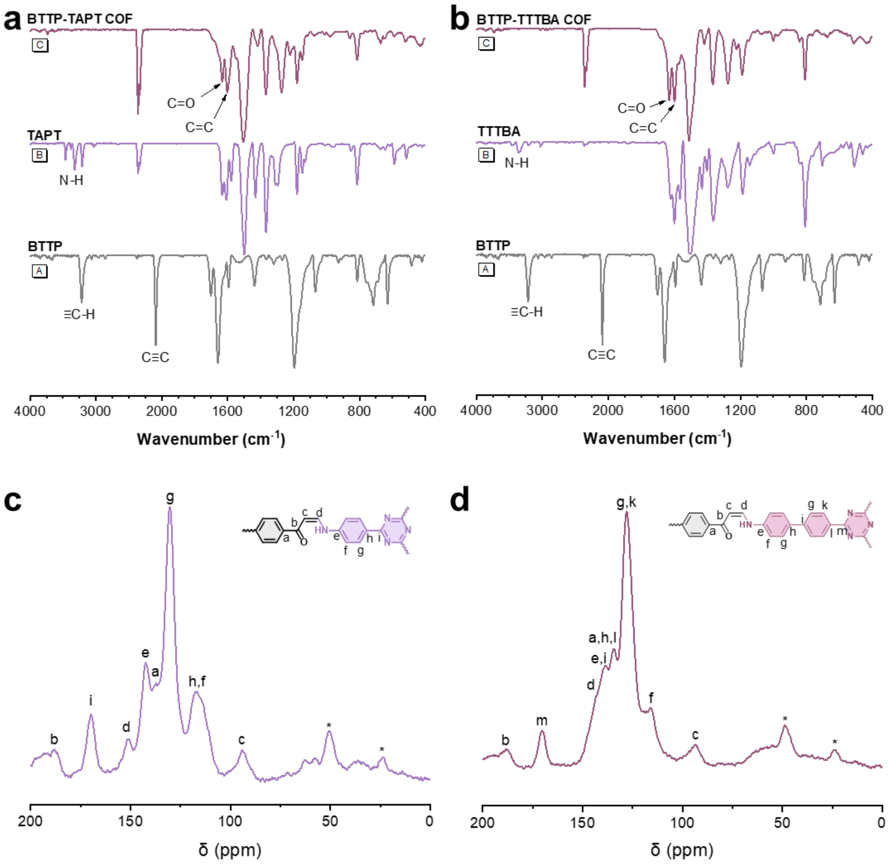

Figure 3. The characterization of BTTP-TAPT COF and BTTP-TTTBA COF. The FT-IR spectra of (a) BTTP-TAPT COF, and (b) BTTP-TTTBA COF. ^{13}C NMR spectra of (c) BTTP-TAPT COF, and (d) BTTP-TTTBA COF.

The powder X-ray diffraction (PXRD) was used to characterize the crystallinity of BTTP-TAPT COF and BTTP-TTTBA COF with reaction time of 72 h. The PXRD patterns of both BTTP-TAPT COF (4.69°) and BTTP-TTTBA COF (3.67°) exhibit prominent peaks at lower 2θ values, which proved that both COFs have high

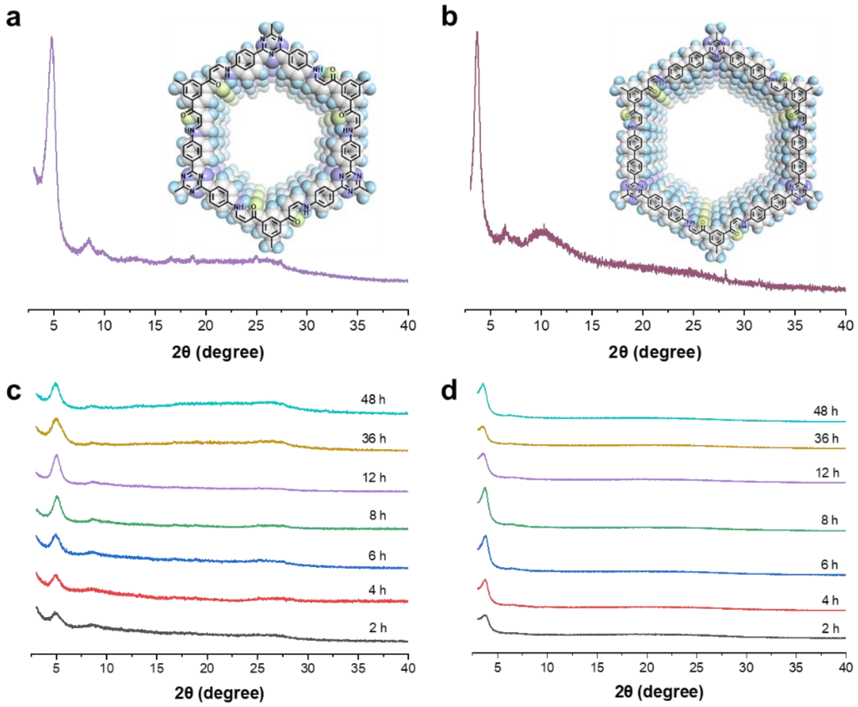

Figure 4. PXRD patterns of BTTP-TAPT COF and BTTP-TTTBA COF at 72 h reaction time ((a) and (b), respectively) and other reaction time (c and d, respectively).

crystallinity (Figure 4a and 4b).

Thanks to its high "click" efficiency, excellent regio-/stereo-selectivity, and especially its 100% atom economy, the amino-yne click polymerization enables the rapid and efficient synthesis of COFs. To verify the feasibility of this idea, we first shortened the reaction time for COFs synthesis, and then used PXRD to characterize the products with different reaction times. The results are shown in Figures 4c and 4d, which are BTTP-TAPT COF and BTTP-TTTBA COF that reacted for 2, 4, 6, 8, 12, 36 and 48 h, respectively. From the curves, it is concluded that no crystalline peaks of monomers were observed, indicating that the reaction was complete after 2 h. Notably, the crystal peaks could be observed at lower 2θ values from 2 to 48 h, and with the elongation of the reaction time, the peaks of the BTTP-TAPT COF also gradually strengthened, reaching stability after 8 h, whereas, the BTTP-TTTBA COF maintained stable peak intensity after reaction for 6 h. These results unambiguously demonstrate the advantages of the amino-yne click polymerization over other reactions for the preparation of COFs.

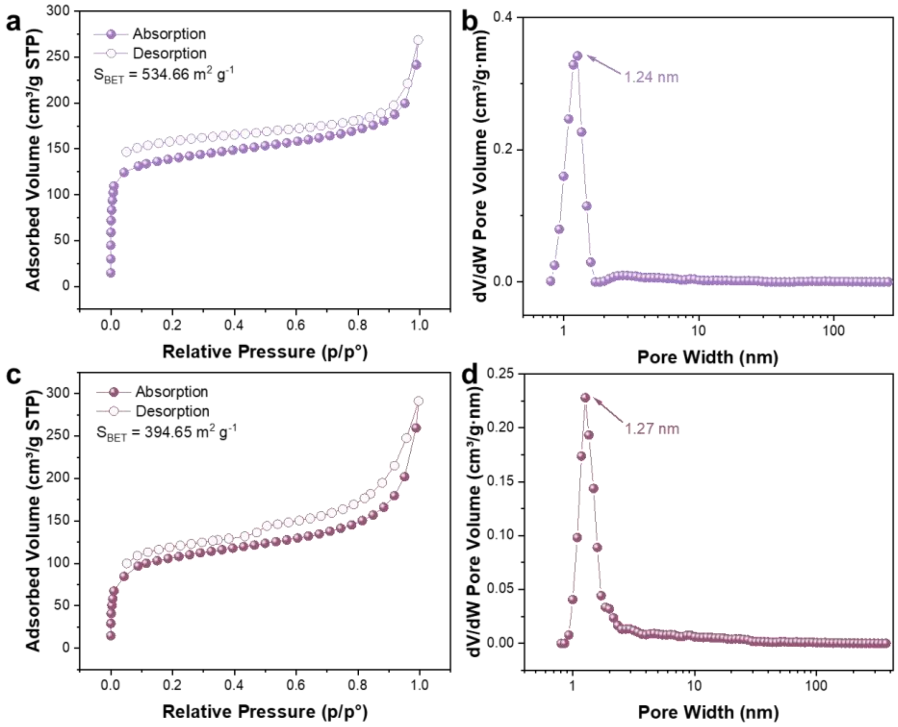

Figure 5. N_2 adsorption-desorption isotherms at 77 K of (a) BTTP-TAPT COF, and (c) BTTP-TTTBA COF. Pore size distributions of (b) BTTP-TAPT COF, and (d) BTTP-TTTBA COF.

The permanent porosity and structural properties of BTTP-TAPT COF and BTTP-TTTBA COF were evaluated by nitrogen (N_2) adsorption-desorption isotherm at 77 K. The rapid N_2 adsorption characteristics of the synthesized COFs were observed in the lower pressure range, and both showed a type I Brunauer-emmet-teller (BET) isotherm, indicating that both COFs have microporous properties (Figure 5a and 5c). The BET surface area (S_{BET}) of BTTP-TAPT COF is 534.66 m^2 g^{-1}, and that for BTTP-TTTBA

COF is 394.65 m^2 g^{-1}. The pore size of BTTP-TAPT COF is mainly distributed at 1.24 nm (Figure 5b), whereas, that for BTTP-TTTBA COF at 1.27 nm (Figure 5d), confirming their porous characteristics.

To further gain insights into the microstructure of the COFs, scanning electron microscopy (SEM) characterization was performed. As shown in Figure 6a, the microstructure of BTTP-TAPT COF is a porous material formed by winding tubes. Meanwhile, BTTP-TTTBA COF appears as porous material deposited by bulk (Figure 6d). TEM images also correspond to SEM images (Figure 6b and 6e). As shown in Figure 6c and 6f, from the crystallinity of the COFs and the high-resolution TEM images of BTTP-TAPT COF and BTTP-TTTBA COF (Figure 6c and 6f), it can be observed that the interlayer spacings of both COF are 0.38 nm and 0.44 nm, respectively.

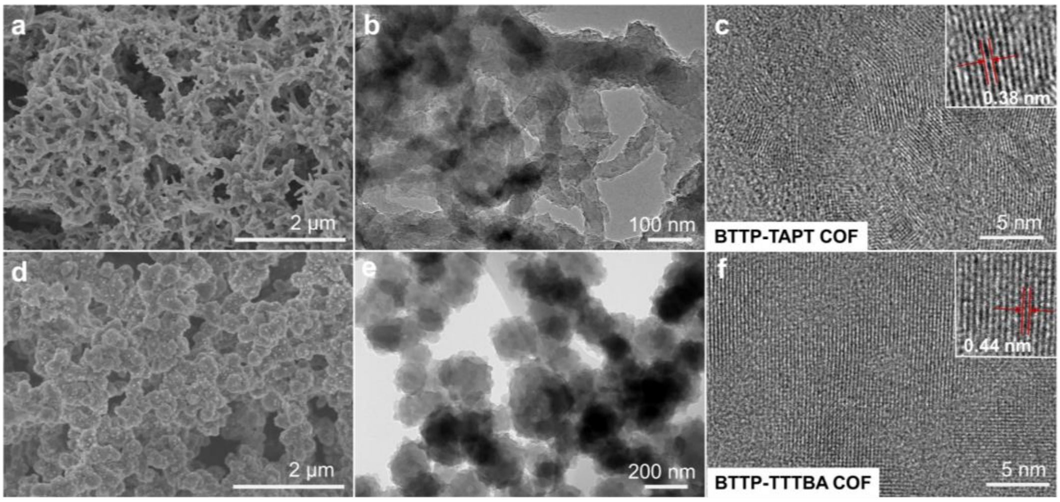

Figure 6. SEM images of (a) BTTP-TAPT COF, and (d) BTTP-TTTBA COF. High-resolution TEM images of (b,c) BTTP-TAPT COF and (e,f) BTTP-TTTBA COF.

CONCLUSIONS

In this study, for the first time, we developed a new strategy by employing amino-yne click polymerization of aroylacetylenes and aromatic primary amine monomers to in-situ synthesize COFs even with reaction time as short as 2 h in an atom economic fashion. BTTP-TAPT COF and BTTP-TTTBA COF containing the dynamic *β*-ketoenamine bonds were efficiently produced. The characterization using PXRD and HR-TEM indicated that the products possess highly crystalline features. N_2 adsorption-desorption isotherms characterization confirmed their excellent BET surface area at 77 K, reaching up to 534.66 m^2 g^{-1} for BTTP-TAPT COF, and 394.65 m^2 g^{-1} for BTTP-TTTBA COF. This work broadens the reaction range of COFs preparation and provides a new strategy in the field of COFs synthesis.

METHODS

Synthesis of monomer. Into a dried 250 mL two-mouth flask were added 1,3,5-triacetyl benzene (0.32 g, 2.0 mmol) and THF (12 mL) under nitrogen. After the reactant was dissolved by stirring, the solution was cooled to 0 °C, 0.5 M ethynylmagnesium bromide (24 mL, 12 mmol) in THF was added dropwise under stirring. The mixture was stirred at room temperature for 1 hour, then quenched by addition of saturated aqueous NH_4Cl solution. The reaction mixture was extracted with DCM and dried over $MgSO_4$. After filtered, activated manganese(IV) oxide (2.61 g, 30.0 mmol) was added at room temperature. The mixture was stirred for 1 hour and filtered through a short silica gel column to remove the solid. The crude product was purified by silica gel column chromatography using PE/EA (4:1) as eluent. The faint yellow solid powder BTTP (0.26 g) was obtained in a 56.3% yield.

Synthesis of BTTP-TATP COF. BTTP (23.42 mg, 0.1 mmol) and TATP (53.16 mg, 0.15 mmol) were placed in a 10 mL Pyrex tube in the presence of 1,4-dioxane (1.0 mL), mesitylene (1.0 mL) and 6 M acetic acid (0.5 mL). Then the Pyrex tube was ultrasonicated for 10 min to make the monomers dispersed homogeneously. After three successive freeze–pumpthaw cycles, the tube was sealed under vacuum. Then heated at 130 °C for 2 h, 4 h, 6 h, 8 h, 12 h, 36 h, 48 h and 72 h. Afterward, the solid powders were collected by filtration, and washed with THF, acetic acid and ethanol. Finally, the solid powders were dried in a vacuum oven at 55 °C for 6 h to obtain the products.

Synthesis of BTTP-TTTBA COF. BTTP (23.42 mg, 0.1 mmol) and TTTBA (87.41 mg, 0.15 mmol) were placed in a 10 mL Pyrex tube in the presence of 1,4-dioxane (1.0 mL), mesitylene (1.0 mL) and 6 M acetic acid (0.5 mL). The subsequent steps were consistent with BTTP-TATP COF, then obtained the BTTP-TTTBA COF with different reaction times.

AUTHOR INFORMATION

Corresponding Author

Anjun Qin – State Key Laboratory of Luminescent Materials and Devices, Guangdong Provincial Key Laboratory of Luminescence from Molecular Aggregates, South China University of Technology, Guangzhou 510640, China. E-mail: msqinaj@scut.edu.cn

ORCID

AnjunQin: https://orcid.org/0000-0001-7158-1808

NOTES

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (21788102), the Natural Science Foundation of Guangdong Province (2023B1212060003), and the Innovation and Technology Commission of Hong Kong (ITC-CNERC14SC01).

REFERENCES

(1) Yu, C.; Li, H.; Wang, Y.; Suo, J.; Guan, X.; Wang, R.; Valtchev, V.; Yan, Y.; Qiu, S.; Fang, Q. Three-Dimensional Triptycene-Functionalized Covalent Organic Frameworks with hea Net for Hydrogen Adsorption. *Angew. Chem. Int. Ed.* **2022**, *61*(13), e202117101.

(2) Jin, F.; Lin, E.; Wang, T.; Geng, S.; Wang, T.; Liu, W.; Xiong, F.; Wang, Z.; Chen, Y.; Cheng, P.; Zhang, Z. Bottom-Up Syn-thesis of 8-Connected Three-Dimensional Covalent Organic Frameworks for Highly Efficient Ethylene/Ethane Separation. *J. Am. Chem. Soc.* **2022**, *144*(12), 5643-5652.

(3) Wang, Z.; Zhang, Y.; Lin, E.; Geng, S.; Wang, M.; Liu, J.; Chen, Y.; Cheng, P.; Zhang, Z. Kilogram-scale fabrication of a robust olefin-linked covalent organic framework for separating ethylene from a ternary C_2 hydrocarbon mixture. *J. Am. Chem. Soc.* **2023**, *145*(39), 21483-21490.

(4) Wang, H.; Qian, C.; Liu, J.; Zeng, Y.; Wang, D.; Zhou, W.; Gu, L.; Wu, H.; Liu, G.; Zhao, Y. Integrating Suitable Linkage of Covalent Organic Frameworks into Covalently Bridged Inor-ganic/Organic Hybrids toward Efficient Photocatalysis. *J. Am. Chem. Soc.* **2020**, *142*(10), 4862-4871.

(5) Endo, K.; Raza, A.; Yao, L.; Van Gele, S.; Rodríguez-Camargo, A.; Vignolo-González, H.; Grunenberg, L.; Lotsch, B. Downsizing Porphyrin Covalent Organic Framework Particles Using Protected Precursors for Electrocatalytic CO_2 Reduction. *Adv. Mater.* **2023**, 2313197.

(6) Liu, X.; Huang, D.; Lai, C.; Zeng, G.; Qin, L.; Wang, H.; Yin, H.; Li, B.; Liu, S.; Zhang M.; Chen, S. Recent advances in covalent organic frameworks (COFs) as a smart sensing material. *Chem. Soc. Rev*. **2019**, *48*(20), 5266-5302.

(7) Zhang, L.; Yi, L.; Sun, Z. J.; Deng, H. Covalent Organic Frameworks for Optical Applications. *Aggregate* **2021**, *2*(3), e24.

(8) Ge, L.; Qiao, C.; Tang, Y.; Zhang, X.; Jiang, X. Light-activated hypoxia-sensitive covalent organic framework for tandem-responsive drug delivery. *Nano Lett*. **2021** *21*(7), 3218-3224.

(9) Li, W. Y.; Kan, J. L.; Wan, J. J.; Li, Y. A.; Song, T.; Wang, B.; Guan, Q.; Zhou, L. L.; Dong, Y. B. A reactive oxygen species-responsive covalent organic framework for tumor combination therapy. *Chem. Commun.* **2023**, *59*(36), 5423-5426.

(10) Li, S.; Pang, C.; Ma, X.; Wu, Y.; Wang, M.; Xu, Z.; Luo, J. Aggregation-induced electrochemiluminescence and molecularly imprinted polymer based sensor with Fe3O4@ Pt nanoparticle amplification for ultrasensitive ciprofloxacin detection. *Microchem. J.* **2022**, *178*, 107345.

(11) Hamzehpoor, E.; Jonderian, A.; McCalla, E.; Perepichka, D. F. Synthesis of boroxine and dioxaborole covalent organic frameworks via transesterification and metathesis of pinacol boronates. *J. Am. Chem. Soc.* **2021**, *143*(33), 13274-13280.

(12) Han, X. H.; Gong, K.; Huang, X.; Yang, J. W.; Feng, X.; Xie, J.; Wang, B. Syntheses of Covalent Organic Frameworks via a One-Pot Suzuki Coupling and Schiff's Base Reaction for C2H4/C3H6 Separation. *Angew. Chem. Int. Ed.* **2022**, *61*(25), e202202912.

(13) Xu, S. X.; Yao, Z. Q.; Zhang, Y. H. A covalent organic framework exhibiting amphiphilic selective adsorption toward ionic organic dyes tuned by pH value. *Eur. Polym. J*. **2020**, *133*, 109764.

(14) Bi, S.; Thiruvengadam, P.; Wei, S.; Zhang, W.; Zhang, F.; Gao, L.; Xu, J.; Wu, D.; Chen, J. S.; Zhang, F. Vinylene-bridged two-dimensional covalent organic frameworks via knoevenagel condensation of tricyanomesitylene. *J. Am. Chem. Soc*. **2020**, *142*(27), 11893-11900.

(15) Meng, F.; Bi, S.; Sun, Z.; Jiang, B.; Wu, D.; Chen, J. S.; Zhang, F. Synthesis of Ionic Vinylene-Linked Covalent Organic Frameworks through Quaternization-Activated Knoevenagel Condensation. *Angew. Chem. Int. Ed.* **2021**, *60*(24), 13614-13620.

(16) Rao, M. R.; Fang, Y.; De Feyter, S.; Perepichka, D. F.; Conjugated covalent organic frameworks via michael addition–elimination. *J. Am. Chem. Soc*. **2017**, *139*(6), 2421-2427.

(17) Guan, X.; Qian, Y.; Zhang, X.; Jiang, H. L. Enaminone-Linked Covalent Organic Frameworks for Boosting Photocatalytic Hydrogen Production. *Angew. Chem. Int. Ed.* **2023**, *135*(31), e202306135.

(18) Huang, D.; Liu, Y.; Qin, A.; Tang, B. Z. Recent advances in alkyne-based click polymerizations. *Polym. Chem.* **2018**, *9*(21), 2853-2867.

(19) He, B.; Su, H.; Bai, T.; Wu, Y.; Li, S.; Gao, M.; Hu, R.; Zhao, Z.; Qin, A.; Ling, J.; Tang, B. Z. Spontaneous Amino-Yne Click Polymerization: A Powerful Tool toward Regio-and Ste-reospecific Poly(β-aminoacrylate) s. *J. Am. Chem. Soc*. **2017**, *139*(15), 5437-5443.

(20) Si, H.; Wang, K.; Song, B.; Qin, A.; Tang, B. Z. Organobase-Catalysed Hydroxyl–Yne Click Polymerization. *Polym. Chem.* **2020**, *11*(14), 2568-2575.

(21) Yao, B.; Mei, J.; Li, J.; Wang, J.; Wu, H.; Sun, J. Z.; Qin, A.; Tang, B. Z. Catalyst-Free Thiol–Yne Click Polymerization: A Powerful and Facile Tool for Preparation of Functional Poly(vinylene sulfide)s. *Macromolecules* **2014**, *47*(4), 1325-1333.

(22) Joshi, G.; Anslyn, E. V. Dynamic thiol exchange with β-sulfido-α, β-unsaturated carbonyl compounds and dithianes. *Org. Lett*. **2012**, *14*(18), 4714-4717.

(23) Kariyawasam, L. S.; Highmoore, J. F.; Yang, Y. Chemically Recyclable Dithioacetal Polymers via Reversible Entropy-Driven Ring-Opening Polymerization. *Angew. Chem. Int. Ed.* **2023**, *62*(26), e202303039.

(24) Chen, X.; Bai, T.; Hu, R.; Song, B.; Lu, L.; Ling, J.; Qin, A.; Tang, B. Z. Aroylacetylene-based amino-yne click polymerization toward nitrogen-containing polymers. *Macromolecules* **2020**, *53*(7), 2516-2525.

(25) Chen, X.; Hu, R.; Qi, C.; Fu, X.; Wang, J.; He, B.; Huang, D.; Qin, A.; Tang, B. Z. Ethynylsulfone-based spontaneous amino-yne click polymerization: a facile tool

toward regio-and stereoregular dynamic polymers. *Macromolecules* **2019**, *52*(12), 4526-4533.

(26) Fu, X.; Qin, A.; Tang, B. Z. Dynamic covalent polymers generated from X-yne click polymerization. *J. Polym. Sci*. **2023**, 1–12.

(27) Fu, X.; Qin, A.; Tang, B. Z. X-yne click polymerization. *Aggregate* **2023**, *4*(5), e350.

(28) Ding, J.; Guan, X.; Chen, X.; Nan, P.; Qiu, S.; Fang, Q. Quantitative Assessment of Crystallinity and Stability in β-Ketoenamine-Based Covalent Organic Frameworks. *Chem. Eur. J.* **2023**, *29*(67), e202302290.

(29) Guan, X.; Qian, Y.; Zhang, X.; Jiang, H. L. Enaminone-Linked Covalent Organic Frameworks for Boosting Photocatalytic Hydrogen Production. *Angew. Chem. Int. Ed.* **2023**, *135*(31), e202306135.