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A Sequential One-Pot Block Copolymer Synthesis: Toward Mesoporous Carbon Materials for Selective CO₂ Adsorption

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ABSTRACT

Polymer-derived porous carbon nanomaterials are pivotal for addressing global challenges, particularly in energy storage as well as carbon capture, utilization, and storage (CCUS). Herein, we report a facile one-pot synthetic route to block copolymer (BCP) precursors for mesoporous carbons using a photo-iniferter reversible addition-fragmentation chain transfer (PI-RAFT) polymerization. This scalable approach yields well-defined polyacrylonitrile-*block*-poly(acrylonitrile-*co*-*n*-butyl acrylate) (PAN-*b*-P(AN-*co*-BA)) block copolymers with molecular weights up to 286 kg mol^{−1}, alongside other common PAN BCPs. The characteristics of the BCPs are confirmed exemplary for PAN₂₀₉-*b*-P(AN₂₀₇-*co*-BA₁₄₉)^{41.2} by differential scanning calorimetry, evidenced by two glass transition temperatures (91.5 °C and −13.7 °C) and by atomic force microscopy, which confirmed distinct phase separation of thin films. Also, the robustness of the polymerization was demonstrated by synthesizing multiple sets of BCPs and a numbering-up experiment with 10 samples, showing an average size of 49.8 ± 2.3 kg mol^{−1} with a dispersity *D* of 1.22 ± 0.01. Subsequent electrospinning and carbonization transformed BCP into a nitrogen-doped (11 at.%) hierarchical porous carbon membrane. This membrane exhibited promising CCUS performance, characterized by high CO₂ adsorption capacity (2.52 mmol g^{−1}), rapid desorption kinetics, and high selectivity over N₂. This work establishes a streamlined platform to produce functional carbon architectures for environmental remediation.

1 | Introduction

Advances in reversible deactivation radical polymerization (RDRP) have revolutionized the design of block copolymers (BCPs) with precise architectures [1, 2]. The inherent ability of BCPs to self-assemble into micro- to nanoscale domains, which include spherical, cylindrical, and lamellar morphologies, is governed by the degree of polymerization (*N*), the volume

fraction of the blocks (*f*), and the Flory–Huggins interaction parameter (*χ*) [3]. Recently, research interest has shifted toward complex continuous morphologies, such as the well-known gyroidal or orthorhombic equilibrium structures, as well as various metastable network structures [4, 5]. These interconnected morphologies offer high interfacial areas and superior transport properties, making them ideal for applications in membrane filtration [6, 7], electrochemical energy storage [8], and catalysis

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[9–11]. In this context, high- χ BCPs are particularly advantageous, as they enable the formation of domains from sub-10 nm up to several hundred nanometers [12]. However, synthesizing high-molecular-weight (HMW) or ultra-high-molecular-weight (UHMW) linear BCPs with highly incompatible segments is often limited due to insufficient solubility over the course of the polymerization, typically resulting in a kinetic drop-off accompanied by premature precipitation or micelle formation. Furthermore, high- χ BCPs ($\chi \sim 0.2$) often reach the strong segregation limit (SSL) at intermediate molecular weights ($M_n > 50 \text{ kg mol}^{-1}$) [13, 14]. This, combined with increased chain entanglement events, often traps these BCPs in metastable morphologies [15, 16]. While achieving highly ordered equilibrium microstructures is a classical goal in polymer science, the energy input required to overcome the barrier to their formation is often not industrially feasible or profitable. Nowadays, nanostructured materials with disordered network structures are frequently reported, offering easy access to unique functional materials via scalable microfabrication techniques, indicating that highly ordered equilibrium structures, though desirable, are not always required [17–20].

Among these functional materials, BCP-derived porous carbons have gained significant traction due to their high surface areas, tunable porosities, and chemical robustness [21, 22]. In particular, block copolymer-templated carbons have emerged as highly promising materials for selective gas separation and carbon capture applications [23]. PAN-based BCP systems, particularly polyacrylonitrile-*block*-poly(*n*-butyl acrylate) (PAN-*b*-PBA), pioneered by Matyjaszewski and Kowalewski, have been studied for decades [24–26]. A significant breakthrough occurred when Liu et al. demonstrated that carbonized poly(methyl methacrylate)-*block*-polyacrylonitrile (PMMA-*b*-PAN) nonwoven membranes outperformed traditional carbon membranes made from pure PAN or PAN/PMMA blends [18, 27, 28]. Subsequent work by Álvarez-Gómez et al. on polystyrene-*block*-polyacrylonitrile (PS-*b*-PAN) further highlighted that fiber-based architectures possess superior electrical properties compared to carbonized bulk materials [29]. Their work revealed the suitability of BCP-templated porous carbon fibers across different applications, such as supercapacitors, capacitive deionization, and as MnO_2 -electrodes, with references to other electrochemical applications like batteries, fuel cells, and catalyst supports [18, 30].

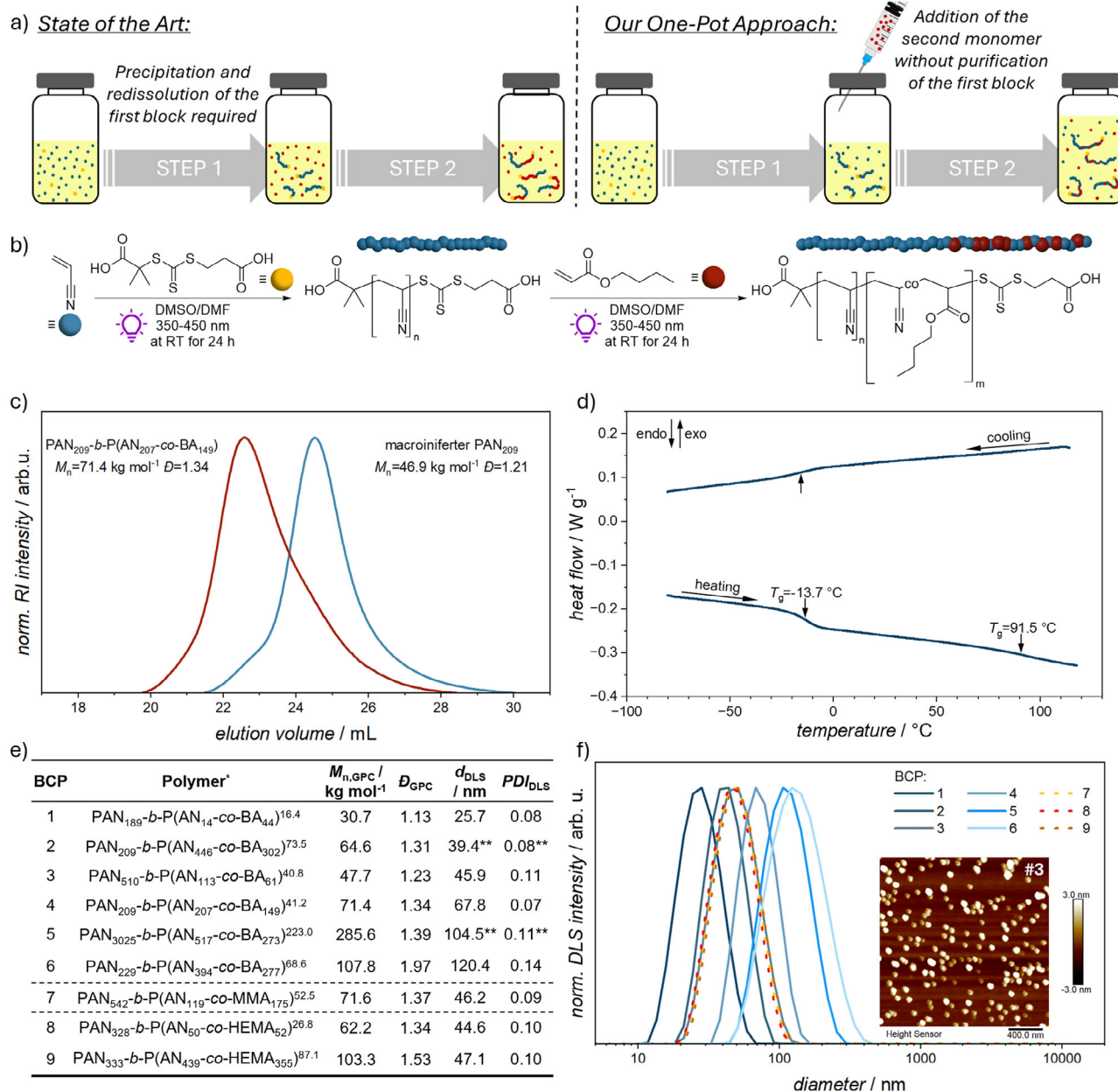
Despite these promising advancements and significant progress in BCP synthesis, the common sequential synthesis of PAN-based BCPs, which involves labor-intensive intermediate clean-up, often used in reversible addition-fragmentation chain transfer (RAFT) or atom transfer radical polymerization (ATRP), remains cost-ineffective for industrial application [1]. To bypass these limitations, a one-pot synthetic strategy has been proposed, utilizing supplemental activator and reducing agent (SARA) ATRP for the preparation of PAN-*b*-PBA, but it has not been further investigated in carbonization and application due to the random/gradient-like second block [31]. Furthermore, while PI-RAFT polymerization has recently been successfully applied to the controlled homopolymerization of acrylonitrile under mild [32] and even aqueous conditions [33], its potential in a sequential one-pot BCP synthesis for subsequent processing into porous carbon membranes has not yet been explored.

In this work, we introduce a simplified advanced polymerization method combined with the manufacturing by electrospinning, to produce PAN-*b*-P(AN-*co*-BA) nonwoven membranes. Our synthetic approach features a PI-RAFT polymerization with a dual-solvent system as a sequential one-pot process (Scheme 1a). A characteristic of one-pot synthesis is that the reaction occurs in a single vessel without intermediate cleanup. In our case, to obtain a pure PAN block, we introduced the second monomer sequentially after the desired reaction time. Compared with the commonly reported ATRP or RAFT polymerization approaches [25–27, 29], the PI-RAFT polymerization presented here does not require any additional initiators, catalysts, or ligands. It also enables the production of high molecular weight polymers, as the absence of an external initiator reduces the number of dead chains [34]. Additionally, the polymerization occurs at room temperature and is initiated by light, which significantly lowers the risk of thermal runaway in larger batches and supports precise spatiotemporal control of the polymerization [35].

2 | Results and Discussion

This one-pot reaction significantly reduced synthetic effort by skipping the purification of the first block and directly adding the second monomer to the reaction solution. As a result, the second block was formed as a copolymer block from the remaining acrylonitrile and added *n*-butyl acrylate (Scheme 1b). The obtained model PAN-*b*-P(AN-*co*-BA) block copolymer was analyzed by NMR, gel permeation chromatography (GPC), and differential scanning calorimetry (DSC). In the GPC traces (Scheme 1c), a clear shift to a smaller elution volume indicated a successful synthesis of the second block. However, a slight broadening ($\mathcal{D} = 1.21$ to 1.34) hinted at traces of dead polymer chains or reinitiation inefficiencies. The $M_{n, \text{NMR}}$ of the BCP 4 was 41.2 kg mol^{-1} , while GPC relative to a PMMA standard resulted in a $M_{n, \text{GPC}}$ of 71.4 kg mol^{-1} . Variations in M_n reflect the differences in the hydrodynamic volume of the reference system, which is typical for PAN-BCPs [36].

The DSC thermogram (Scheme 1d) revealed two distinct glass transition temperatures (-13.7 and 91.5°C), confirming the formation of a phase-separated BCP. The glass transition at -13.7°C lay between the values of the two homopolymers, PAN (95.5°C) and PBA (-53.0°C) (Figure S2), indicating that the second block was a copolymer containing about 63.5 wt.% *n*-butyl acrylate and 36.5 wt.% acrylonitrile, as calculated by the Flory-Fox equation given in the Supporting Information (SI). The platform character of this synthetic strategy was demonstrated by successful feasibility trials for PAN block copolymers with methyl methacrylate (MMA), and 2-hydroxyethyl methacrylate (HEMA) (Scheme 1e,f). Further, the reproducibility of a standard PAN/PBA system was evaluated, using a set of ten experiments, obtaining an average M_n of 49.8 kg mol^{-1} with a standard deviation of 2.3 kg mol^{-1} and a $\mathcal{D}$ of 1.22 (Table S4 and Figure S5). BCP 3 represents pooling aliquots from all ten trials to investigate its properties. Dynamic light scattering (DLS) experiments were performed and confirmed a homogeneous micelle formation, indicating the quality of BCP formation and the ability of the BCP to phase-separate in a selective solvent. BCPs listed in Scheme 1f showed increasing micelle diameter according to the increase in $M_{n, \text{GPC}}$. Further, monomodal micelle formation with a narrow



SCHEME 1 | Characteristics of the sequential one-pot polymerization of PAN block copolymers. (a) Comparison of our one-pot approach to the conventional synthetic approach; (b) Reaction scheme for the PI-RAFT polymerization of the BCP carbon precursor; (c) GPC traces of the macroiniferter and the BCP measured in DMAc/LiCl vs. PMMA reference standards for the model BCP 4 PAN₂₀₉-b-P(AN₂₀₇-co-BA₁₄₉)^{41.2}; (d) DSC thermogram of the representative BCP with two distinct glass transitions; (e) Table presenting GPC and DLS data for a selection of PAN-based BCPs with various comonomers, obtained from the experimental setups in Table S1, where BCP 6 is exemplary of an uncontrolled polymerization; (f) DLS size distribution plot of micellar diameters formed from 0.02 wt.% BCP solution in methanol/DMF(4:1 v/v) supported by an AFM height image, showing a narrow distribution of the features and indicating a mean size of 71 ± 7 nm obtained from BCP 4 (N = 50). *The molecular weight M_n and the BCP composition x_i were determined by ¹H NMR and DSC measurements and are reported as PAN₂₀₉-b-P(AN₂₀₇-co-BA₁₄₉)^{41.2} with the corresponding degree of polymerization as a subscript and the $M_{n, NMR}$ as a superscript (see Supporting Information). ** Micelles were formed by a 0.05 wt.% BCP solution in methanol/DMF (1:1 v/v), as the other composition already forms aggregates.

size distribution ($PDI < 0.12$) was observed for BCPs with low dispersity D . In addition, SEM investigations of the micelles were conducted to confirm the homogeneity, therefore, a few droplets of the micellar solution were applied on a silicon wafer, dried, and sputtered with 2 nm platinum (Figure S6). AFM investigation of BCP 4 yielded a micelle size of 71 ± 7 nm (Scheme 1f, Figure S7), which is in good agreement with the DLS measurements.

To the best of our knowledge, only the microphase separation of PAN-based BCP with two distinct homopolymers has been investigated in the literature. Herein, it was crucial to determine whether the homopolymer-*block*-copolymer architecture would still show a phase separation. For this, atomic force microscopy (AFM) imaging of spin-coated BCP thin-films was performed (Figure 1, Figure S8). The height profiles, shown in

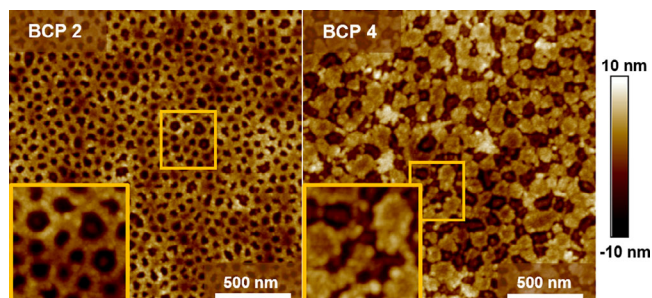


FIGURE 1 | AFM height-imaging of BCP thin films made from PAN₂₀₉-*b*-P(AN₄₄₆-*co*-BA₃₀₂)^{73.5} (BCP 2) and PAN₂₀₉-*b*-P(AN₂₀₇-*co*-BA₁₄₉)^{41.2} (BCP 4). Bright and dark regions correspond to the PAN and PBA-rich phases, respectively.

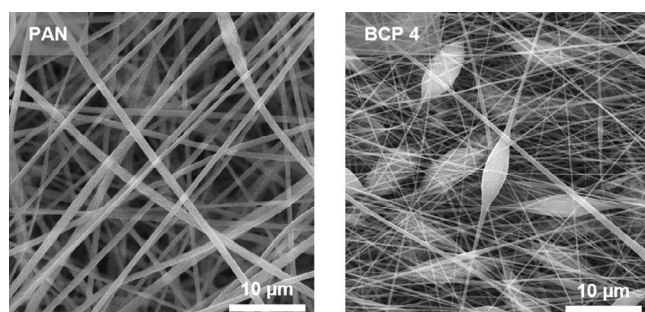


FIGURE 2 | SEM imaging of electrospun polymer membranes made from (a) a 15.0 wt.% PAN homopolymer solution in DMF, and (b) a 22.2 wt.% BCP solution in DMF.

Figure 1, confirmed a well-developed nanostructure for the BCP 2 and 4. The irregular but dense pore morphology, characterized by larger pores containing interpenetrating sub-structures, supported the presence of the intended network-like arrangement. Although the incorporation of acrylonitrile units into the second block should lower the nominal χ parameter relative to a PAN-*b*-PBA system, our BCP still exhibited pronounced microphase separation, indicating high- χ BCP characteristics (BCP 2: $w_{2,\text{block, BA}} = 52.7$ wt.%, $d_{\text{pores}} = 42.4$ nm). A reasonable assumption is that the strong dipole-dipole interactions of neighboring nitrile moieties are disrupted by the steric hindrance of the nonpolar *n*-butyl acrylate in the second block [37].

Following, a PAN homopolymer and BCP 4 with narrow molecular weight distributions were electrospun separately into non-woven membranes. Successful parameter optimization for the PAN homopolymer ($M_n = 125.8$ kg mol⁻¹, $\bar{D} = 1.24$) produced by PI-RAFT polymerization was achieved, resulting in uniform fibers with a mean diameter of 735.2 ± 100.8 nm. Despite adjusting the viscosity and extensively modifying the spinning parameters, the narrowly dispersed BCP 4 still produced noticeable bead formation and irregular fiber structures (Figure 2). The effect of parameter variation is exemplarily shown for the structurally related BCP 3 in the Supporting Information (Figure S9). Interestingly, the mean diameter of 219.2 ± 39.5 nm was much smaller than that of the PAN homopolymer. This observation was made across multiple polymer sets, confirming the critical role of high-molecular-weight chains in jet stabi-

lization [38]. Membrane formation could be improved by using higher molecular weight BCPs, often with broader dispersity, or by adding salt to the solution. However, the individual fibers were still below 400 nm, which appeared to be too thin for the intended subsequent carbonization, as they fuse together (Figure S10), resulting in not achieving the desired porosity.

Preservation of the intrinsic microstructure of the BCP and sufficient carbonization were achieved with the model BCP 2 and BCP 4, resulting in beaded carbon membranes. To convert the electrospun BCP membrane into a carbon membrane, a multistep thermal process was utilized. This included drying the BCP membrane in N₂ (I), stabilization of the PAN segment in air (II), decomposition of the sacrificial second block in N₂ (III), followed by carbonization in N₂ (IV) (Figure 3a, Figure S11). The mass loss of 32 wt.% at 400 °C aligned well with the BCP composition, which contained 26.3 mol% PBA, equivalent to 46.3 wt.%. Regarding the PAN content in the entire BCP, a carbon yield of 70.2 % was achieved. FTIR analysis confirmed the chemical changes at each stage to be consistent with the literature (Figure 3b) [39, 40]. Additionally, the Raman spectra of the carbonized BCP showed almost identical vibrational bands when compared to pure PAN fibers. The presence of pronounced D and G bands (first-order) and the appearance of a broad second-order D' band indicated a partially graphitized carbon structure with many defects and structural disorder, which were beneficial for CO₂ adsorption (Figure 3c) [41]. Moreover, DSC measurements were used to investigate the stabilization reaction, comparing BCP with PAN homopolymer. Here, the shape of the stabilization peak and temperature were similar, with a slight shift to higher temperature by 2 °C for the BCP ($T_{\text{stab.,PAN}} = 271$ °C and $T_{\text{stab.,BCP}} = 273$ °C). Furthermore, the stabilization enthalpy corresponded with the overall PAN content, resulting in 45 % (242 J g⁻¹) of the enthalpy of PAN homopolymer (535 J g⁻¹), which was slightly lower than the PAN mass fraction (53.7 wt.%) of the BCP determined by NMR (Figure S12). The formation of heteroaromatic-doped carbon material with a graphene-like structure was also supported by XPS measurements, depicted by the characteristic nitrogen (N) signal (Figure 3d). Through spectral deconvolution, a precise assignment of nitrogen species was achieved, including pyridinic, pyrrolic, graphitic, and pyridine-*N*-oxidic nitrogen [42, 43]. The overall composition of the carbon fibers was 83.6 at.% carbon, 11.4 at.% nitrogen, and 5.0 at.% oxygen. Detailed information is available in the SI (Figure S13).

After confirming the targeted chemical composition, the preservation of the mesostructured BCP fibers following carbonization, which resulted in mesoporous carbon material, was verified using scanning electron microscopy (SEM) and small-angle X-ray scattering (SAXS) (Figure 4). Figure 4a shows the fibrillar structure of three carbonized membranes from the top view (I–III) and cross-section (IV–VI). Here, we compared a carbonized PAN membrane (I, IV), with two membranes of BCP 4, which differed in their post-treatment: (II, V) underwent direct stabilization and carbonization, and (III, VI) were carbonized after annealing at 120 °C in DMF vapor. As noted earlier, M_n of the BCP was quite low, and $\bar{D}$ was narrow, leading to a non-homogeneous fiber matrix with noticeable bead formation. Nevertheless, SEM images revealed that both BCP membranes exhibited a clear mesoporous struc-

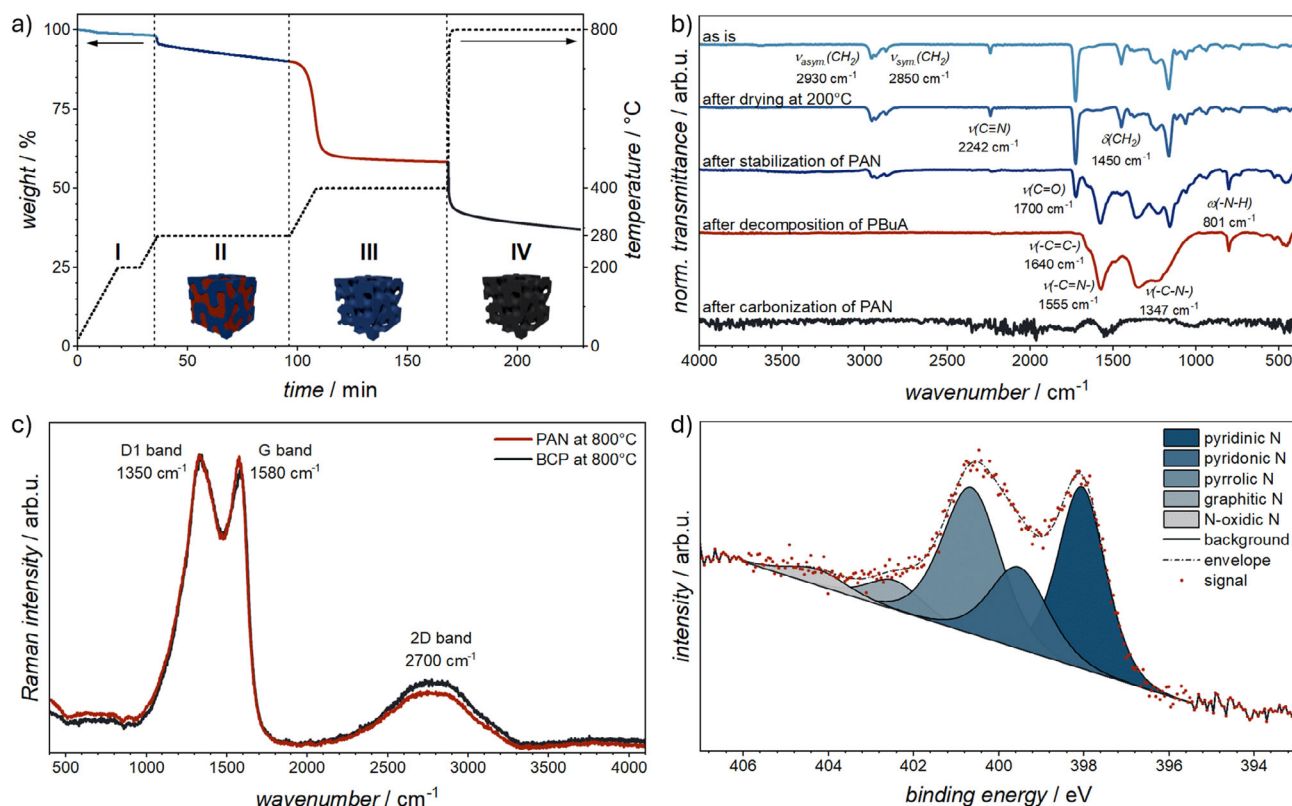


FIGURE 3 | Thermal modification of the BCP-templated carbon precursor, which includes stabilization of PAN at 280 °C in air (II), decomposition of the PBA sacrificial block at 400 °C in N_2 (III), and carbonization of the stabilized PAN at 800 °C in N_2 (IV).: (a) thermogram of the thermal modification; (b) FTIR spectra of the BCP fibers at different degrees of thermal modification; (c) comparison of the Raman spectra of the BCP and pure PAN fibers after carbonization at 800 °C; (d) deconvoluted XPS spectrum of the N 1s orbital of the carbonized BCP membranes.

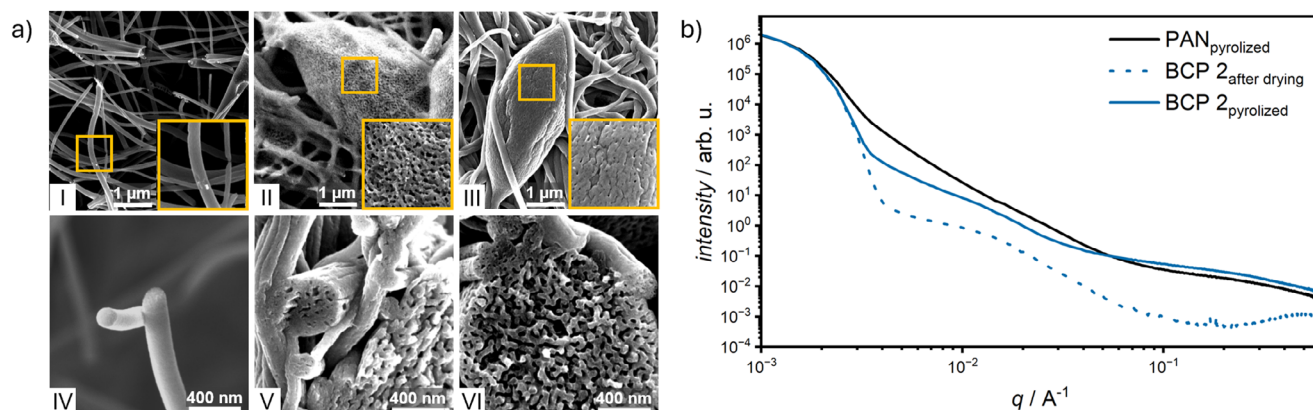


FIGURE 4 | Morphology of the carbonized membranes. (a) SEM images of fibers, beads, and their cross sections investigating carbonized PAN fibers (I, IV), carbonized BCP fibers (II, V), and carbonized BCP fibers annealed in DMF vapor before carbonization (III, VI). (b) SAXS measurement of the carbonized PAN membrane compared to the dried and pyrolyzed BCP membrane derived from BCP 2.

ture, whereas the PAN membrane only showed a rough surface with no visible mesopores. Surfaces (II, III) and cross-sections (IV, V) of the bead-like structure illustrated the effect of the annealing step. With direct carbonization, an open, randomized porous surface structure was obtained, whereas the annealed membrane exhibited a more closed but also more organized microstructure, typical for BCP phase separation. This impression was confirmed

by the cross sections, where annealed beads showed a more uniform microstructure spacing, indicating an equilibrated state. Even the connected beads of several micrometers exhibited a well-defined, homogeneous porous microstructure throughout the entire volume. Also, the nanofibers (168–254 nm) showed the desired porosity (Figures S14–S16), although the structural features did not indicate typical equilibrium structures, due to

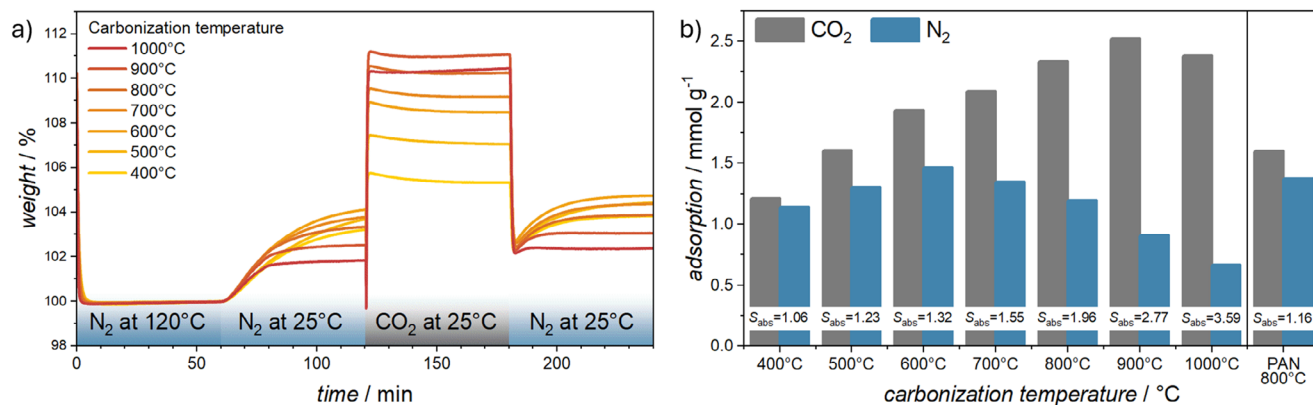


FIGURE 5 | TGA investigation of CO₂ adsorption at ambient pressure. (a) TGA thermogram showing the mass change during N₂/CO₂ adsorption/desorption of the porous carbon membranes after carbonization at different temperatures; (b) Comparison of the N₂ and CO₂ adsorption capacities after carbonization at different temperatures.

a combination of shear-induced ordering and interfacial effects [44, 45]. Furthermore, it is worth noting that BCP fibers exhibited lower dimensional shrinkage, with 76.7 % of the initial fiber diameter retained, compared to 48.6 % for the PAN homopolymer (Table S5 and Figure S17). To confirm the size of the structural features, SAXS was performed for BCP 2, revealing an average structural peak corresponding to a mean diameter of 36.6 nm (Figure 4, Table S6), which aligns with the domain spacing of the BCP thin film measured by AFM (42.4 nm). Figure 4 shows the structural evolution from phase-separated BCP membrane to the carbonized BCP membrane, alongside a comparison with the carbonized pure PAN membrane. The comparison clearly indicates that the structural features of the BCP are retained to some extent after carbonization. Assuming log-normally distributed spherical pores, a unified fit according to Beaucage [46], was performed using IRENA [47]. For the carbonized membrane of BCP 2, mesopores with a mean radius of 7.2 nm and micropores of 0.2 nm were estimated. The mesopores (q : 0.006 to 0.03 Å⁻¹) exhibit a mass-fractal dimension of 2.755, indicating a densely packed, interconnected pore network spanning from the macropore to the mesopore regime (confirmed by SEM and pore distribution, Figure 4, Figure S19) [48, 49]. The micropores (q : 0.167 to 0.45 Å⁻¹), determined by an additional Guinier fit resulting in a sphere-equivalent diameter of 1.2 nm, are not part of the hierarchical structure and more likely represent a separate population. These findings are supported by the N₂ adsorption isotherm of a membrane produced from BCP 2, which shows an average pore diameter (d_{av}) of 7.60 nm. BCP 4 yielded a smaller pore size (d_{av} = 5.64 nm), consistent with its molecular weight. All BCP membranes also exhibited a higher specific surface area than the PAN membrane, with a maximum of 593.1 m² g⁻¹, calculated using the Brunauer–Emmett–Teller (BET) method, even though they are more likely to sinter together compared to the one from homopolymer (Table S7). Investigations of N₂ physisorption for PAN, BCP 2, BCP 3, and BCP 4 membranes show variations in isotherm types, ranging from a Type II isotherm with weak H3 hysteresis and minimal porosity for PAN, to a Type IV(a) isotherm with H1 hysteresis, indicating narrow, uniformly distributed mesopores for BCP 2 and BCP 4, and finally to a highly complex Type IV(a) isotherm with H2 hysteresis for BCP 3, so-called ink-bottle mesopores, which also show the highest overall porosity (Figure S20) [50].

To explore the application of mesoporous carbon membranes in carbon dioxide capture, preliminary gravimetric CO₂ adsorption experiments were conducted in a TGA furnace (Figure 5). Figure 5a displays the thermogravimetric traces of an adsorption/desorption cycle by first heating the sample in a nitrogen atmosphere, followed by conditioning at 25 °C under N₂, then switching the gas atmosphere to CO₂ for adsorption, and finally returning to N₂ to verify complete CO₂ desorption (Table S8). Depending on the carbonization temperature, the material demonstrated a CO₂ adsorption capacity of up to 2.52 mmol g⁻¹ at ambient pressure and 25 °C (SI), which is comparable to other carbon-based adsorbents reported in literature and within the range necessary for industrial applications [51]. Standard bulk-carbonized PAN homopolymers (carbonized at 850 °C under N₂) typically exhibit a low CO₂ adsorption capacity of approximately 0.7 mmol g⁻¹ (at 25 °C, 740 Torr, ~1 bar) [52]. In contrast, our electrospun PAN fibers reach 1.60 mmol g⁻¹ (at 25 °C and 760 Torr ~ 1 bar), demonstrating that the fibrous architecture itself boosts accessible surface area and adsorption capacity. The BCP-templated carbon membranes outperform this, matching the performance of conventional, multi-step synthesized BCP carbon materials reported in the literature (e.g. 2.3 mmol g⁻¹ at 25 °C and 760 Torr ~ 1 bar for conventional BCP-derived carbon carbonized at 800 °C under N₂) [23]. To evaluate the material's potential performance under competitive gas exposure, the affinity towards CO₂ was investigated as an apparent selectivity, defined as the ratio of separately measured single-component CO₂ and N₂ uptakes (Figure 5b), which demonstrates a simplified screening method. The material showed increasing apparent selectivity with increasing carbonization temperature, indicating the highest selectivity for CO₂ adsorption, with up to 3.59 times more CO₂ than N₂. In this preliminary study, the material showed fast adsorption and desorption (Figure 5a) and high apparent selectivity towards CO₂ over N₂ (Figure 5b), also over multiple cycles (Table S9 and Figure S21), providing an excellent basis for the development of future high-performance functional materials in the field of CCUS. Although this is not the most precise method, as it does not account for competitive adsorption under mixed-gas conditions, it still provides valuable insight by enabling direct comparison of the apparent selectivity across samples carbonized at different temperatures, as well as with the pure PAN membrane.

3 | Conclusions and Outlook

In summary, we have successfully developed a variable and robust sequential one-pot PI-RAFT polymerization approach to synthesize narrowly distributed PAN-based BCPs with molecular weights up to 286 kg mol^{-1} . By eliminating the costly and tedious intermediate purification of the macro-initiator, a more sustainable method for generating BCPs was demonstrated, yielding BCPs that still exhibited distinct phase separation. Further, high molecular weight PAN-*b*-P(AN-*co*-BA) BCPs ($>> 50 \text{ kg mol}^{-1}$) were realizable, allowing the fabrication of electrospun membranes for straightforward access to BCP-templated mesoporous carbon membranes with a high residual carbon mass of 70.2 wt.% related to the PAN content in the BCP. A defect-rich, partially graphitized hierarchical structure was obtained, showing high selectivity for CO_2 over N_2 , as well as sufficient and fast functionality for room temperature CO_2 sorption/desorption with a capacity of 2.52 mmol g^{-1} . In this initial communication, we focus on demonstrating the synthesis and feasibility of accessing carbonized membranes with the gradient PAN-BCPs, laying the foundation for future studies encompassing optimization of the membrane structure, systematic tailoring of the pore structure, and systematic evaluation of gas separation performance.

With this work, we demonstrated the initial step toward building a versatile toolbox for accessing BCP-based hierarchical porous PAN membranes, which exhibited intrinsic stabilization and can serve as a foundation for innovative carbon materials. Our material provides a broadly applicable platform suitable for multiple applications, including CCUS, as shown by initial CO_2 adsorption tests, and energy storage or water remediation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in RADAR at <https://radar.kit.edu/radar/en/dataset/fjgg8tameu8xtr7r> and <https://radar.kit.edu/radar/en/dataset/10.35097/y2rhza9zyh3c80t0>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: marc70437-sup-0001-SuppMat.docx.