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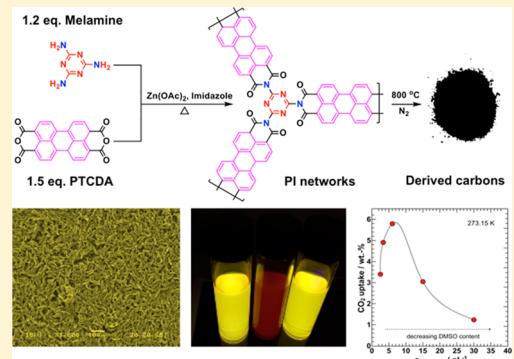
Yaozu Liao,[†] Jens Weber,[‡] and Charl F. J. Faul*,[†]

[†]School of Chemistry, University of Bristol, Bristol BS8 1TS, U.K.

[‡]Department of Chemistry, Hochschule Zittau/Görlitz (University of Applied Science), Theodor-Körner-Allee 16, D-02763 Zittau, Germany

Supporting Information

ABSTRACT: Carbon dioxide (CO₂) capture from point sources like coal-fired power plants is a potential solution for stabilizing atmospheric CO₂ content to avoid global warming. Sorbents with high and reversible CO₂ uptake, high CO₂ selectivity, good chemical and thermal stability, and low cost are desired for the separation of CO₂ from N₂ in flue or natural gas. We report here, for the first time, on the synthesis of new microporous polyimide (PI) networks from the condensation of perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) and 1,3,5-triazine-2,4,6-triamine (melamine) using a Lewis acid catalyst zinc acetate/imidazole complex. These PI network materials, prepared in the absence and presence of dimethyl sulfoxide (DMSO) as weak solvent template, exhibit strong fluorescence. Nitrogen-containing carbons can be accessed from our PI networks via a simple thermal pyrolysis route. The successful construction of new microporous PI networks and derived N-containing carbons is shown here to provide promising CO₂ sorbents with high uptake capacities (15 wt %) combined with exceptional selectivities over N₂ (240), while their fluorescent properties can be exploited for simple sensing.



INTRODUCTION

Carbon dioxide (CO₂) capture from point sources like coal-fired power plants is a potential solution for stabilizing atmospheric CO₂ content to avoid global warming.¹ Sorbents with high and reversible CO₂ uptake, high CO₂ selectivity, good chemical and thermal stability, and low cost are desired for the separation of CO₂ from N₂ in flue or natural gas. It has recently been shown that porous organic polymers (POPs) are promising CO₂ sorbents because of their simple syntheses and high physicochemical stabilities, combined with high surface areas and unique porosities and low skeleton densities.² This field of research has witnessed the emergence of several new types of POPs including polymers of intrinsic micro-porosity (PIMs),³ covalent organic frameworks (COFs),⁴ covalent triazine-based frameworks (CTFs),⁵ conjugated microporous polymers (CMPs),⁶ and hyper-cross-linked polymers (HCPs).⁷

In order to maximize the CO₂ uptake capacity, a great deal of work, beside optimization of pore sizes, has focused on the introduction of polarizable sites through post-synthesis modification or introduction of nitrogen-rich and/or oxygen-rich building blocks to increase the CO₂–POP interaction energy via either dipole–quadrupole or hydrogen-bonding interactions, or both.^{8–10} However, post-synthetic modification requires additional synthetic efforts and makes this route less attractive (especially for large-scale application). This approach usually also leads to a decrease of surface areas and pore blocking. To avoid these obstacles, careful selection of

functionalized building blocks as starting materials and the introduction of chemical heterogeneity in the polymerization protocol are feasible options.⁶ Recent studies showed that the CO₂ uptake of several CMPs could be improved by substituting a phenyl node for a triazine unit, which also provides opportunities for further functionalization,¹¹ e.g., to efficiently immobilize platinum nanoparticles, activate and convert methane,¹² and improve hydrogen generation.¹³ Despite these advances, it is still highly desirable to improve the CO₂ storage capacity and selectivity through the development of new materials that do not require post-synthetic modifications or processing.

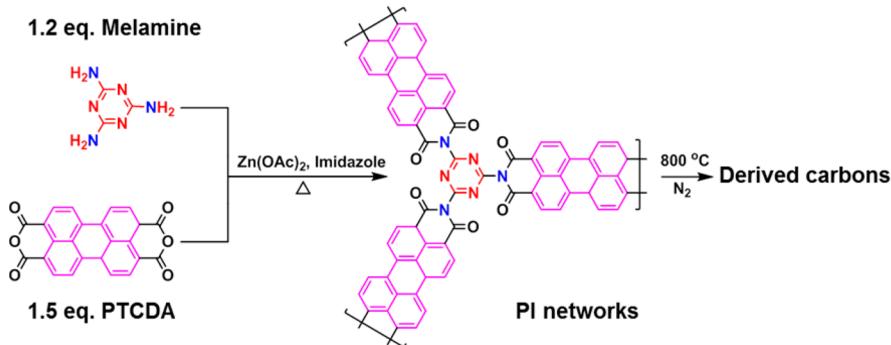
Microporous polyimide (PI) networks¹⁴ are attractive for energy storage applications because of their high mechanical strength, interesting redox behavior, good thermal stability, and outstanding chemical resistance compared with other porous polymers. Selective CO₂ adsorption (over N₂ or CH₄) and good H₂ uptake have been reported recently for this class of POPs.^{9,10,13,15–21} Microporous PI networks are usually synthesized in solution by condensation of polyamines and dianhydrides, including pyromellitic dianhydride (PMDA), 3,3',4,4'-biphenyltetracarboxylic dianhydride (BPDA), naphthalene-1,4,5,8-tetracarboxylic dianhydride (NTCD), and triptycene-based dianhydride (TPDA). These reactions are typically

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Scheme 1. Synthetic Route to PI Networks and Derived Nitrogen-Doped Carbons

performed in high boiling point organic solvents such as *m*-cresol,^{10,18,20} imidazole,¹⁹ dimethyl sulfoxide (DMSO),¹⁵ and isoquinoline.^{15,20} Such solvents, especially DMSO, have been shown to interact with formed network structures and serve as weak templates for the formation and control of porosity in CMPs.^{22–24} Interestingly, a well-known and commercially available dianhydride, perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA), has rarely been used to make such promising PI networks,^{18,19} probably due to its high rigidity and poor processability in nonaqueous solvents. In particular, no effort has—to the best of our knowledge—been devoted to combine the functionalities of PTCDA and triazine.

In this study, we report the synthesis of new microporous PI networks from the condensation of PTCDA and 1,3,5-triazine-2,4,6-triamine (melamine) using a Lewis acid catalyst zinc acetate/imidazole complex²⁵ (Scheme 1). These reactions are performed in both the absence and presence of DMSO at different concentrations, a good solvent for both starting compounds. Notably, both the perylene and triazine precursors used in this study have a planar structure, which is in contrast to the contorted structures of monomers used in most previously reported microporous PI networks. As perylene derivatives have interesting optical properties, we present initial data on the exploitation of these attractive materials as sensors. Finally, nitrogen-containing carbons can be accessed from our PI networks via a simple thermal pyrolysis route. The successful construction of new microporous PI networks and the derived N-containing carbons is shown here to provide promising CO_2 sorbents with high uptake capacities and selectivities.

RESULTS AND DISCUSSION

Synthesis, Chemical Structure, and Physical Properties. PI networks were prepared in the absence (PI-2) and presence of DMSO at a fixed concentration ($c_{\text{melamine}} = 15\text{ g L}^{-1}$, denoted as PI-1), thus exploring the influence of this cosolvent on the physicochemical properties of the obtained polymers. The zinc acetate/imidazole catalyst–solvent complex solubilized the PTCDA efficiently²⁵ and afforded a homogeneous reaction mixture with melamine to yield black insoluble microporous PIs in yields of 45–60% after 72 h (see Experimental Section and Figure S1).

Scanning electron microscopy (SEM) images revealed that the morphology of PI-1 consists of uniformly condensed large particles of several micrometers in dimension and hundreds of nanometers thick (Figure 1), similar to the morphologies observed in PPV-, aza-, and FeP-based CMPs.²⁶ In contrast, the morphology of PI-2 composed of irregular aggregates. Transmission electron microscope (TEM) images for both

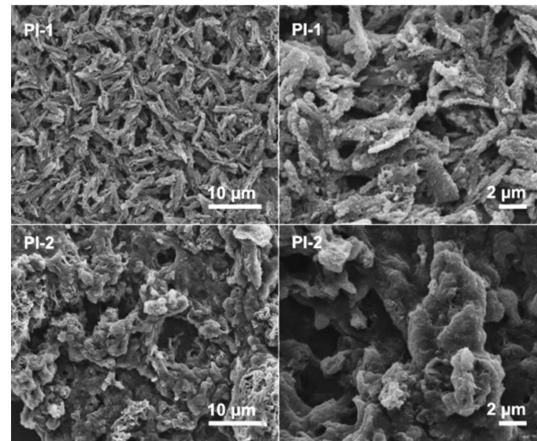


Figure 1. SEM images of PI-1 and PI-2 at (left) low and (right) high magnifications.

networks showed typical irregular structures as usually found for microporous polymer morphologies (Figure S2).

The PI networks exhibited good thermal stability with the onset of decomposition at ca. $400\text{ }^{\circ}\text{C}$ and char yields up to 45% at $1000\text{ }^{\circ}\text{C}$ in N_2 (Figure S3, as determined by thermogravimetric analysis, TGA). Small weight losses were observed at the initial stages due to solvent trapped inside the polymer networks. The high thermal stability of these PIs is ascribed to the covalent linkages and high cross-linking density of the networks formed (in addition to the intrinsic thermal stability of the used perylene materials). Direct pyrolysis of PI-1 in argon at $800\text{ }^{\circ}\text{C}$ generated 68% char product. Fourier transform infrared (FT-IR) spectra of the char showed that the carbonyl and imide peaks became invisible (Figure S4), implying that a PI-based carbon material (PI-1-C) was successfully created. Elemental analyses, SEM (Figure 2), and TEM (Figure 3 and Figure S5) results indicated that PI-1-C has a microporous structure with a nitrogen content of 3% (maximum 8% in theory). Selected area electron diffraction (SAED) analysis

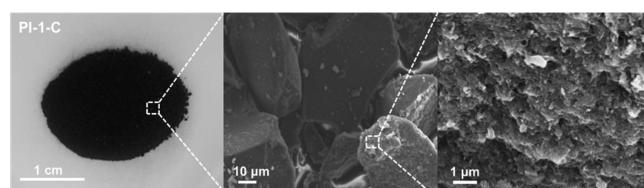


Figure 2. Carbon materials obtained via simple thermal pyrolysis of PI-1 at $800\text{ }^{\circ}\text{C}$ in argon.

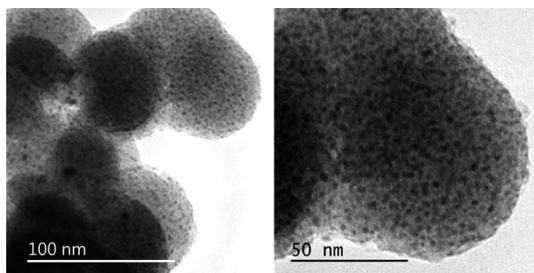


Figure 3. TEM images of PI-1-C at (left) low and (right) high magnifications.

showed that PI-1-C is an amorphous carbon material (see Figure S5). Energy dispersive X-ray (EDX) spectra (Figure S6) and elemental analyses indicated that zinc and sulfur residues were present at very low concentrations (0.09 and 0.08%, respectively) in PI-1-C.

PI network connectivity and the presence of derivatives of both building blocks were confirmed by solid-state ultraviolet visible near-infrared (UV-vis/NIR) and FT-IR spectroscopies. The UV-vis absorption band edges of PI-1 and PI-2 are \sim 1340 and 1360 nm, corresponding to low band gap energies of 0.93 and 0.91 eV (Figure 4), respectively. These values stand

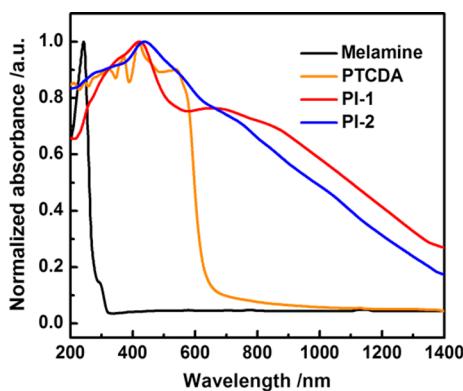


Figure 4. Solid-state UV-vis/NIR spectra of melamine, PTCDA, PI-1, and PI-2.

in noticeable contrast those observed in the respective monomers, melamine (320 nm, 3.88 eV) and PTCDA (670 nm, 1.85 eV), clearly indicating that products with new optoelectronic properties were formed. As shown in Figure 5, the FT-IR spectra of PI-1 and PI-2 showed that the carbonyl stretch frequency shifted toward lower energy by approximately 70 cm^{-1} relative to PTCDA (ν_{imide} , 1685 cm^{-1} vs $\nu_{\text{carboxylic dianhydride}}$, 1755 cm^{-1}), indicating imide bond formation.^{15,21} The free primary amine ($-\text{NH}_2$) stretch vibrations at 3468 and 3417 cm^{-1} were undetectable, suggesting complete conversion of the starting melamine primary amine groups. No strong signals of either the carboxyl ($-\text{COOH}$, 1740 – 1706 cm^{-1}) stretching vibrations or dianhydride ($-\text{COOOC}-$, 1300 cm^{-1}) bending vibrations were visible in the FT-IR spectra of the products. These results indicate that the imide ring closure worked well, with the exception of a few defects, which are always expected during the formation of highly cross-linked polymer networks.

Detailed analysis of the chemical structure of the PI networks was further performed by solid-state ^{13}C cross-polarization magic angle spinning (CP/MAS) NMR spectrometry. The ^{13}C

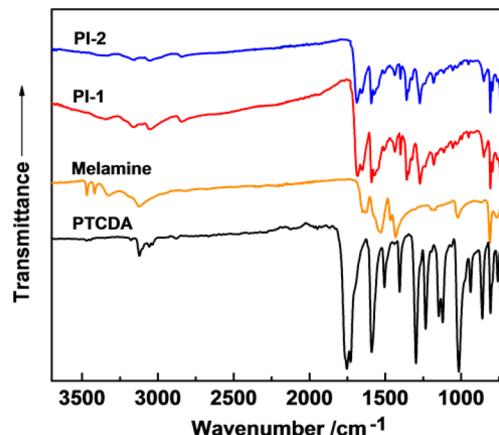


Figure 5. FT-IR spectra of PTCDA, melamine, PI-1, and PI-2.

CP/MAS NMR spectrum of PI-1 showed three resonances at 165, 161, and 128 ppm (Figure S7). The first two very weak resonances were assigned to the carbon atoms present in the triazine ring of the melamine core^{15,27} and the carbonyl group of the imide,^{15,21} respectively, whereas the multiple signals centered at 128 ppm originated from the CH aromatic carbons of the perylene units. Resonances at 195 and 60 ppm are ascribed to spinning sidebands. The results show, in accordance with the results from the UV-vis/NIR and FT-IR analyses, that PI networks consisting of perylene and triazine units were formed.

Powder X-ray diffraction (XRD) measurements of PI-1 and PI-2 showed two broad halos centered around 10° and 27° , respectively (Figure 6 and Table S1), as commonly observed

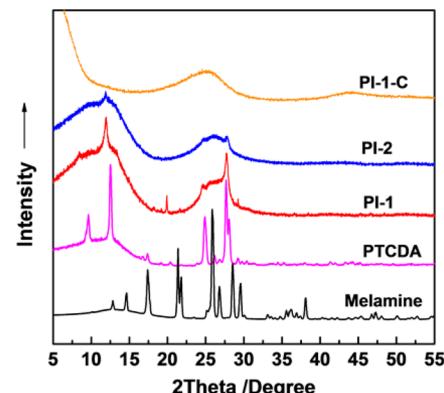


Figure 6. XRD patterns of melamine, PTCDA, PI-1, PI-2, and PI-1-C.

for POPs. Several sharp reflexes were superimposed on these broad halos, with comparable reflex positions for PI-1 and PI-2 (however with higher intensity reflections for PI-1). The sets of characteristic reflexes from the starting materials could not be identified in the products. However, the reflection at 27.6° for both PI-1 (well-defined) and PI-2 is indicative of π -stacking interactions ($d = 0.32\text{ nm}$), as commonly found for perylene-based materials, including the starting PTCDA here.²⁸ The slow addition of melamine dissolved in DMSO during the synthesis of PI-1 favored ordered domains in the product PI-1 (and thus yielding more well-defined scattering from π -stacks). In the absence of DMSO (PI-2), less order is observed, providing the first indications that DMSO plays a role in the structure-formation and growth processes. This observation

was further reinforced when analysis of the porosity of the materials was performed (see below). After pyrolysis, the derived amorphous carbon materials showed only two broad halos, centered at $2\theta = 25.2^\circ$ and 43.9° , typical for the 002 and 101 reflections, respectively, of turbostratic nitrogen-containing carbons.²⁹ No sharp reflection were found corresponding to Zn-related salts, which is in accordance with the results from SAED and elemental analyses reflecting the very low residual content.

We further investigated the chemical composition of the as-synthesized PIs and derived carbons by using X-ray photoelectron spectroscopy (XPS). The XPS survey scans of PI-1, PI-2, PI-1-C, and PI-2-C clearly showed the presence of C, N, and O as well as Zn (Figure S8). Additionally, the spectrum of PI networks synthesized with DMSO (PI-1) displayed weak peaks at 228.08 and 164.08 eV due to the sulfur residues. With only the C, N, and O atoms taken into account, the relative composition contents of C atoms furthermore increased after the PIs were carbonized, while those of N and O decreased (Table S2). The C 1s core-level XPS spectra of both PI-1 and PI-2 showed three peaks: ~ 288.4 eV (peak I: originating from the carbonyl groups), ~ 285.7 eV (peak II: originating from the triazine units), and ~ 284.9 eV (peak III: aromatic benzene type units)³⁰ (Figure 7). The N 1s core level showed two peaks at ~ 400.5 eV (peak I: imide moieties) and ~ 398.5 eV (peak II: triazine units)^{30,31} (Figure 8). Oxygen O 1s peak deconvolution

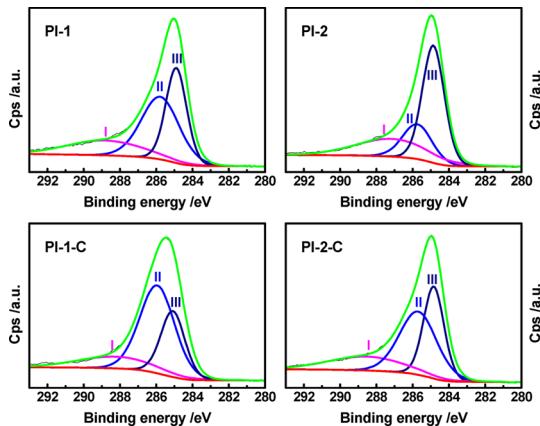


Figure 7. C 1s core-level XPS spectra of PIs and derived carbons.

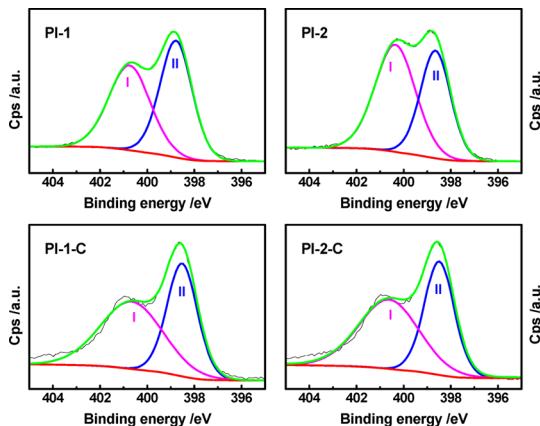


Figure 8. N 1s core-level XPS spectra of PIs and derived carbons.

revealed two peaks at ~ 532.8 eV (peak I: carbonyl groups) and ~ 531.3 eV (peak II: quinone groups)³² (Figure 9). The

similarity of the XPS spectra (apart from very weak sulfur residues in PI-1) implies that the addition of DMSO cosolvent did not change the chemical structure of PI networks.

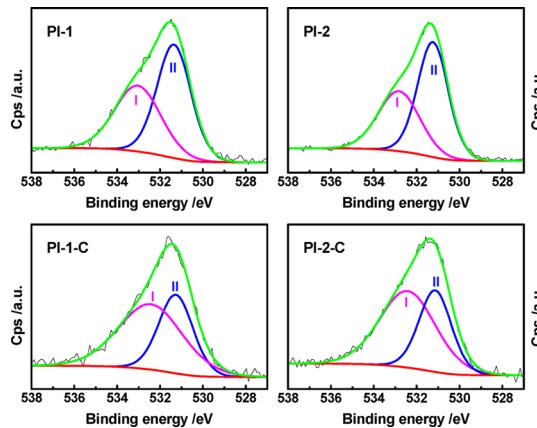


Figure 9. O 1s core-level XPS spectra of PIs and derived carbons.

Theoretically, only three units (1,3,5-triazine, imide, and perylene) make up the PI networks. Upon carbonization, these units either remained and/or were transformed to pyridine- and graphite-type carbons. The relative areas of all the peaks dramatically changed and their binding energies slightly decreased, indicating substantial changes of the chemical structure. After carbonization, the area ratios of peak II/peak I of N 1s ($R^{II/I}$) observed in PI-1 and PI-2 increased from 0.82 to 1.07 and 0.76 to 0.82 (Table S3), while those values of O 1s ($R^{II/I}$) decreased from 1.28 to 0.64 and 1.42 to 1.07, respectively. The results furthermore indicated that some of the imide nitrogen content either was lost to the gas phase or was transferred to pyridine-type nitrogens during the pyrolysis. This is well in accordance with the area ratio changes that were observed for C 1s peaks, in which the relative concentrations of oxygen-connected carbons ($R^{I/III}$) decreased (e.g., PI-1 and PI-1-C: 0.56 vs 0.46) while those of pyridine-type carbons ($R^{II/III}$) increased (e.g., PI-1 and PI-1-C: 1.32 vs 2.07). The XPS results indicated that the obtained carbons consist mainly of remained PI segments, pyridinic and triazine structures, and extended aromatic carbon sheets.

Fluorescence and Sensing Properties. The THF dispersions (0.5 g L^{-1}) of PI-1 and PI-2 displayed strong yellow-green fluorescence and stand in contrast to the weak red fluorescence of PTCDA (Figure 10, left panels) recorded at the same concentration. Compared with the PTCDA monomer, the fluorescence spectra (Figure 10, right panels) showed hypsochromic shifts (530 vs 522 nm) of the maximum emission bands for PI, with the Stokes shift decreased by 21 nm (23 vs 44 nm) and the fluorescence intensities increased 7 times. Based on the fluorescence emission (Figure 10, right panels) and UV-vis/NIR absorbance (Figure S9) of the THF dispersions, the fluorescence quantum yields of the PTCDA and PIs can be further calculated and compared.³³ It was found that the fluorescence quantum yields were increased 21 times (0.85 vs 0.04) for our PI materials. The reduced $\pi-\pi$ stacking of PIs relative to PTCDA would likely hinder self-quenching that arises from strong interactions among the perylene molecules and hence explains the amplified fluorescence that was observed.

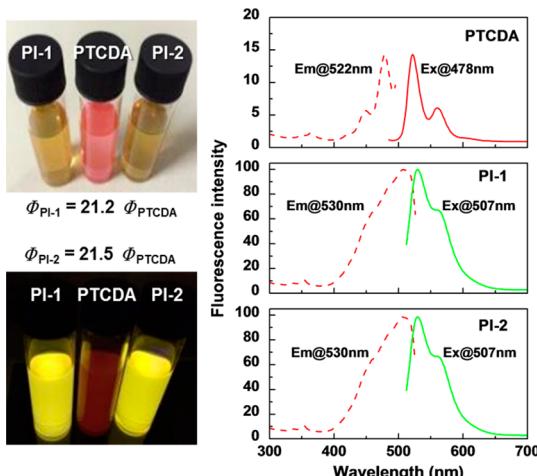


Figure 10. Left panels: PI-1, PI-2, and PTCDA as THF dispersions (0.5 g L^{-1}) excited by sunlight and 365 nm UV-vis light. Right panels: excitation and emission fluorescence spectra of corresponding samples.

We further investigated the fluorescence stability against external stimuli. Upon addition of different heavy metal ions (1 mmol L^{-1}) including Cu^{2+} , Fe^{2+} , Co^{2+} , Mn^{2+} , Pb^{2+} , Fe^{3+} , and Al^{3+} into the PI-1 dispersion, we observed 15–20% decreases in fluorescence intensities for most of the metal ions (Figure S10). Obvious fluorescence quenching (56%) was however found for Fe^{3+} . Among these ions, Fe^{3+} is the most electron-deficient ion and possesses the highest electron affinity. Fe^{3+} could easily form a complex with electron-rich units³⁴ such as perylene, leading to typical fluorescence quenching. The sensitivity toward Fe^{3+} was however quite low (since a high concentration, 1 mmol L^{-1} , of sensing target was used). As the PI networks are not soluble, the perylene units can be only accessed by the metal ions either via the fairly small micropores (see details in below) or through interactions with the particle outer surface. Diffusion into the small pores could be hindered, thus making sensing application of the materials less likely. Considering their low band gap energies ($\sim 0.9 \text{ eV}$), electron-donor characteristics, and stable fluorescence, the PI networks may however be useful in some target applications that require organic conjugated materials with stable and robust optical properties.

Surface Area and Porosities. Initial porosity analyses of PI-1, PI-2, and PI-1-C were conducted using N_2 adsorption/desorption experiments at 77.4 K (see Figure S11 and Table 1). No significant uptake of N_2 into micropores was observed for these materials. Some uptake was observed at higher relative pressure, indicative of the presence of interparticle void spaces or macropores.

This finding is in accordance with electron microscopy data (Figures 1–3 and Figure S2). Low specific BET surface areas of $< 20 \text{ m}^2 \text{ g}^{-1}$ were calculated from the adsorption data, also in line with the presence of an outer surface only. It is well-known that very narrow and small micropores are hard to assess by cryogenic N_2 adsorption/desorption. However, CO_2 adsorption at 273.15 K provides a feasible option³⁵ for such materials where microporosity is expected but hard to assess; we hence analyzed the CO_2 adsorption characteristics.

CO_2 adsorption/desorption was initially measured at 273.15 K for analytical purposes. Figure 11 shows the CO_2 adsorption/

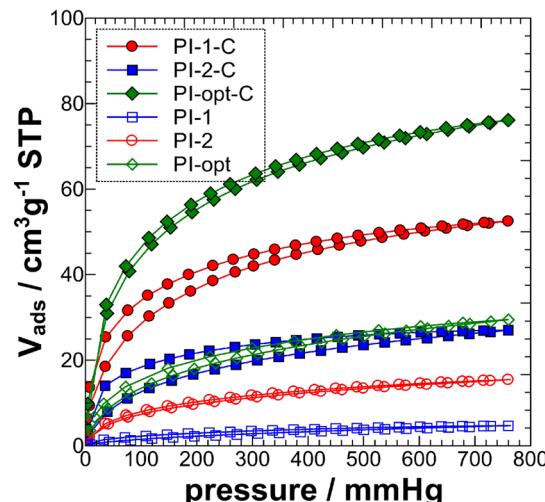


Figure 11. CO_2 adsorption/desorption isotherms of PI networks and derived carbons at 273.15 K.

desorption isotherms of PI-1 and PI-2 along with other materials (e.g., derived carbons, discussed later in the article). It should be noted that the materials showed a weak adsorption/desorption hysteresis. PI-1 does show a moderate CO_2 uptake of $\sim 0.7 \text{ mmol g}^{-1}$ (3 wt %). This value is comparable to results found for previously synthesized BPDA-based PIs.¹⁵ Pore size distribution analysis (using the adsorption branch, Figure 12) by commercialized methods (grand-canonical Monte Carlo, GCMC) indicated a micropore surface area of $148 \text{ m}^2 \text{ g}^{-1}$ and a narrow pore size distribution with a maximum at $\sim 2.5 \text{ \AA}$ pore radius. In contrast, PI-2 synthesized in the absence of DMSO did not show any significant CO_2 uptake ($\sim 0.2 \text{ mmol g}^{-1}$, 0.9 wt %) and was hence not further analyzed.

The porosity difference between PI-1 and PI-2 triggered the question as to whether DMSO acts as an indirect template. In order to test these hypotheses, a series of PI networks were prepared using various amounts of DMSO during synthesis.

Table 1. Porosity Parameters and CO_2 Sorption Properties of the PIs and Derived Carbon

materials	$S_{\text{BET}}^a (\text{m}^2 \text{ g}^{-1})$	$S_{\mu\text{-pore}}^b (\text{m}^2 \text{ g}^{-1})$	$V_{\text{micropore}}^b (\text{cm}^3 \text{ g}^{-1})$	CO_2 uptake at 1 bar (mmol g^{-1} (wt %))	
				273 K	303 K
PI-1	19	148	0.043	0.69 (3.0)	0.44 (1.9)
PI-2	16	n.d.	n.d.	0.21 (0.9)	n.d.
PI-opt	n.d.	283	0.084	1.31 (5.8)	n.d.
PI-1-C	13	483	0.125	2.35 (10.3)	1.76 (7.7)
PI-opt-C	181	710	0.177	3.40 (15.0)	2.42 (10.6)

^aSurface area calculated from nitrogen adsorption isotherms using the BET equation. ^bFrom GCMC analysis of the CO_2 adsorption data at 273 K; n.d. = not determined.

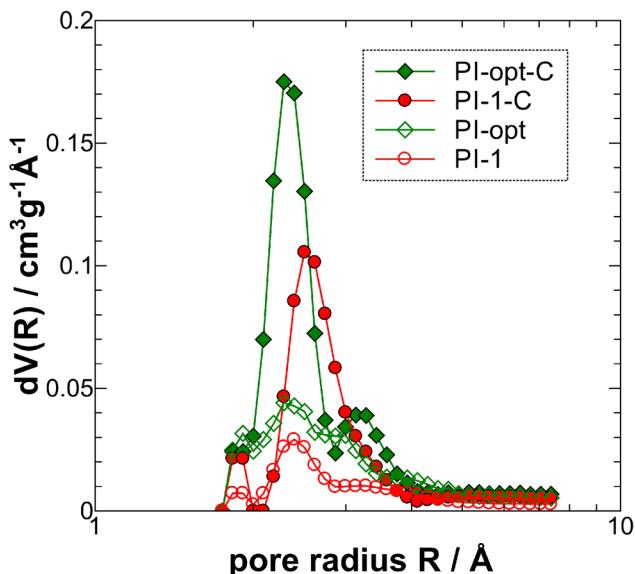


Figure 12. Pore size distribution (PSD) of PI-1, PI-opt, and the derived carbons (PI-1-C and PI-opt-C) as determined from GCMC-analysis of CO_2 adsorption isotherms at 273.15 K.

Melamine was dissolved in DMSO at concentrations of 30, 6, 3.3, and 2.5 g L^{-1} , and those solutions were used to prepare different PI networks for comparison. According to the CO_2 adsorption/desorption isotherms of the series (measured at 273.15 K, Figure S12), the obtained PIs showed an increasing porosity with increasing DMSO content up to a maximum level of CO_2 uptake of 5.9 wt % at 273.15 K and 1 bar (Figure 13).

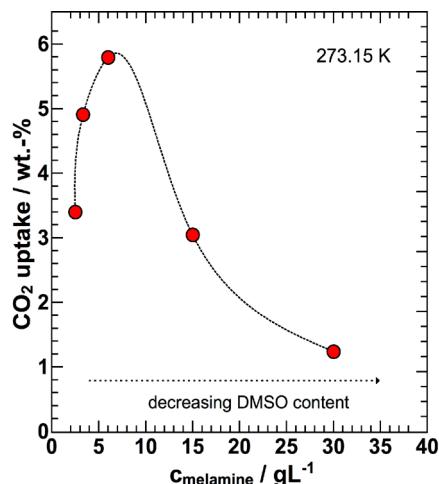


Figure 13. CO_2 uptake (at 273.15 K and 1 bar) of PI-1 type networks synthesized using various concentrations of melamine in DMSO (and hence different DMSO content within the reaction mixtures).

This maximum was observed at a melamine concentration of 6 g L^{-1} corresponding to a DMSO content of 25 mL within the reaction mixture. The maximum CO_2 uptake is more than 6 times higher than the value obtained by PI-2 synthesized without DMSO (5.9 vs 0.9 wt %).

Interestingly, the porosity showed a strong decrease upon further increasing the DMSO content within the mixture (Figure S13). We suspect that the DMSO content (which makes up half of the total solvent for these materials, e.g., for that 2.5 g L^{-1} investigation) is too high to allow for efficient

cross-linking. This in turn could lead to a lowered porosity at such high dilutions, as the connection between high conversion and high porosity is well accepted.^{22,23} In contrast, high reactant concentrations ($c_{\text{melamine}} \geq 30 \text{ g L}^{-1}$) led to gelation within the first few minutes of the polymerization. This could again hinder efficient cross-linking and full conversion. Polymer precipitates easily formed at moderate concentrations (3.3–15 g L^{-1}), leading to permanent micropores. In summary, a strong dependence of the observable porosity within the PI-1 type networks on the DMSO content is obvious. Whether this effect is indeed templating or whether it could be explained by the changed phase separation conditions can however not be answered in full detail at this stage but presents a facile approach to tuning porosity and related properties.

The PI synthesized with the optimal DMSO content as identified (PI-opt), $c_{\text{melamine}} = 6 \text{ g L}^{-1}$ was also carbonized at 800 °C under argon, producing derived carbon material PI-opt-C for comparison to the carbons obtained from pyrolysis of PI-1 and PI-2 (PI-1-C and PI-2-C). PI-1-C shows significant microporosity when analyzed by CO_2 adsorption with micro-pore surface areas up to $483 \text{ m}^2 \text{ g}^{-1}$ and a very narrow pore size distribution with pore sizes predominantly below 0.6 nm (see Table 1 and Figures 11 and 12). In contrast, PI-2-C does show only slightly increased porosity ($S_{\mu\text{-pore}} = \sim 260 \text{ m}^2 \text{ g}^{-1}$) compared to the parent PI-2. Further analysis did hence not include PI-2-C.

Compared to PI-1-C, PI-opt-C has a much higher porosity as evidenced from CO_2 adsorption ($S_{\mu\text{-pore}} = \sim 710 \text{ m}^2 \text{ g}^{-1}$). Interestingly, cryogenic N_2 adsorption also evidenced some microporosity ($S_{\text{BET}} = \sim 181 \text{ m}^2 \text{ g}^{-1}$), which is in contrast to the other carbon materials addressed herein. Still, the N_2 adsorption seems to underestimate the microporosity, which is a common problem for materials with very small pore sizes. Table 1 summarizes the porosity data; Figure S14 and Table S5 provide a detailed comparison with other microporous materials. The PI-opt-C showed the highest CO_2 uptake of 3.4 mmol g^{-1} (15 wt %) at 273 K and 1 bar, which is highly comparable with some state-of-the-art carbon materials such as carbon molecular sieves (CMS), activated carbons, and other nitrogen-containing carbons³⁶ and considerably better than most reported results for PIs as well as other recently reported porous materials³⁷ with significantly higher BET surface areas (see Figure S14 for a graphical comparison of our and related materials). PI-1-C and PI-2-C showed only 2.35 mmol g^{-1} (10.3 wt %) and 1.22 mmol g^{-1} (5.4 wt %) of CO_2 uptake under the same conditions, respectively. Based on the data obtained from CO_2 adsorption, it can be stated that pyrolysis led to increased porosity compared with the parent PI in all cases, and the structure-templating role of DMSO was also reflected in the CO_2 uptake and thus also applicable to the produced carbons. A high porosity of the initial PI network is however required for a highly porous carbon.

It appears that the main fraction of pores of PI-opt-C is of even smaller size than those of PI-1-C. Such very narrow pore size distributions can indeed be of interest for gas separation processes by a combination of kinetic separation and chemical enhancement provided by surface functionalities.³⁸ Hence, the gas adsorption characteristics in terms of gas selectivity of the two carbons and one parent PI network were analyzed in greater detail and are discussed in the next section.

CO_2 Adsorption and Selectivity at Ambient Temperature (303 K). To predict the potential of the materials for CO_2/N_2 separation, it is necessary not only to measure single

gas uptake capacities but also to estimate gas selectivity. To do so, we make use of the ideal adsorbed solution theory (IAST).³⁹ Selectivity calculations are based on the respective adsorption isotherms that were measured at 303 K, i.e., near ambient temperatures that are relevant for real applications (Table S4). PI-1 showed a low CO₂ uptake of 0.44 mmol g⁻¹ (1.9 wt %) at 303 K and 1 bar. The N₂ uptake of PI-1 under same conditions was also low at 0.0166 mmol g⁻¹ (0.046 wt %), resulting in an equilibrium selectivity of 26.5. We also analyzed the IAST selectivity for PI-1, which gave extremely high selectivities of $\alpha(\text{CO}_2/\text{N}_2) > 1000$ at a gas composition of 15 vol % CO₂ (balance made up with N₂; see Figures S15 and S16). Such high values have also been reported for other microporous PIs,⁴⁰ which had however a slightly higher total CO₂ uptake. However, although the selectivity calculated here is high, the overall predicted uptake of CO₂ from the gas mixture is only 0.18 mmol g⁻¹ at 303 K and 1 bar, which is too low for any reasonable application.

The favorable pore size distributions of PI-1-C and PI-opt-C (Figure 12), which are comparable to those of corresponding parent PI networks, indicated promise for CO₂ separation. PI-1-C and PI-opt-C showed good CO₂ uptake of 1.76 mmol g⁻¹ (7.7 wt %) and 2.42 mmol g⁻¹ (10.7 wt %) at 303 K and 1 bar (Figure S17), respectively. The N₂ uptakes of PI-1-C and PI-opt-C under the same conditions were 0.12 mmol g⁻¹ (0.33 wt %) and 0.19 mmol g⁻¹ (0.53 wt %), resulting in a moderate equilibrium selectivity of 14.7 and 12.7, respectively. We also calculated the IAST selectivity and predicted adsorption isotherms of the carbons based on the fitted adsorption branches of the isotherms (Figures S18 and S19). For PI-1-C, a high IAST CO₂ over N₂ selectivity, $\alpha(\text{CO}_2/\text{N}_2) \sim 85$ was found at 303 K and 1 bar, at a gas composition of 15 vol % CO₂ (balance made up with N₂, see Figure 14). The predicted

high selectivity and indeed make such materials promising for gas separation applications, especially as the working capacity exceeds that of benchmark and activated carbons (BPL and MAXSORB), which were reported to have working capacities of 0.4–0.5 mmol g⁻¹ at 1 atm.⁴¹

The high selectivity can, in our opinion, be mainly attributed to the presence of very narrow micropores, which are known to adsorb CO₂ strongly at ambient pressures.^{40,42,43} The high selectivity might additionally benefit from a moderately high estimated isosteric heat of adsorption, which is probably due to a combination of the very narrow pores, which lead to increased bond strength due to overlap of attractive potentials from both pore walls, and the chemical functionalities that were evidenced by XPS. The heat of adsorption q_{st} was found to vary from 38 kJ mol⁻¹ at zero loading to 25 kJ mol⁻¹ at 2 mmol g⁻¹ CO₂ loading (PI-1-C). The variation of the heat of adsorption with loading is also reflected in the fit quality. The CO₂ adsorption branch could only be fitted using a dual-site Langmuir approach, indicating the energetic and morphological heterogeneity of the surface. It is noteworthy that the CO₂ and N₂ adsorption data of PI-1-C and PI-opt-C at 303 K showed some hysteresis, which was typically observed for ultrasmall pore sizes and kinetic issues of microporous materials.⁶

We also analyzed the IAST selectivity of PI-1-C based on the desorption branches of CO₂ and N₂ isotherms (see Figure S18) and found much higher selectivity of ~500 at 1 bar and 303 K at a comparable CO₂ uptake from the mixture (see Table S5 for a detailed comparison of the values obtained here with other published data). The difference in values (when compared to data from the adsorption branches above) might be related to the different slopes at high pressure and predictions about total uptake obtained from the fit parameters of the Langmuir models. At this stage, we can nevertheless summarize that carbon materials of very good CO₂ sorption capacity were prepared. First predictions concerning the selectivity (demonstrated for the CO₂/N₂ gas pair) indicate excellent selectivity and make these materials promising for real gas separation applications.

CONCLUSIONS

We have successfully synthesized novel microporous polyimide (PI) networks composed of perylene and triazine units via a condensation method. The obtained PI networks (in the presence or absence of DMSO, a high boiling point solvent and indirect template) showed good thermal stability and could be further pyrolyzed to produce microporous carbon materials. Both PIs and derived carbon materials have moderate micropore surface areas (up to 483 and 710 m² g⁻¹, respectively) and feature a very sharp and narrow pore size distribution, with uniform ultramicropores less than 6 Å. The parent PIs feature extremely high selectivity for CO₂ over N₂ (>1000) with moderate CO₂ capacity (5.9 wt %). The derived carbon materials however show significantly higher CO₂ uptakes of up to 15 wt % while maintaining very good CO₂/N₂ adsorption IAST selectivities of $\alpha = 240$ at 303 K and 1.0 bar. These results show that this novel class of PIs and carbons derived from perylene and triazine units are very competitive candidates for CO₂ capture. With the low band gap energy (~0.9 eV), fluorescence, and electron-donor characteristics, parent PI networks are also promising for other target applications such as organic photovoltaics, solar cells, and photocatalysis.

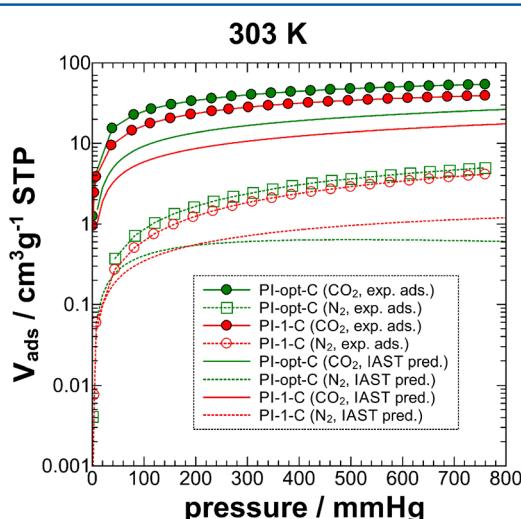


Figure 14. CO₂ and N₂ experimental adsorption isotherms (single gas) of PI-1-C and PI-opt-C at 303 K (symbol + line) together with predicted adsorption isotherms (line only) from a 0.15/0.85 v/v gas mixture of CO₂ and N₂ at 303 K (based on IAST methodology).

adsorption capacity of CO₂ from the gas mixture is 0.8 mmol g⁻¹ (3.4 wt %), which is approximately a factor of 2 lower compared to the capacity with respect to the pure gas. For PI-opt-C, the predicted selectivity and adsorption capacity of CO₂ over N₂ (15:85) could be improved to 240 and 1.18 mmol g⁻¹, respectively. Such values are very acceptable given the rather

■ EXPERIMENTAL SECTION

Materials. Perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA), melamine, imidazole, Zn(OAc)₂, dimethyl sulfoxide (DMSO), dimethylformamide (DMF), tetrahydrofuran (THF), and other solvents with an assay of >97% were purchased from Sigma-Aldrich and used as received.

Synthesis of PI Networks. PTCDA (594 mg, 1.5 mmol) was mixed with imidazole (52.5 g) and Zn(OAc)₂ (417 mg) and stirred at 200 °C under a nitrogen atmosphere for 30 min until dissolved. To this mixture melamine (150 mg, 1.2 mmol) dissolved in DMSO (10 mL, i.e., the concentration of melamine in DMSO is 15 g L⁻¹)⁴⁴ was added dropwise (~3 μL s⁻¹) and stirred at 200 °C for 24 h. The mixture was then reacted at 180 °C for a further 72 h. After this, the reaction mixture was cooled to 100 °C and methanol was added. The formed precipitate was collected by filtration, followed by washing with DMF and methanol, and then dried overnight at 100 °C in a vacuum oven to obtain 360 mg of **PI-1** (yield: 54%). Anal. Calcd for C₆₉H₃₀N₆O₆: C, 73.76; H, 2.91; N, 8.09; O, 9.24. Found: C, 73.46; H, 3.65; N, 9.43; O, n.d. A series of concentrations of melamine in DMSO normally 30, 15, 6, 3.3, and 2.5 g L⁻¹ were used to synthesize PI networks in order to investigate the “template” effect of DMSO in micropore formation. If it is not specifically indicated, **PI-1** mentioned is the PI network synthesized at a concentration of 15 g L⁻¹. **PI-2** was synthesized in the absence of DMSO for comparison. The same reaction procedure as described for the synthesis of **PI-1** provided 315 mg of **PI-2** (yield: 47%). Anal. Calcd for C₆₉H₃₀N₆O₆: C, 73.76; H, 2.91; N, 8.09; O, 9.24. Found: C, 70.11; H, 2.65; N, 8.34; O, n.d.

Synthesis of PI-Derived Carbon Materials. **PI-1** powder (320 mg) was heated to 800 °C under argon at a rate of 5 °C/min and then carbonized for 30 min; 215 mg of nitrogen-doped carbon materials (**PI-1-C**) with a char yield of 67.9% was obtained. Anal. Found for **PI-1-C**: C, 83.31%; H, 0.78%; N, 3.01%; S, 0.08%.

Characterization and Measurements. Elemental analyses (C/H/N/S) were carried out using a Euro Vector EuroEA3000 elemental analyzer. A weighed sample was decomposed in Aqua Regia and then diluted to an accurate volume. Then the zinc content was determined on a GBC Avanta Sigma atomic absorption spectrophotometer operating in the Graphite Furnace mode against known standards. Solid-state and dispersion-state ultraviolet visible near-infrared (UV-vis/NIR) spectra of samples as powders and THF dispersions were acquired on a Shimadzu UV-2600 spectrometer, respectively. Fourier transform infrared (FT-IR) spectra were taken on a PerkinElmer Spectrum 100 spectrometer. Fluorescence spectra of PTCDA, **PI-1**, and **PI-2** as THF dispersions were acquired on a JASCO FP-6500 spectrofluorometer. Powder X-ray diffraction (XRD) patterns were obtained on a Bruker D8 Advance diffractometer (40 kV, 30 Ma) using Cu Kα radiation (2θ = 5°–55°). Solid-state ¹³C CP/MAS nuclear magnetic resonance (¹³C CP/MAS NMR) spectra were recorded at Solid state NMR Service, Durham University, on a Varian VNMRS-600 spectrometer using a spin rate of 6800 Hz. X-ray photoelectron spectra were obtained at the National EPSRC XPS User's Service (NEXUS) at Newcastle University using a K-Alpha (Thermo Scientific, East Grinstead, UK) facility (X-ray energy: 1486.6 eV; spot size: 400 × 800 μm; pass energy: surveys 200 eV, high-resolution regions 40 eV; dwell time: surveys 10 ms, high-resolution regions 100 ms; charge neutralization: ON). The obtained spectra were further analyzed using a CasaXPS software. Thermal gravimetric analysis (TGA) was carried out on a TGA Q500 apparatus in a nitrogen atmosphere (flow rate 30 mL min⁻¹) in the temperature range 30–1000 °C (heating rate 10 °C min⁻¹). Scanning electron microscope (SEM) images and energy dispersive X-ray (EDX) spectra were obtained on a JEOL 5600LV SEM microscope equipped with an EDX spectrometer. High-resolution transmission electron microscope (TEM) images and selected area electron diffraction (SAED) patterns were obtained on a JEOL 2010 TEM microscope. Nitrogen adsorption/desorption measurements at 77.4 K were performed after degassing the samples under high vacuum at 70 °C for at least 20 h using a Quantachrome Quadrasorb SI-MP machine. CO₂ and N₂ adsorption/desorption isotherms at 273 and 303 K were conducted on

a Quantachrome Autosorb-1MP instrument after prior degassing under high vacuum (turbomolecular pump) and 70 °C. The specific surface areas were calculated by applying the Brunauer–Emmett–Teller (BET) model to adsorption branches of the isotherms (N₂ at 77.4 K) the QuadaWin 5.05 software package. Analysis of the isotherms by commercialized grand-canonical Monte Carlo (GCMC) methodology⁴⁵ was also done using either the QuadaWin 5.05 or AS1Win package of Quantachrome Instruments.

Fluorescence Quantum Yield Calculation and Sensing Properties.

The relative fluorescence quantum yield (Φ) of the PTCDA and PIs in solution can be calculated using eq 1.³³

$$\Phi_s = \frac{n_s^2 A_r I_s \Phi_r}{n_r^2 A_s I_r} \quad (1)$$

Here A_r and A_s are the absorbances of the sample and reference solutions at the excitation wavelength; I_s and I_r are the corresponding emission integration areas; and Φ_s and Φ_r are quantum efficiencies of the sample and reference compound; n_s and n_r are refractive indices of the sample and standard solutions. In this study, Rhodamine 101 and THF were used as the fluorescent reference and solvent. The fluorescence quantum yields of PTCDA, **PI-1**, and **PI-2** are calculated to be 0.04, 0.85, and 0.86, respectively. The sensing properties were studied based on the standard fluorescence quenching protocol. Fluorescence quenching was performed by sequentially adding 0.2 mL of different analytes including Cu²⁺, Fe²⁺, Co²⁺, Mn²⁺, Pb²⁺, Fe³⁺, and Al³⁺ to 3 mL of a **PI-1** THF dispersion (0.5 g L⁻¹).

IAST Calculations. Selectivity was calculated using the common IAST equation:³⁹

$$\alpha = \frac{x_{\text{CO}_2}/x_{\text{N}_2}}{y_{\text{CO}_2}/y_{\text{N}_2}} \quad (2)$$

Here α is the selectivity, x is the adsorbed amount, and y represents the gas phase composition. x_{CO_2} was determined using a Newton–Raphson method implemented within a MatLab (R2011a) script or an octave (open source software) script; these scripts are available for download at <http://f-n.hszg.de/fakultaet/hochschullehrerinnen/jens-weber/jens-weber/vermisctesdownloads.html> or upon request via e-mail. The amount adsorbed from the mixed-gas phase was also determined following the known protocols based on ref 41 using the respective fit parameters as basis for the analytical description of the single-gas adsorption isotherms. The gas phase composition was set 15 vol % CO₂ and 85 vol % N₂, i.e., $y_{\text{CO}_2} = 0.15$ and $y_{\text{N}_2} = 0.85$.

■ ASSOCIATED CONTENT

§ Supporting Information

Figures S1–S19 and Tables S1–S5. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: charl.faul@bristol.ac.uk (C.F.J.F.).

Notes

The authors declare no competing financial interest.

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(44) DMSO, imidazole, *m*-cresol, and isoquinoline are typical solvents with high boiling point (>180 °C) used for syntheses of microporous PI networks according to previous studies. DMSO and imidazole are relatively cheaper and lower toxic solvents and able to dissolve melamine well. Solubility tests indicate that other common high boiling point solvents such as *N*-methyl-2-pyrrolidone and dimethylformamide are unable to dissolve melamine. Therefore, DMSO and imidazole are the only two solvents used in this study.

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