# Rapid synthesis of functional poly(ester amide)s through thiol-ene chemistry

Taoguang Qu[1], Kevin N. West[2] and Paul A. Rupar[1]*

[1]Department of Chemistry & Biochemistry, The University of Alabama, Tuscaloosa, Alabama 35487-0336, United States
[2]Department of Chemical & Biomolecular Engineering, The University of South Alabama, Mobile, Alabama, 36688-0001, United States

Supporting Information

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## Experimental and Characterization

Unless stated otherwise, all reagents and solvents were either purchased from commercial suppliers and used directly without further purification or synthesized following literature procedures. All manipulations were carried out under an air atmosphere. Nuclear magnetic resonance ($^1$H NMR) spectra were recorded with a Bruker AVANCE NEO III HD 500 spectrometer equipped with a cryoprobe. Gel permeation chromatography (GPC) was performed using a TOSOH BIOSCIENCE Gel Permeation Chromatograph equipped with an RI detector, an automatic sampler, a pump, an injector, an inline degasser, a column oven (35 °C), two in-series TSKgel SuperAWM-H SEC columns, and a TSKgel SuperAW2500 column. HFIP with $CF_3COOK$ (3.0 mg/mL) was used as the mobile phase at a flow rate of 0.1 mL/min. Fourier transform infrared spectroscopy spectra were obtained on a Perkin-Elmer Spectrum Two FT-IR Spectrometer. DSC analysis was performed on a TA Discovery DSC 250 with a heating/cooling rate of 10 °C/min. For the DSC data collection, all samples were heated through 3 complete heating/cooling cycles. The data from the 3rd cycle is reported. TGA analysis was performed on a PerkinElmer STA 8000 or a TA Discovery SDT 650 with a heating rate of 10 °C/min. Terephthalic acid was generated from hydrolyzing post-consumer PETE based on the literature procedure.[1] Terephthaloyl chloride was synthesized based on the literature procedure.[2] **Terephthalaziridine (TP-Az)** was synthesized based on our recently reported procedure.[3] 1,6-bis(maleimido)hexane (**1,6-BMH**) was synthesized based on the literature procedure (Figure S8).[4]

**General procedure for step-growth polymerizations of TP-Az with itaconic acid for PA-1 synthesis**

A single neck 50 mL round bottom flask equipped with a stir bar was charged with **TP-Az** monomer (405 mg, 1.89 mmol, 1.00 equiv), itaconic acid (243 mg, 1.89 mmol, 1.00 equiv), THF (18.0 mL), and $Et_3N$ (26.3 μL, 0.189 mmol, 0.100 equiv) in sequence under air atmosphere. Then, the vial was capped and immersed in a preheated oil bath (50 °C). The solution was stirred for 72 h and then precipitated into methanol. The precipitate was collected by centrifugation and dried under vacuum overnight to obtain the polymer as white powder.

**PA-1** (Table 1, entry 1): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 1.44 (s, 4H), 2.05 (s, 4H), 3.41 (s, 4H), 4.26 (s, 4H), 8.07 (m, 6H) (Figure1 and S1).

**Thiol−ene "click" for PA-1's post-polymerization modification (thermal initiation)**

Using the preparation of **PA-1A** (Table 1, entry 2) as an example. **PA-1** (23 mg, 0.06 mmol alkenyl groups, 1.00 equiv), 1-dodecanethiol (0.14 mL, 0.06 mmol, 10.00 equiv) and DMF (1.2 mL) were added to a one-dram glass vial equipped with a stir bar. The reaction mixture was stirred for 24 h at 50 °C, and then precipitated into methanol. The precipitate was collected by centrifugation and dried under vacuum overnight to obtain the desired product **PA-1A** as white powder.

For the preparation of poly(ester amide) copolymers with other pendant moieties (Table 1, entry 3-7), different thiols were used with the same molar ratios as above. The reaction temperature, amount of solvent and polymerization time were also the same as the **PA-1A** synthesis. The purification process of **PA-1B** to **PA-1E** was the same as that of **PA-1A**. For **PA-1F**'s purification, the DMF solvent was removed under reduced pressure at 50 °C overnight. The off-white crude was dissolved into 5 mL deionized water and dialyzed for 2 days against deionized water (SpectraPor® 6 Standard RC Pre-wetted Dialysis Tubing, 1000 MWCO). The resulting white powder was dried and used for characterizations.

**PA-1A** (Table 1, entry 2): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 0.82-1.37 (br, 23H), 2.36 (s, 2H), 2.64 (br, 4H), 2.95 (s, 1H), 3.49 (s, 4H), 4.11 (br, 4H), 7.90 (s, 4H), 8.65 (br, 2H) (Figure 1 and S2).

**PA-1B** (Table 1, entry 3): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 2.70 (br, 8H), 2.96 (s, 1H), 3.50 (s, 4H), 4.10 (m, 4H), 7.21 (m, 5H), 7.88 (s, 4H), 8.65 (m, 2H) (Figure S3).

**PA-1C** (Table 1, entry 4): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 2.69 (m, 6H), 2.97 (quintet, 1H), 3.48 (m, 6H), 4.12 (m, 4H), 4.78 (t, 1H), 7.90 (s, 4H), 8.69 (m, 2H) (Figure S4).

**PA-1D** (Table 1, entry 5): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 2.70 (m, 4H), 3.04 (s, 1H), 3.23 (s, 2H), 3.49 (s, 4H), 4.14 (s, 4H), 7.90 (s, 4H), 8.67 (m, 2H), 12.61 (br, 1H) (Figure S5).

**PA-1E** (Table 1, entry 6): white powder, $^1$H NMR (500 MHz, DMSO-$d_6$): δ 2.64 (m, 4H), 2.96 (quintet, 1H), 3.49 (m, 4H), 3.70 (s, 2H), 4.14 (m, 4H), 6.20 (s, 1H), 6.30 (s, 1H), 7.51 (s, 1H), 7.89

(s, 4H), 8.68 (m, 2H) (Figure S6).

**PA-1F** (Table 1, entry 7): white powder, $^{1}$H NMR (500 MHz, DMSO-$d_6$): δ 2.69 (m, 8H), 2.97 (quintet, 1H), 3.49 (s, 4H), 4.11 (d, 4H), 7.91 (s, 4H), 8.74 (m, 2H) (Figure S7).

**Reversible formation and decrosslinking of poly(ester amide) organogel based on PA-1E**

The poly(ester amide) organogel preparation was conducted by dissolving the furan-bearing **PA-1E** (27 mg, 0.060 mmol diene, 2.0 equiv) into 0.6 mL DMF, followed by adding 1,6-bis(maleimido)hexane (**1,6-BMH**, 8.3 mg, 0.03 mmol, 1.0 equiv) into the reaction mixture. Ultrasound was applied to promote dissolution until a homogeneous solution was formed. At room temperature, the medium stopped flowing within 5 mins to afford a gelled material. The system was then heated to 100 °C for 5 mins for network decomposition to form a homogeneous mixture, as in the initial state. After the removal of the heat source, the system was gradually cooled down to room temperature to reform the organogel (Figure 3).

**Synthesis of bio-derived polyurethane (PU) based on PA-1C**

The formation of **PU** was divided into two steps: firstly, **PA-1C** (50 mg, 0.12 mmol including 0.12 mmol hydroxyl groups), deionized water and PMDETA were dissolved in 0.60 mL DMF in a weight ratio of 100:1 :0.5. 4,4'-methylenediphenyl diisocyanate (**4.4'-MDI**, 15 mg, 0.06 mmol including 0.12 mmol isocyanate groups) was then dissolved in 0.2 mL DMF and added to the above reaction mixture (-NCO : -OH equal to 1 : 1). Secondly, the mixture was heated at 120 °C for 30 mins to cure completely. Then DMF was removed under vacuum (50 °C) overnight to afford **PU** as colorless films for FT-IR characterization.

**Polyurethane (PU)**: colorless film, IR (neat): 3308 (w), 2896 (w), 1736 (m), 1711 (m), 1625 (s), 1540 (s), 1495 (m), 1267 (s), 1205 (s), 1124 (m), 1083 (m) $cm^{-1}$, as shown in Figure 4.

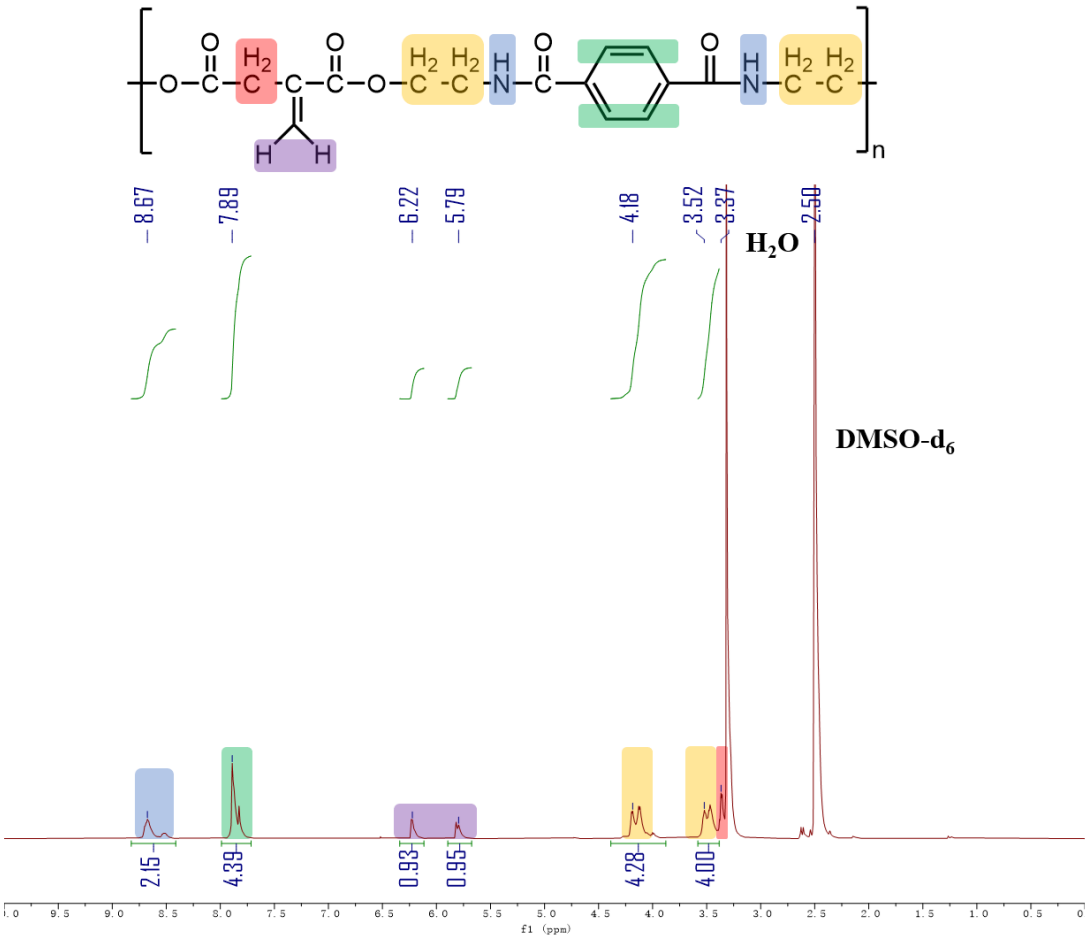



Figure S1. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) (**PA-1**) from the polymerization of **TP-Az** and **itaconic acid**. This spectrum was adapted from our recent manuscript.[3]

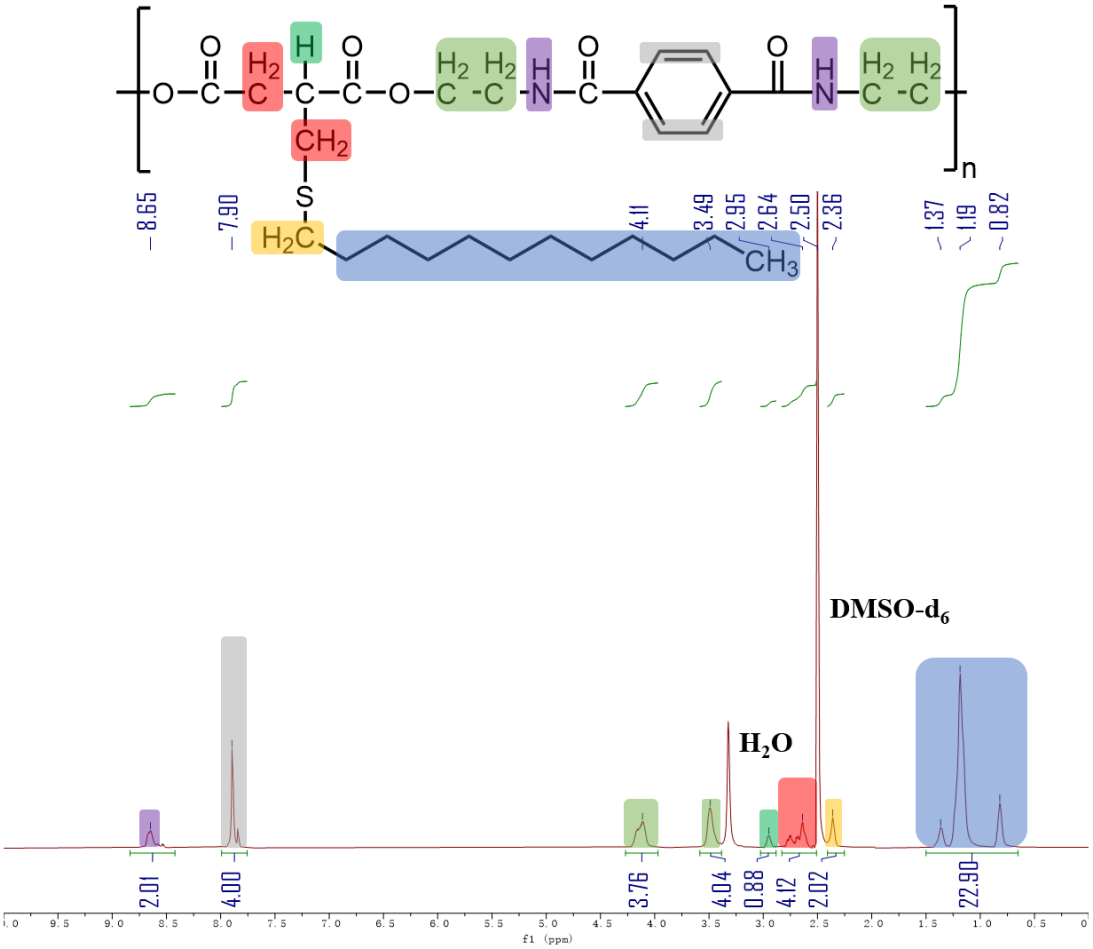



Figure S2. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **1-dodecanethiol**.

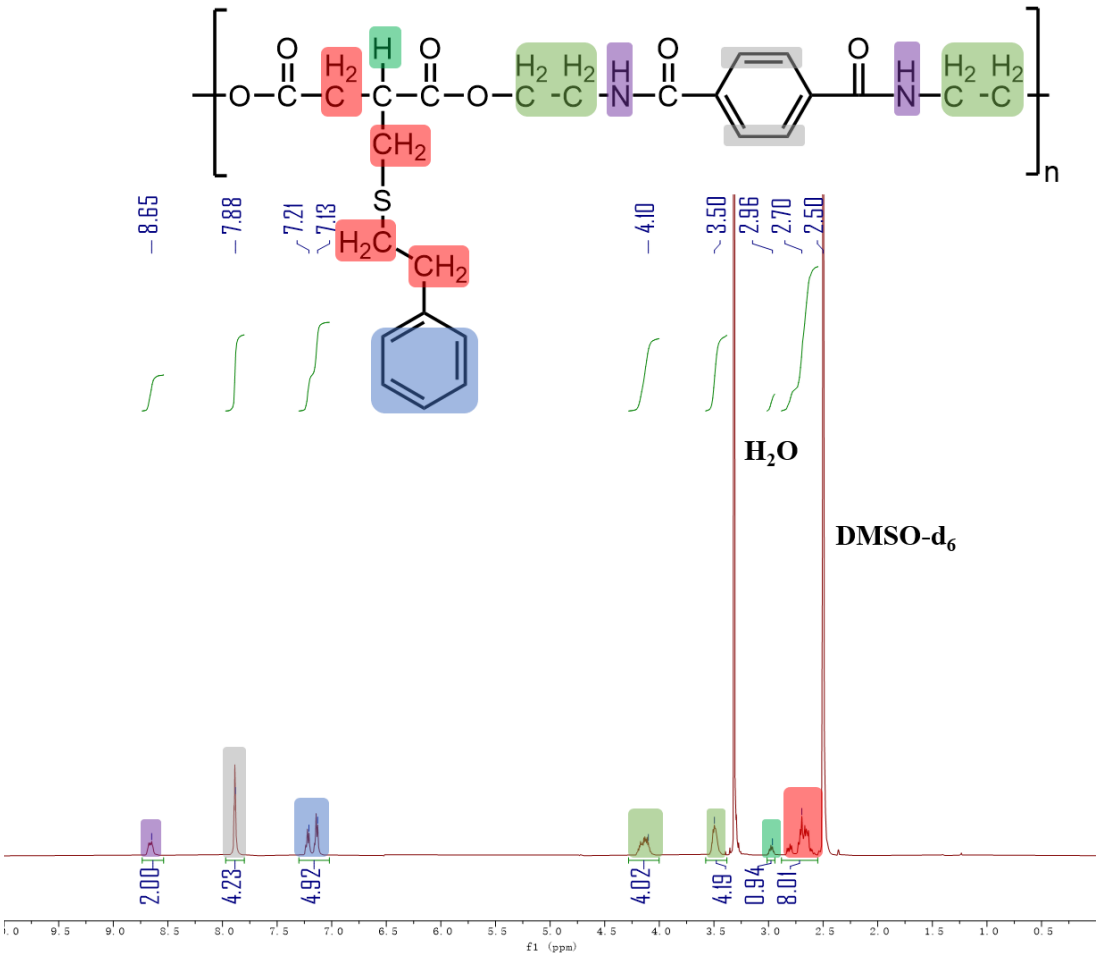



Figure S3. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **2-phenylethanethiol**.

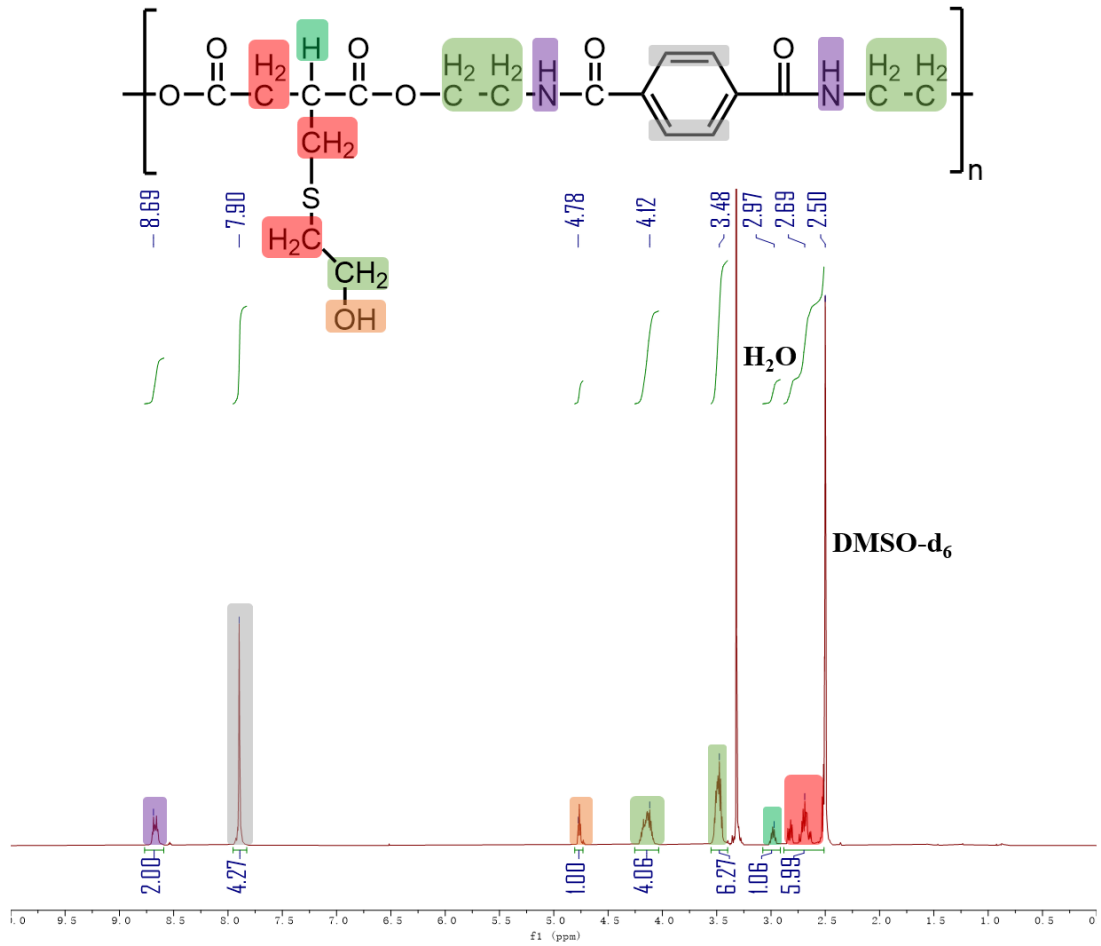



Figure S4. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **2-mercaptoethanol**.

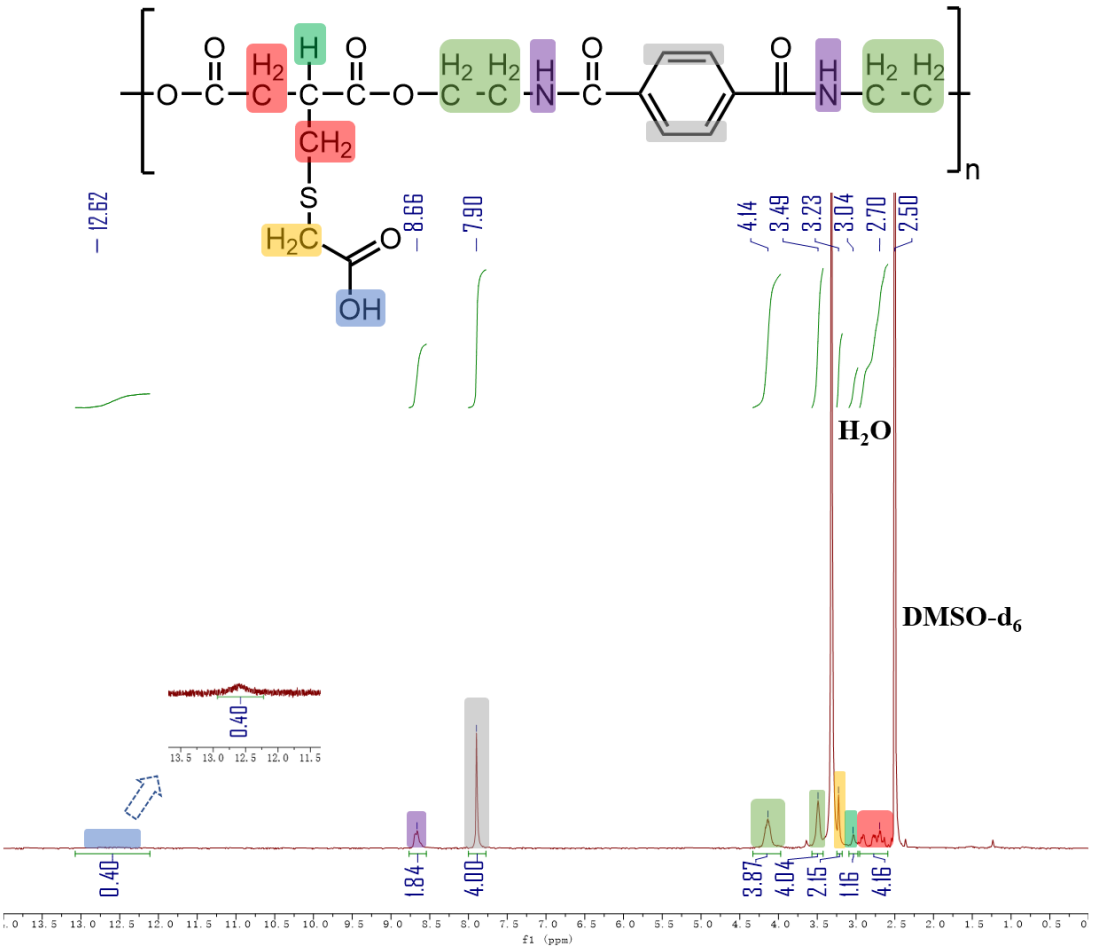



Figure S5. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **thioglycolic acid**.

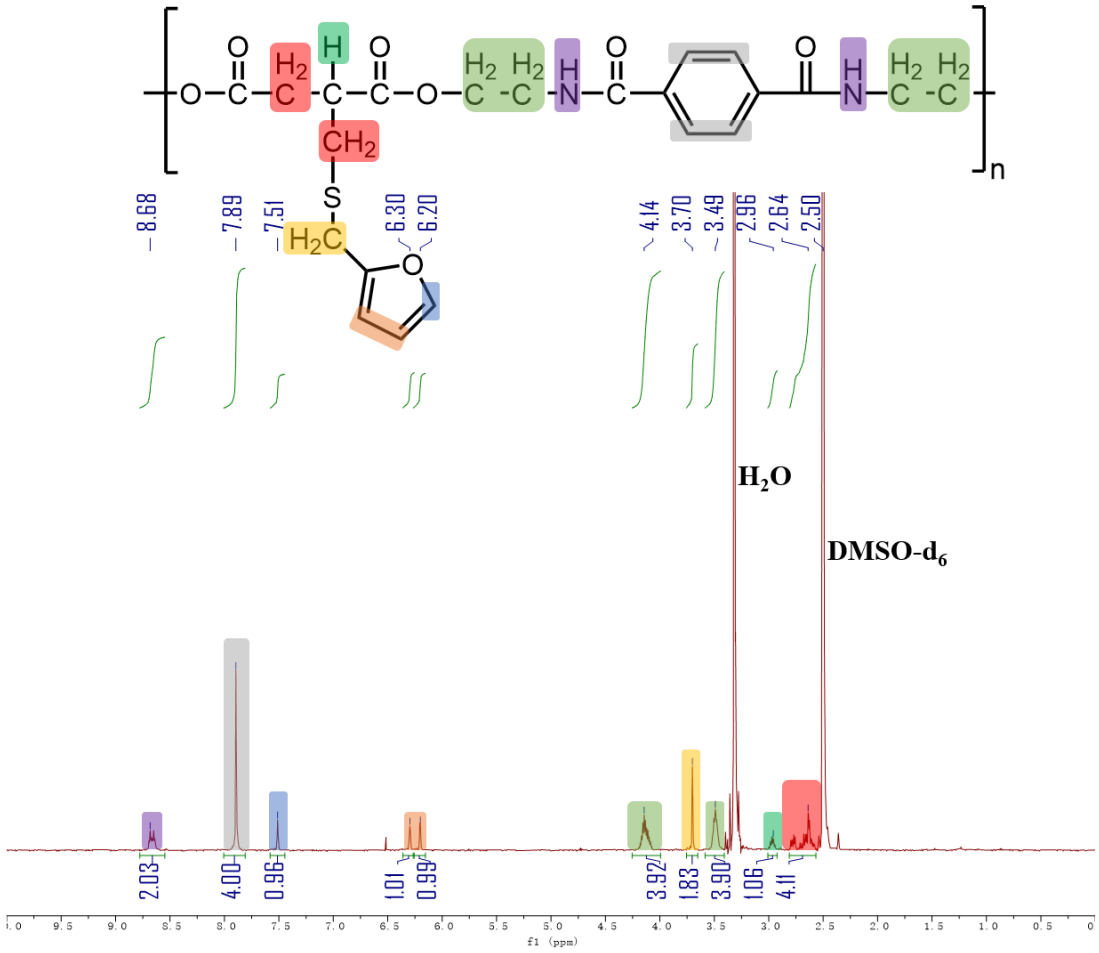



Figure S6. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **furfuryl mercaptan**.

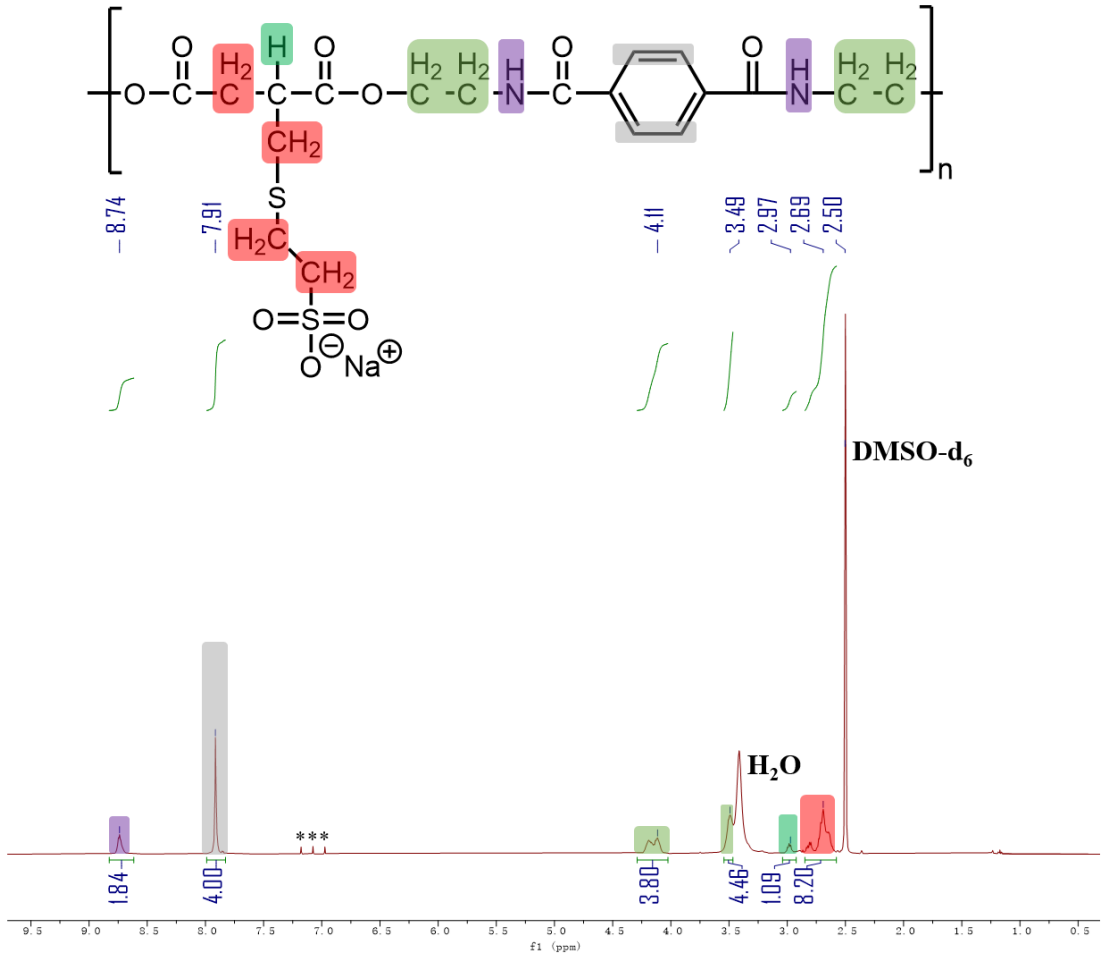



Figure S7. $^{1}$H NMR spectrum (500 MHz, DMSO-$d_6$) of the poly(ester amide) from the thiol−ene "click" of **PA-1** and **sodium-2-mercaptoethanesulfonate**. * These peaks are likely from the $NH_4^+$, since a 0.05% sodium azide solution is used as a preservative solution in the package of dialysis tubing. When N atoms are in a highly symmetric environment, like $NH_4^+$, the $^{14}$N splits the proton signal into a triplet as shown in the spectrum.

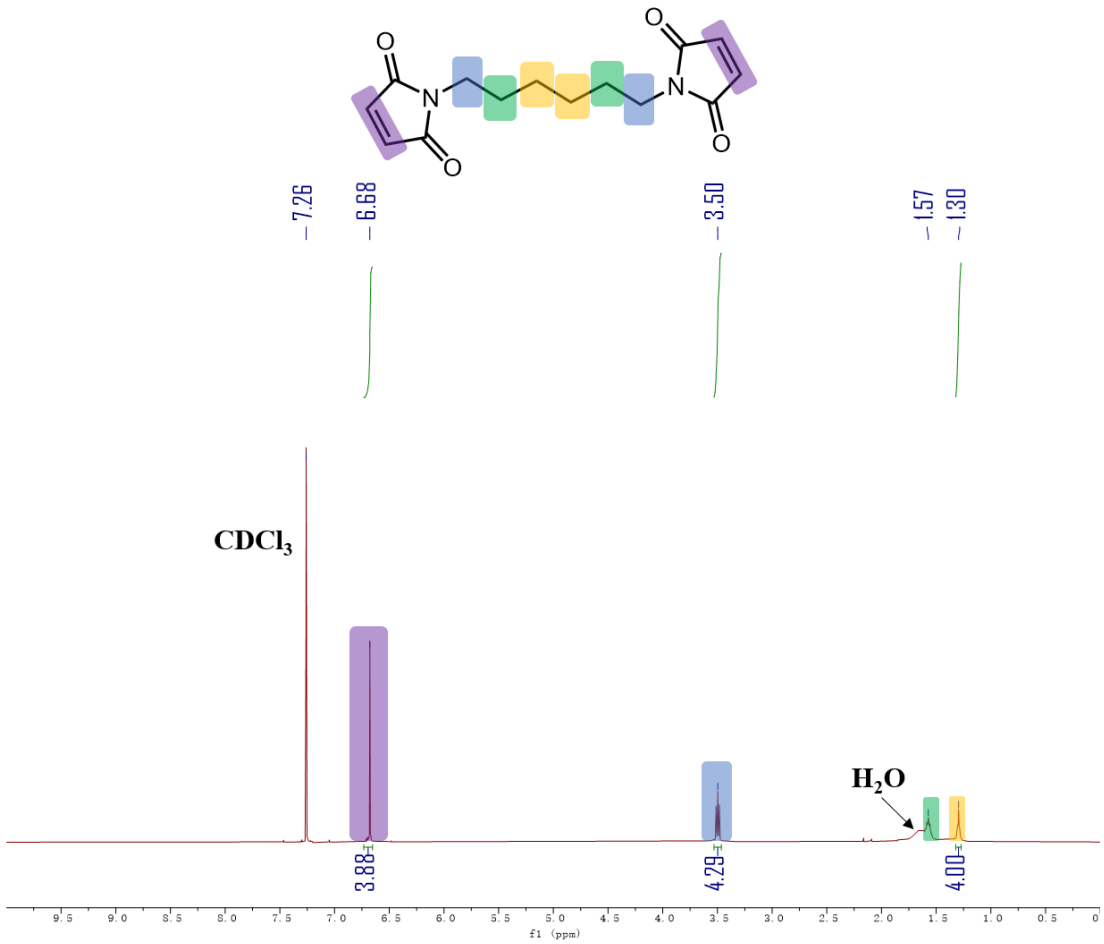



Figure S8. $^{1}$H NMR spectrum (500 MHz, $CDCl_3$) of 1,6-bis(maleimido)hexane (**1,6-BMH**).[4]

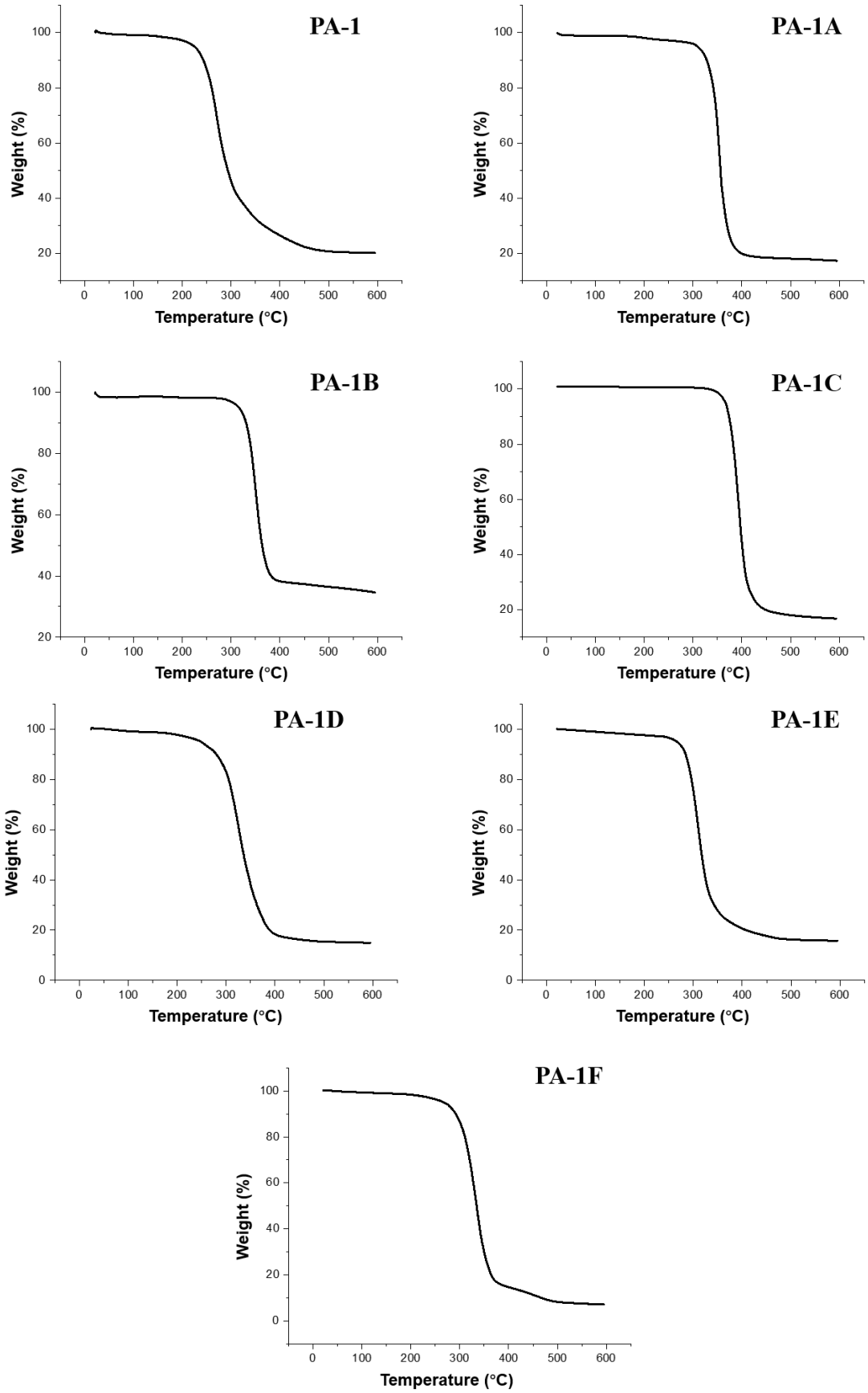
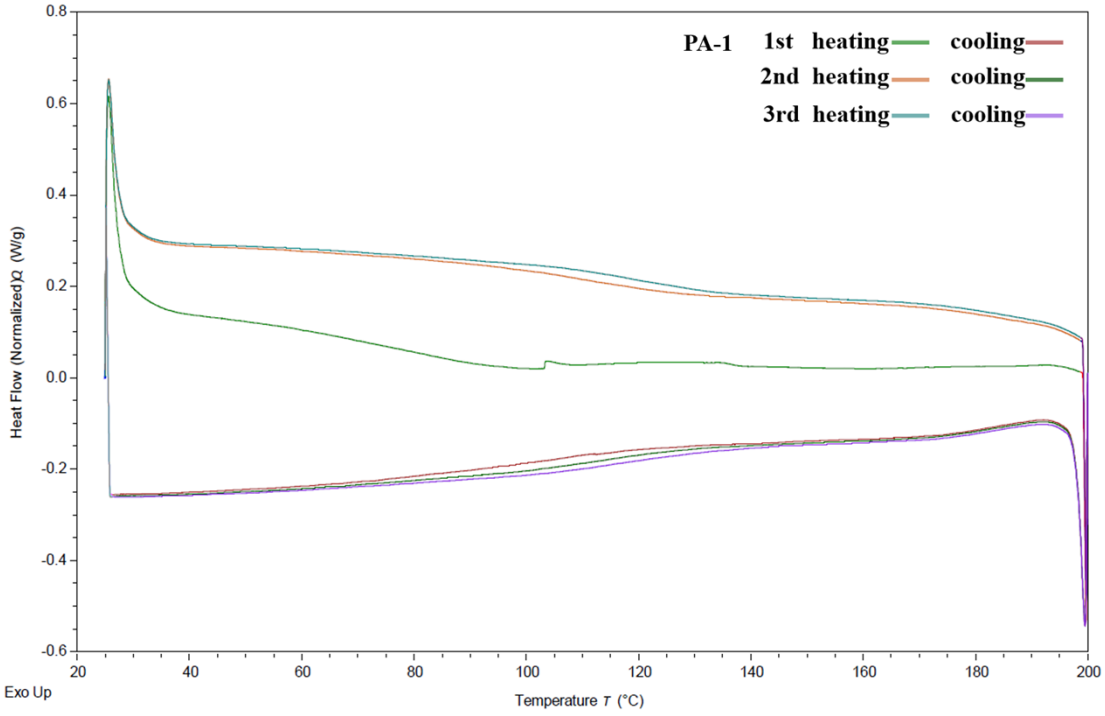
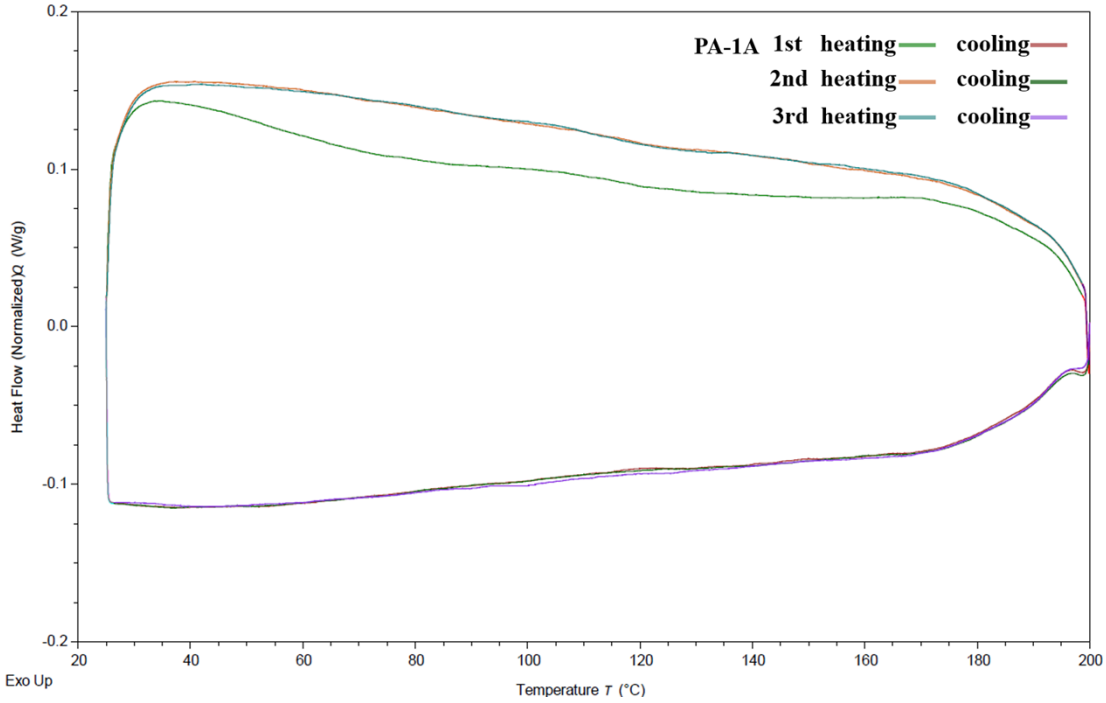
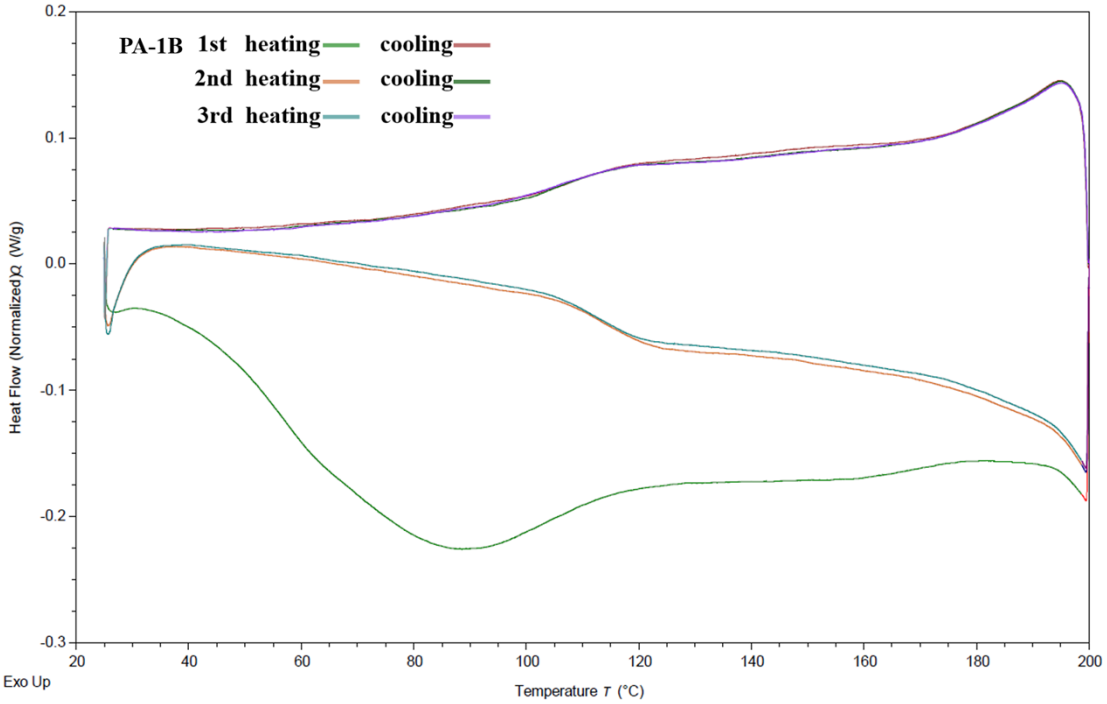
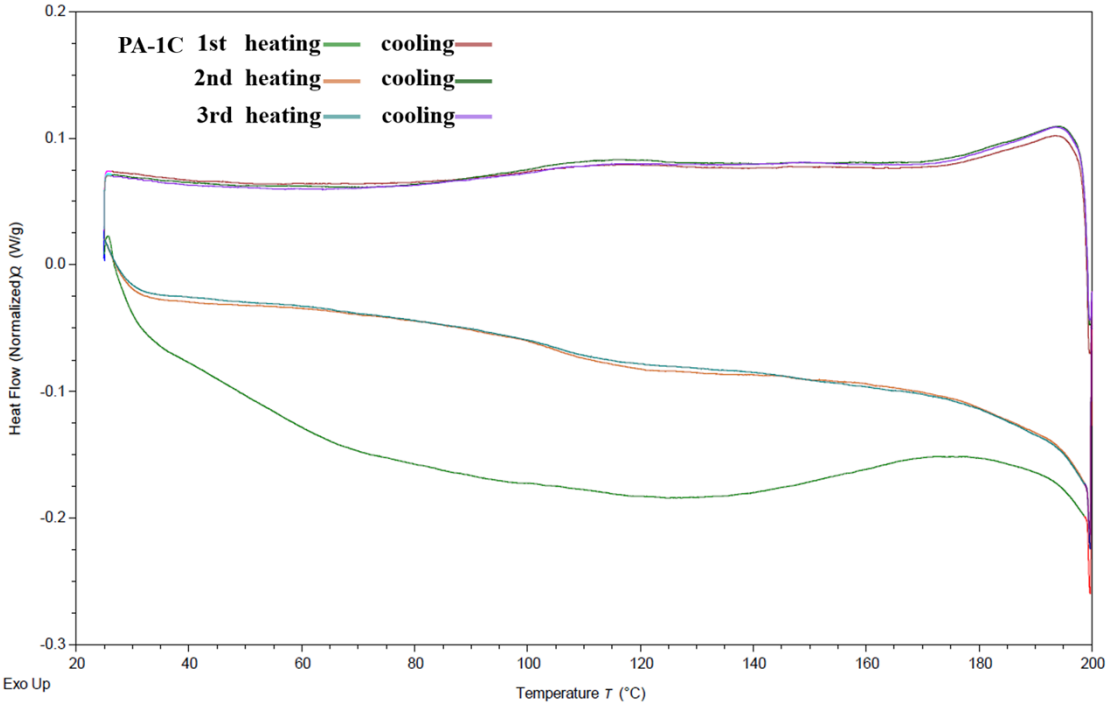


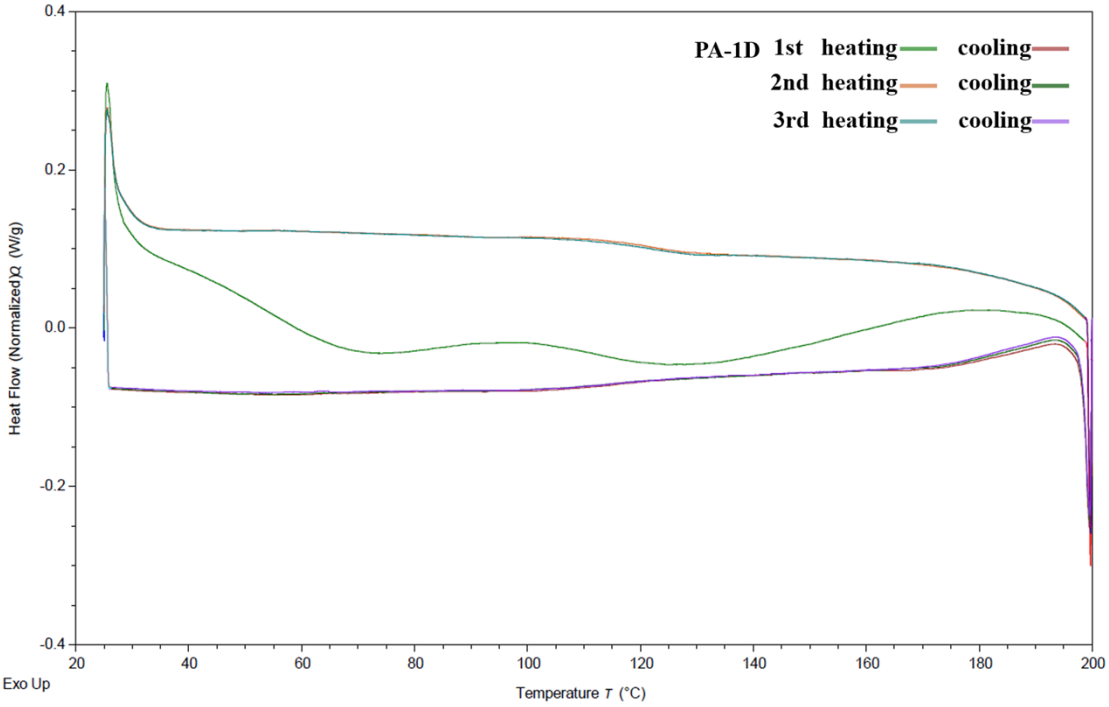

Figure S9. TGA curves of the parent poly(ester amide) (**PA-1**) and poly(ester amide)s bearing pendant thiol groups (**PA-1A** to **PA-1F**) with a heating rate of 10 °C /min under nitrogen.

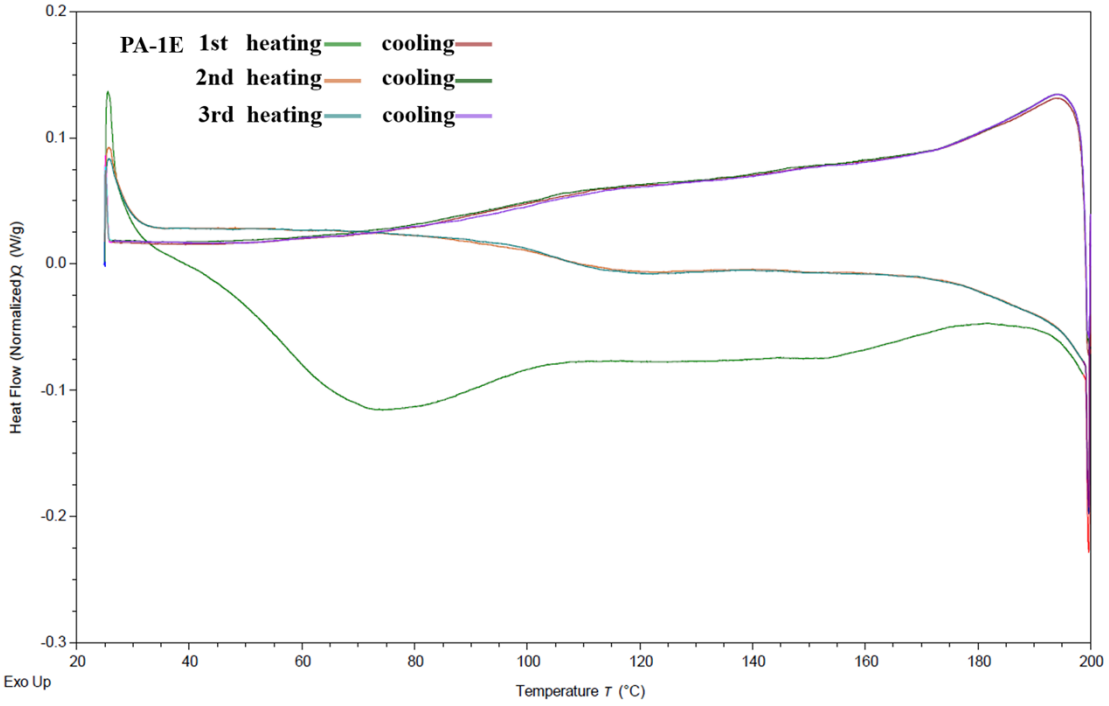

PA-1
1st heating
cooling
2nd heating
cooling
3rd heating
cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)


PA-1A
1st heating
cooling
2nd heating
cooling
3rd heating
cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)


PA-1B 1st heating
cooling
2nd heating
cooling
3rd heating
cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)


PA-1C 1st heating
cooling
2nd heating
cooling
3rd heating
cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)


PA-1D 1st heating cooling
2nd heating cooling
3rd heating cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)
0.4
0.2
0.0
-0.2
-0.4
20
40
60
80
100
120
140
160
180
200


PA-1E 1st heating cooling
2nd heating cooling
3rd heating cooling
Heat Flow (Normalized)Ω (W/g)
Exo Up
Temperature T (°C)
0.2
0.1
0.0
-0.1
-0.2
-0.3
20
40
60
80
100
120
140
160
180
200

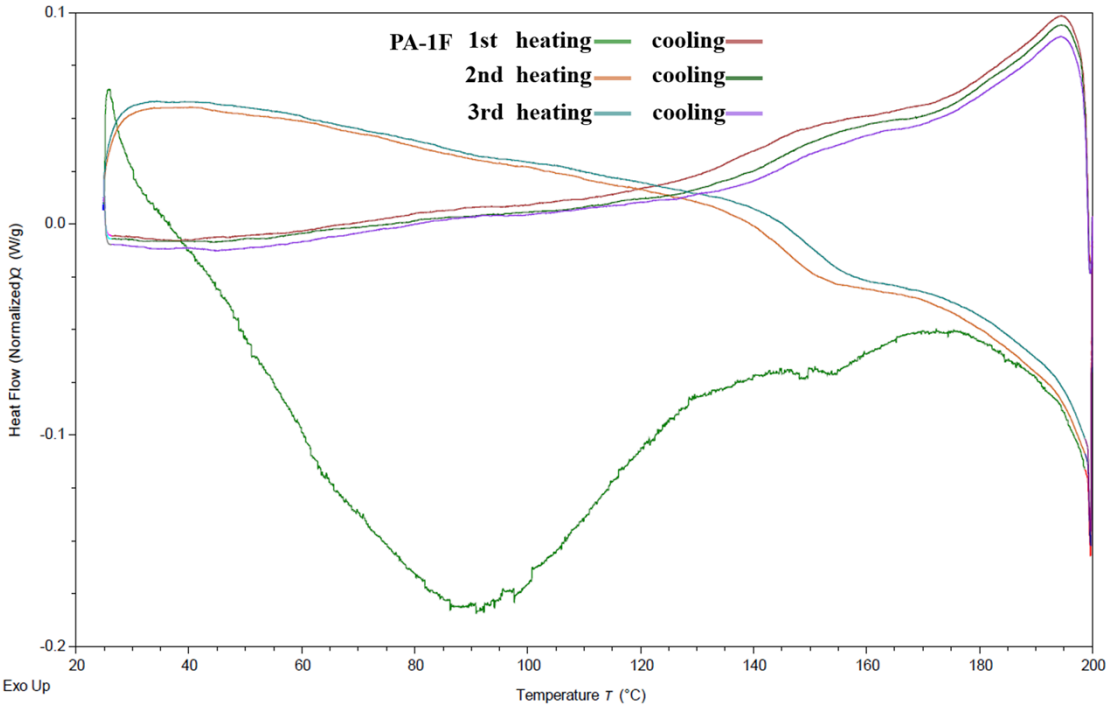
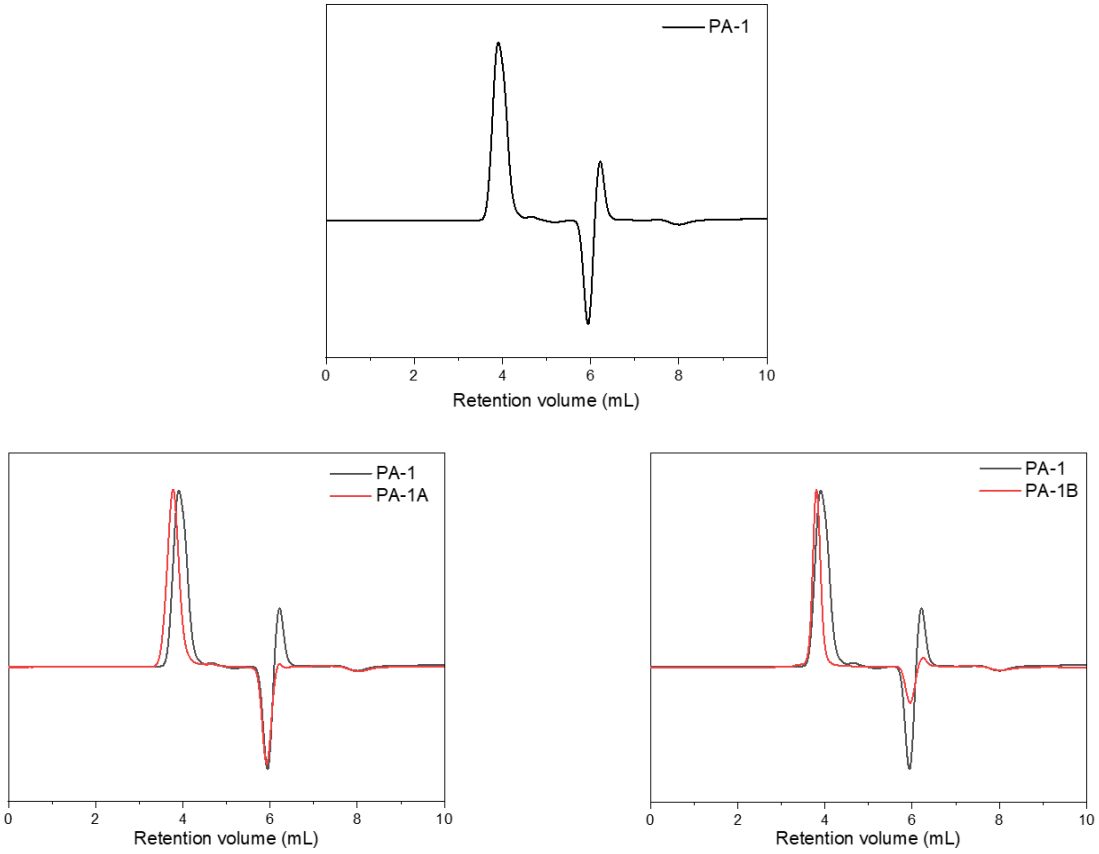



Figure S10. The DSC curves of the parent poly(ester amide) (**PA-1**) and poly(ester amide)s bearing pendant thiol groups (**PA-1A** to **PA-1F**) (heating/cooling rate, 10 °C/min; under nitrogen). All samples were heated through 3 complete heating/cooling cycles.



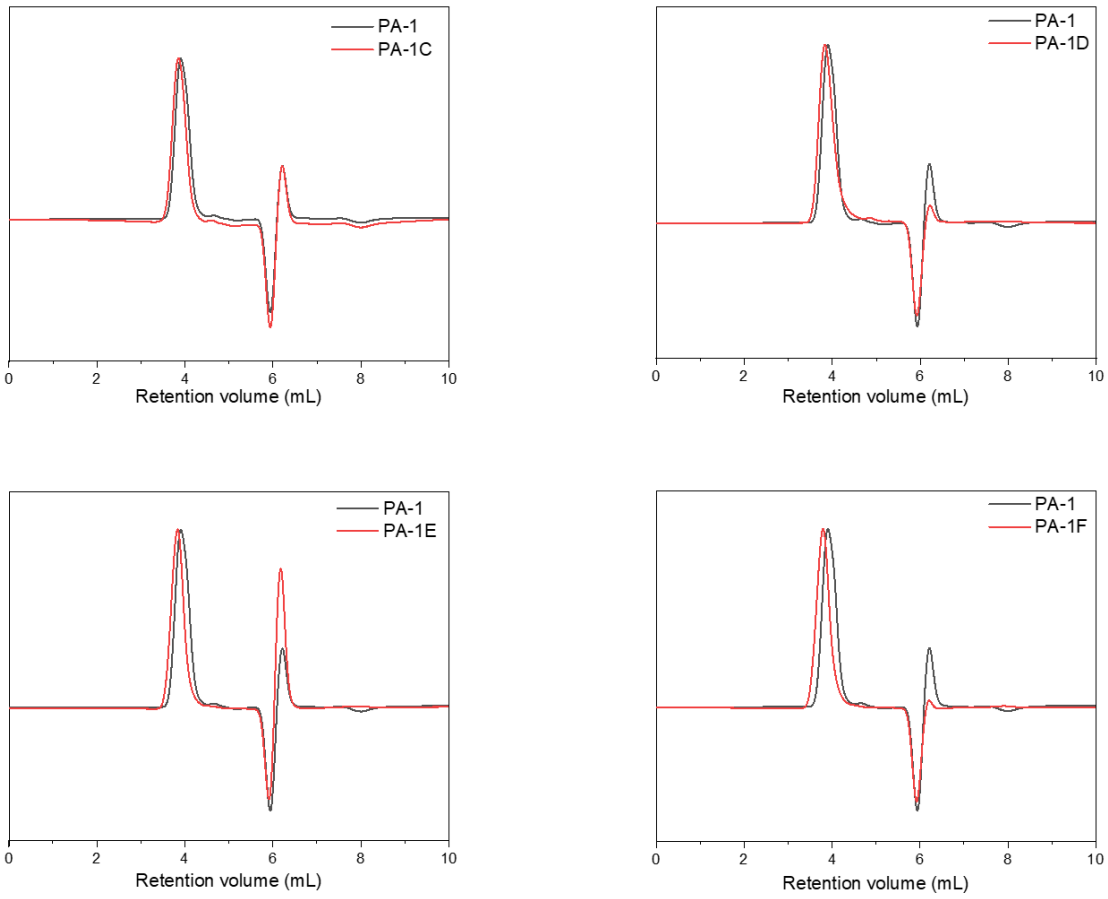



Figure S11. GPC traces of poly(ester amide)s (**PA-1** and **PA-1A** to **PA-1F**) synthesized in this manuscript. All polymers were analyzed in a GPC running HFIP with 3.0 mg/mL $CF_3COOK$.

## References

1. Yang, W.; Wang, J.; Jiao, L.; Song, Y.; Li, C.; Hu, C., Easily recoverable and reusable p-toluenesulfonic acid for faster hydrolysis of waste polyethylene terephthalate. *Green Chem.* **2022,** *24* (3), 1362-1372.

2. Alpers, T.; Muesmann, T. W. T.; Temme, O.; Christoffers, J., Aromatic Esters, Carbinols, and Derivatives Thereof with Perfluorohexyl Residues as Alternatives to Perfluoroalkanecarboxylic and -sulfonic Acids. *Eur. J. Org. Chem.* **2017,** *2017* (3), 609-617.

3. Qu, T.; Rupar, P. A., Carbonyl Aziridines: Strained Amides for Rapid Polyamide Synthesis. *Macromolecules* **2022,** *55* (21), 9513-9519.

4. Canadell, J.; Fischer, H.; De With, G.; van Benthem, R. A. T. M., Stereoisomeric effects in thermo-remendable polymer networks based on Diels–Alder crosslink reactions. *J. Polym. Sci., Part A: Polym. Chem.* **2010,** *48* (15), 3456-3467.