Polydopamine-Modified Metal Organic Framework Membrane with Enhanced Selectivity for Carbon Capture

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ABSTRACT: In this work, a versatile postmodified dopamine (PDA) grafting is reported for improving CO$_2$ separation performance of MOF membranes. Owing to the strong bioadhesion, PDA can be deposited on the UiO-66 membrane through a simple and mild process. Since PDA impregnation in invalid nanometer-sized pinholes and grain boundaries of the MOF membrane suppress nonelective gas transports, the modified PDA/UiO-66 membrane exhibits significantly enhanced CO$_2$/N$_2$ and CO$_2$/CH$_4$ selectivities of 51.6 and 28.9, respectively, which are 2-3 times higher than the reported MOF membranes with similar permeance. Meanwhile, because PDA modification does not change UiO-66 intrinsic pores and membrane thickness is submicrometer-sized, the CO$_2$ permeance is 2-3 orders of magnitude larger than those membranes with similar selectivity, up to $3.7 \times 10^{-7}$ mol m$^{-2}$ s$^{-1}$ Pa$^{-1}$ ($1115$ GPU). Moreover, the PDA/UiO-66 membrane with good reproducibility has excellent long-term stability for CO$_2$ capture under moist condition in 36 h measurement period.

The excess emissions of greenhouse gases cause various environmental issues including global warming, ocean acidification and ecological damage. With population growth and industrial progress, the atmospheric concentrations of CO$_2$ has increased more than twice from 280 ppm in 1975 to 410 ppm in 2015, which are remarkably higher than the preindustrial level of 280 ppm. A package of programs to reduce CO$_2$ concentration, such as the Paris Agreement, has been prompted by governments and industries. Besides development of clean energy that can be utilized without carbon emission, capture of CO$_2$ from low-grade natural gases and the gases produced by combustion of fossil/coal/coal-based fuels is very important. Conventional technologies for CO$_2$ capture based on gas liquid phase change, such as absorption, cryogenic distillation and condensation, are energy intensive and uneconomic. Membrane separation has great potential for capture of CO$_2$, due to its merits of simple operation, small footprint, high efficiency, no phase change and environmental friendliness. For membrane materials, polymeric membranes have advantages of low cost, high processability and acceptable selectivity. However, small permeability, a few tens of Barrer (1 Barrer = $3.348 \times 10^{16}$ m mol m$^{-2}$ s$^{-1}$ Pa$^{-1}$), brings about a stringent requirement of large membrane area, even for dealing with a small industrial station, which increases equipment costs tremendously. In order to improve permeation property, inorganic micro/nanoparticles are used as fillers for changing the formation and construction of polymeric membranes to form mixed-matrix membranes (MMMs). Some other materials, for example, zeolites, metal organic frameworks (MOFs), microporous polymers, and graphene and its derivatives, have been proposed for fabricating high-performance membranes as well.

Thanks to the large surface areas, appropriate apertures and unique nities, MOF membranes show impressive performance in hydrogen purification and hydrocarbon separation, and can easily surpass the trade-off line of polymeric membranes. For examples, the CuBTC membranes exhibited high permeance and H$_2$/CO$_2$ selectivity about 7.0. The NH$_2$-MIL-53 membranes could separate H$_2$/CO$_2$, H$_2$/N$_2$, and H$_2$/CH$_4$ mixtures with selectivities about 20. and the ZIF-8 membranes displayed excellent propylene permeability over 100. Comparatively, the reports about MOF membranes for CO$_2$ capture are relatively fewer. Yin et al. reported that the amino-functionalized CAU-1 membrane had high CO$_2$ permeance of $8.0 \times 10^{-7}$ mol m$^{-2}$ s$^{-1}$ Pa$^{-1}$ and CO$_2$/N$_2$ selectivity of 14.8. Cacho-Bailo et al. deposited the ZIF membranes on inner surface of polymeric hollow fibers. The membranes showed CO$_2$/CH$_4$ selectivity up to 37.7.
while small permeance about $1.2 \times 10^{-9} \text{ mol m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$.

From the economic evaluation, the membranes with high permeance over 1000 GPU (1 GPU = $3.348 \times 10^{-10} \text{ mol m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$) and good selectivity larger than 20 are desired for CO$_2$ capture from air gases. Therefore, the CO$_2$ separation performance of MOF membranes should be improved further.

Postmodification is commonly applied for adjusting the pore structures and adsorptions of MOF materials. For MOF membranes, molecular sieving is a well-known mechanism for gas separation. However, precise design of MOFs with pore size between the kinetic diameters (KD) of two light gases, such as CO$_2$ (KD: 0.33 nm) and N$_2$ (KD: 0.364 nm), is extremely difficult. Moreover, the exibility of frameworks increases the difficulty of structural construction. The interaction between MOFs and components to be separated significantly in uences performance as well. On the one hand, superior a nity of penetrated component in MOFs may enhance its sorption or diminish the di usion of blocked component, and then improve selectivity. On the other hand, strong interaction of blocked molecules in MOFs may suppress molecule migration in membranes, thereby leading to high perme selectivity. In addition to regulation of apertures and a nities, postmodi cation can restrain the bypass gas penetration through the non active nanometer-sized pinholes and grain boundaries, and then enhance separation performance. Huang et al. modi ed the ZIF-90 membranes by ethanolamine and 3-aminopropyltriethoxysilane. The grafted MOF membranes with constricted pore sizes and reduced nonselective passageways showed improved H$_2$ perme selectivity. To increase the permeance of MOF membranes, Lee et al. employed linker exchange for transforming the top layer of the ZIF-8 membrane to ZIF-90 that had larger apertures. However, the modi cation based on the reaction between the introduced substances and linkers with functional groups limits the types of applied MOFs. Herein, we report a versatile polydopamine (PDA) postmodi cation strategy to obtain high-performance MOF membranes for CO$_2$ capture, because PDA can be simply deposited on membranes owning to its strong bioadhesion.

**EXPERIMENTAL DETAILS**

Materials. ZrCl$_4$, 1,4-dicarboxybenzene (BDC), N,N-dimethylformamide (DMF) and methanol were purchased from Kutai Chemical Reagent Co., China. Anodic alumina oxide (AAO) substrate with pore size of 20 nm and diameter of 25 mm was supplied by Liangwen Chemical Reagent Co., China. All regents were used as received.

Preparation of Uio-66 Membranes. ZrCl$_4$ (0.16 g), BDC (0.11 g) and deionized water (11.9 mL) were dispersed in DMF (25 mL). The mixture was dissolved by ultrasonic treatment to obtain transparent solution. For seeding, AAO substrate was horizontally immersed in precursor solution and thermally treated at 120 °C for 3 days. After natural cooling, the AAO substrate covered with Uio-66 crystals was taken out and tenderly washed by DMF. For preparation of the Uio-66 membrane, the seeded AAO substrate was vertically soaked in DMF and methanol, and then dried at room temperature for use.

Preparation of PDA/UiO-66 Membranes. 3-Hydroxytryptamine hydrochloride (40 mg) was dissolved in deionized water (20 mL). To make the dopamine enter into the potential pinholes of membranes as much as possible, the prepared Uio-66 membrane was rst soaked in above solution at room temperature for 12 h. The dopamine bu rring solution with pH of 8.5 was prepared adding tris(hydroxymethyl)aminomethane (THAM) solution (24 mg THAM in 20 mL water) in 3-hydroxytryptamine hydrochloride solution. For PDA postmodi cation, the Uio-66 membrane after soaking was immersed in bu rring solution for another 12 h. After deposition, the white UiO-66 membrane changed to the dark brown PDA/UiO-66 membrane. The prepared PDA/UiO-66 membrane was washed by DMF and methanol, and then dried at room temperature for use.

Separation Performance. The experimental setup for gas permeation and separation is presented in Supporting Information (SI) Figure S1. The membrane with exposed area of 2.5 cm$^2$ was sealed in a permeation cell by O-ring. The chamber with exposed MOF layer was applied as feed side. The permeation data was recorded after running steadily. For single-gas permeation, various gases were measured with order of H$_2$, CO$_2$, N$_2$, CH$_4$, CH$_4$, N$_2$, CO$_2$, and H$_2$. The ideal selectivity ($u_j$) was calculated as the ratio of two gas permeances ($P$) by $u_j = P_j/P_i$. For gas separation, the binary mixture of CO$_2$/$N_2$ or CO$_2$/$CH_4$ was used as feed gases with ow rate of 50 mL min$^{-1}$. The temperature was kept at 25 °C. The sweep gas was Ar with ow rate of 50 mL min$^{-1}$. The feed pressure was 0.1 MPa. The gas concentration was studied by a thermal conductivity detector (TCD) and a steel
Fourier transform infrared spectrophotometer (FTIR).

The chemical structure of the samples was studied by using a Raman spectrometer (RTier-100, Shimadzu CO.). A RBD upgraded PHI-5000C ESCA system (PerkinElmer) was employed to perform X-ray photoelectron spectroscopy (XPS) experiment. Gas adsorption and desorption isotherms were recorded by using a physisorption analyzer (Autosorb IQ, Quantachrome Co.). The specific surface area was calculated by Brunauer Emmett Teller (BET) method. Gas adsorption isotherms were collected at temperature of 25 °C. The crystalline structure of the samples was investigated by Raman, X-ray diffraction (XRD) (D2 Phaser, Bruker Co.) with Cu Ka radiation at 30 kV and 10 mA. The sample was scanned between 5° and 40° with step size of 0.01° and scan speed of 0.2 s per step. The morphology of the membranes was characterized by using a field-emission scanning electron microscope (SEM) (Ultra-55, Zeiss Co.). The chemical structure of the samples was studied by using a Fourier transform infrared spectrophotometer (FTIR, IRT racer-100, Shimonazu Co.). A RBD upgraded PHI-5000C ESCA system (PerkinElmer) was employed to perform X-ray photoelectron spectroscopy (XPS) experiment. Gas adsorption and desorption isotherms were recorded by using a physisorption analyzer (Autosorb IQ, Quantachrome Co.). The specific surface area was calculated by Brunauer Emmett Teller (BET) method. Gas adsorption isotherms were collected at temperature of 25 °C.

**RESULTS AND DISCUSSION**

Preparation of UiO-66 Membranes. The postmodication of MOF membranes is presented in Figure 1. As above-mentioned, the strong di erentiation in a nit of MOFs to feed components may be beneficial to membrane separation. UiO-66, a chemically stable Zr-MOF with octahedral cage, is composed of Zr6O4(OH)4 nodes and BDC linkers. Because of the large adsorption capacity for CO2,50,52 UiO-66 was employed as probe for synthesizing MOF membranes. For seed deposition, AA0 substrate was horizontally immersed in precursor solution and thermally treated at 120 °C for 3 days. To obtain the UiO-66 membrane, the seed substrate was vertically in precursor solution and treated under the same conditions for another two times. The obvious characteristic peaks in XRD pattern of the prepared membrane indicated that the synthesized layer had pure UiO-66 crystalline structure (Figure 2). For MOF membrane synthesis, the heterogeneous growth on substrates is bene cial to formation of continuous membranes, yet the competition from homogeneous crystallization in solutions is undesirable.53 Because there no

![Figure 2. Photographs and XRD patterns of the UiO-66 and PDA/UiO-66 membranes.](image)

which was smaller than that of most reported MOF membranes.19,24 SEM image with low magnification indicated that the prepared UiO-66 membrane was uniform in large scale (SI Figure S2). Besides AA0 substrate, polymeric hollow bers with high processability, low cost and large membrane area per volume could also be employed to prepare the UiO-66 membranes (SI Figure S3).

Post-Modication of UiO-66 Membranes. For postmodication, the prepared UiO-66 membrane was rst immersed in dopamine aqueous solution to make the introduced component enter into the potential pinholes as much as possible. The UiO-66 membrane with impregnated solution was transferred in dopamine buffer solution (pH 8.5) and maintained at room temperature for 12 h. Dopamine could spontaneously polymerized into PDA and deposited on membrane surface. After modication, the color of the UiO-66 membrane transferred from white to dark brown (Figure 2, inset), suggesting the successful PDA deposition.54 Because of the excellent water stability of UiO-66,49 the PDA/UiO-66 membrane maintained good crystalline structure after modication (Figure 2). As shown in SEM image (Figure 3b), the modi ed membrane was still continuous. The membrane thickness showed almost no change relative to the original one, because the PDA layer was ultrathin. Unlike the postmodication of MOF membranes in previous studies,41,44 which would destroy the structure of frameworks more or less, bene ted from the mild conditions of modication and excellent stability of UiO-66, the PDA postmodication did not impact MOF membrane structures.

To confirm the PDA modication, we investigated the chemical structures of the UiO-66 and PDA/UiO-66 membranes. As shown in Figure 4a, C 1s XPS spectrum of the UiO-66 membrane presented intensive peaks of C-C/C-H at 284.5 eV, C-COOH at 285.2 eV and O-C-O at 288.4 eV,55 which were consistent with the chemical structure of BDC linkers. After PDA modication, a new characteristic peak at 285.8 eV for CN, C-N and C-OH occurred (Figure 4b). This result proved that the PDA layer was formed on the surface of the UiO-66 membrane. The strong nitrogen...
peak in spectrum of the PDA/UiO-66 membrane tested the presence of PDA on modified membrane again (Figure 4c). The spectra of both two membranes displayed Zr 3d peaks, while the peak intensity of the PDA/UiO-66 membrane was smaller than that of the original one due to PDA coating (Figure 4d). The Zr 3d peak in spectrum of the modified membrane implied that the PDA layer was ultrathin, on account of the small XPS detecting depth of several nanometers. The deposition of PDA was also analyzed by FTIR (SI Figure S4). Both UiO-66 and PDA/UiO-66 membranes exhibited the peaks at 660 cm$^{-1}$ for stretching vibration of O\_Zr bond and at 1585 cm$^{-1}$ for asymmetric stretching vibration of O\_C\_O bond. Two new characteristic peaks of PDA at 1270 and 1492 cm$^{-1}$ appeared in the spectrum of the modified UiO-66 membrane. These peaks were derived from the stretching vibration of C\_O/\_NH$_2$ bonds and bending vibration of N\_H bond. All XPS and FTIR results demonstrated the successful self-polymerization of dopamine on the surface of the UiO-66 membrane.

Separation Performance of UiO-66 and PDA/UiO-66 Membranes. The single-gas permeation properties of various gases through the UiO-66 and PDA/UiO-66 membranes were measured. Unlike the MOF membranes based on molecular sieving effect, which generally showed smaller permeances for the gases with larger kinetic diameters, the UiO-66 membrane showed higher CO$_2$ permeance of 5.8$\times$10$^{-7}$ mol m$^{-2}$ s$^{-1}$ Pa$^{-1}$ than that of H$_2$ (KD: 0.289 nm), N$_2$ and CH$_4$ (KD: 0.38 nm) (Figure 5a). This phenomenon was explained by that the UiO-66 membrane was mainly governed by preferential adsorption. In other words, although the H$_2$ might have faster diffusion rate than CO$_2$, its lower adsorption led to the smaller permeance. The ideal selectivities of H$_2$/N$_2$, H$_2$/CH$_4$, CO$_2$/N$_2$ and CO$_2$/CH$_4$ were 10.8, 6.9, 26.5, and 17.0, respectively (Figure 5b), which were obviously greater than the corresponding Knudsen diffusion coefficients and similar to...
After postmodication, CO₂ permeance decreased as expected, but still kept at 3.9 × 10⁻⁷ mol m⁻² s⁻¹ Pa⁻¹ (Figure 5a and SI Table S1). Compared with the MOF membranes modified by the reaction between linkers and grafting molecules, CO₂ permeance decreased to 3.2 × 10⁻⁷ mol m⁻² s⁻¹ Pa⁻¹ and CO₂/CH₄ selectivity of 28.9 at 0.1 MPa. With the increasing of pressure, the permeance and selectivity decreased to 3.2 × 10⁻⁷ mol m⁻² s⁻¹ Pa⁻¹ and 21.7, respectively. When the pressure returned to pressure of 0.1 MPa, the permeance and selectivities recovered to initial ones, demonstrating the good pressure stability of the PDA/UiO-66 membrane. The effect of CO₂ concentration of feed mixtures on separation performance of the PDA/UiO-66 membrane was investigated. The selectivity and permeance increased as CO₂ concentration increased (SI Figure S5). It should be noted, for the CO₂ concentration of 10%, atypical CO₂ concentration in the feed gas, the selectivity and permeance still kept at 41.0 and 2.6 × 10⁻⁷ mol m⁻² s⁻¹ Pa⁻¹. Long-term stability of separation membranes is important for industrial application. In a 36-h measurement period, both selectivity and permeance for CO₂/N₂ binary mixture with concentration of 50% only showed small fluctuations (SI Figure S6). Because the feed gas usually has CO₂ concentration of 10% and contains moisture, the long-term stability of the PDA/UiO-66 membrane for binary mixture with CO₂ concentration of 10% was evaluated under moist condition. The membrane showed stable separation performance as well (SI Figure S6). These results suggested the excellent durability of the PDA/UiO-66 membrane.
studying the reproducibility, two additional membranes were prepared and employed for gas permeation and separation. The similar gas permeances and selectivities with small standard deviations indicated the good reproducibility of the PDA/UiO-66 membrane (SI Tables S1 and S3).

Comparison of Separation Performance. Figure 7 presents the comparison of CO2 capture performance between the previously reported membranes made by polymers and MOFs, and the PDA/UiO-66 membrane in this study. The upper bound relationships between permeance and selectivity of polymeric membranes summarized by Robeson in 2008 are common standards for measuring separation performance.23 For polymeric membranes, although the appropriate selectivity can be achieved in CO2/N2 and CO2/CH4 separations, the permeance is usually small. Obviously, the performance of the PDA/UiO-66 membrane could exceed the Robeson’s upper-bound for both CO2/N2 and CO2/CH4 systems, and located in the target area (permeance >1000 GPU equal to 3.35 × 10^-7 mol m^-2 s^-1 Pa^-1 and selectivity >20) of CO2 capture from gases for economically industrial application.12,38 In the field of MOF membranes for CO2 capture, Venna and Carreon reported a ZIF-8 membrane with unprecedented high CO2 permeance of 2.4 × 10^-5 mol m^-2 s^-1 Pa^-1 but low CO2/CH4 selectivity of 5.1.60 Yang et al. synthesized a continuous CAU-1 membrane, which showed CO2 permeance of 7.3 × 10^-7 mol m^-2 s^-1 Pa^-1 and CO2/N2 selectivity of 20.3.61 Caro et al. fabricated a ZIF-8 membrane by conversion of ZnAl2(OH)4 layered double hydroxide. The obtained membrane displayed CO2 permeance of 1.6 × 10^-8 mol m^-2 s^-1 Pa^-1 and CO2/CH4 selectivity of 12.9.62 Marti et al. prepared a ZIF-8 membrane with CO2 permeance of 0.7 × 10^-8 mol m^-2 s^-1 Pa^-1 and CO2/N2 selectivity of 52.63 Lin et al. found that the MOF-5 membrane exhibited extremely high selectivity of 410 for the CO2/N2 mixture with CO2 concentration of 87.4%. However, the separation performance for the feed gases with lower CO2 concentration was poor.25 In comparison, the PDA/UiO-66 membrane had competitive separation performance and good balance between permeance and selectivity. Because of the small thickness, intact interior pore structure, preferential CO2 adsorption and suppressed none active passageways, the PDA/UiO-66 membrane possessed 2-3 times higher selectivity than the reported MOF membranes with similar permeance, or 2-3 orders of magnitude larger permeance than those membranes with similar selectivity (SI Tables S4 and S5).

Separation Mechanism. The separation of MOF membranes is controlled by the affinities of selective layers to gas molecules and the apertures of frameworks. The gas sorption of MOFs and the gas diffusion in membranes are vital for separation performance. UiO-66 framework has apertures of 0.6 nm,64 which is bigger than the kinetic diameters of the tested gases. We investigated the porous structures of UiO-66 particles collected from the bulk solution after membrane synthesis by nitrogen adsorption-desorption isotherms (SI Figure S7). The UiO-66 particles had high BET specific surface area of 1332.3 m^2 g^-1 (Figure 8a). The pore width distribution indicated that the UiO-66 possessed mainly apertures of 0.6 and 1.2 nm, which were consistent with the reports in previous studies.60 The adsorption properties of UiO-66 to CO2, CH4 and N2 were studied as well (Figure 8b). Because Zr6O4(OH)4 clusters had specific interaction with CO2, the UiO-66 particles showed much greater CO2 adsorption capability than other two gases. The adsorption capacity was ordered by CO2, CH4 and N2, which agreed with that of the gas permeance. The permeability (P) is related to sorption coefficient (S) and diffusion coefficient (D) through
the invalid channels for nonselective gas transports.\textsuperscript{41,44} On nanometer-sized pinholes and grain boundaries, which o
For MOF membranes, there were often some unobservable
obtaining CO\textsubscript{2} capture separation membranes. Although the membranes reported here provides an alternative route for
enhancement in CO\textsubscript{2}/CH\textsubscript{4} and CO\textsubscript{2}/N\textsubscript{2} di
selectivities. Those results proved that the UiO-66 membrane was mainly governed by preferential adsorption.

After PDA postmodication, the permeance of PDA/UiO-
66 membrane decreased slightly but selectivity increased greatly. In order to investigate whether the dopamine can be impregnated into pore structures of UiO-66 frameworks, we studied the porosity of PDA/UiO-66 particles (Figure 8c). The speci c surface area of 1345.4 m\textsuperscript{2} g\textsuperscript{-1} and pore width
distribution with peaks at 0.6 and 1.2 nm were similar to those of the UiO-66 particles. These results con rmed that the ultrathin PDA was only deposited on the surface and UiO-66 maintained the intact porous structures after postmodication. The intact interior pore structures combined with the thin selective layer resulted in the high permeance of the PDA/
UiO-66 membrane. Figure 8d shows the gas adsorption properties of the PDA/UiO-66 particles. Because the amount of the coated PDA was low, the adsorption capacity only displayed a small change after modi cation. This revealed that the main adsorbents were frameworks for both UiO-66 and
PDA/UiO-66. After modi cation, the simultaneously increased CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2} sorption coe cients brought about the slightly decreased sorption selectivities (SI Table S6). However, similar reduction by 4.5 \times 10\textsuperscript{-8} cm\textsuperscript{2} s\textsuperscript{-1} in di usion coe cients of three gases in membranes caused the signi cant enhancement in CO\textsubscript{2}/CH\textsubscript{4} and CO\textsubscript{2}/N\textsubscript{2} di usion selectivities, since the CO\textsubscript{2} di usion coe cient was remarkably greater than that of CH\textsubscript{4} and N\textsubscript{2} (SI Table S6). The improvement in di usion selectivity was the main factor for the better separation performance of the PDA/UiO-66 membrane than that of the original one. We speculated the enhancement in di usion selectivity of the PDA/UiO-66 membrane as follow. For MOF membranes, there were often some unobservable nanometer-sized pinholes and grain boundaries, which o ered the invalid channels for nonselective gas transports.\textsuperscript{41,44} On account of the similar amount in reduction of CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2} di usion coe cients and the intact interior pore structures of the PDA/UiO-66, the PDA impregnation in invalid pinholes and grain boundaries for suppressing the nonselective permeation was considered as the dominant factor for the improved selectivity. As well as the tailoring of PDA polymer chains to the exposed pores of membrane surface might also contribute to the enhancement in selectivity.

In summary, we have demonstrated that the versatile PDA postmodication can greatly improve CO\textsubscript{2} capture performance of MOF membranes. PDA with strong bioadhesion can be simply grafted on the UiO-66 membrane under mild conditions. The postmidication of PDA/UiO-66 membrane exhibits impressive CO\textsubscript{2} permeance and selectivities in CO\textsubscript{2}/N\textsubscript{2} and CO\textsubscript{2}/CH\textsubscript{4} separations, because PDA blocks the invalid pinholes and grain boundaries but do not change the pore structures of frameworks. The CO\textsubscript{2} capture performance surpasses the trade-o limitation of polymeric membranes easily. The PDA/UiO-66 membrane displays good reproducibility and excellent long-term stability as well. The simple and e cient modi cation processes, coupled with the competitive performance, present that PDA postmodication of MOF membranes reported here provides an alternative route for obtaining CO\textsubscript{2} capture separation membranes. Although the preparation cost of MOF membranes are relative high, regarding the excellent separation performance, we humbly believe the investigations of MOF membranes just the beginning to future prosperity.

ASSOCIATED CONTENT
* Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b00408.
Characterizations (SEM, FTIR, and XRD) and separation performance of the PDA/UiO-66 membrane, and comparison of gas separation performance (PDF)

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Author Contributions

W.L. conceived the research idea and formulated the project. W.W., Z. L., and W.L. performed the fabrication and characterization of UiO-66 particles and membranes. W.W., Y.C., and W.L. carried out the experiments of gas permeation and separation. W.W. and W.L. wrote the paper. All authors contributed to the revising the paper.

Notes

The authors declare no competing fi nancial interest.

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