Supporting Information for

Photo-responsive Bio-Inspired Adhesives: Facile Control of Adhesion Strength *via* Photocleavable Crosslinker

Minkyu Kim[a] and Hoyong Chung[a]*

[a]Department of Chemical and Biomedical Engineering, Florida State University, Tallahassee,

Florida 32310, United States

*Corresponding author: Hoyong Chung, hchung@fsu.edu, Tel: (+1) 850-644-1768, Fax: (+1) 850-410-6150

1. Materials and characterizations

Materials. All reagents were purchased from Sigma-Aldrich Co. and Tokyo Chemical Industry America and used without further purification unless otherwise noted. All solvents were degassed with dry nitrogen gas. Mylar (polyester) film was purchased from McMaster-Carr and cleaned prior to use using ethanol and acetone.

Characterization. Nuclear magnetic resonance (NMR) experiments were performed on either a Bruker Avance III 400 MHz or a Bruker Avance III 600 MHz NMR spectrometer. For monitoring ^{1}H NMR spectroscopy of photocleavable cross-linker **5** over UV irradiation time, **5** was dissolved in a 90:10 THF:water (0.01 M, 3.00 mL). Quartz cuvette containing solvents and sample were placed into the center of the photoreactor chamber and irradiated in a Luzchem LCZ-4X photoreactor equipped with 352 nm bulb (14 bulbs x 8 Watt, Hitachi FL8BL-B) for 3h. Aliquots was taken every 30 min and then ^{1}H NMR (400 MHz, DMSO-d_6) spectrum were subsequently recorded. The UV/vis spectra of polymers were recorded using PerkinElmer UV/vis spectrometer (model: Lambda 950). Polymers were firstly dissolved in DI water (6.00 mg/5 mL), added to a quartz cuvette, placed into the center of the photoreactor chamber, and irradiated using the Luzchem photoreactor system described above for different periods of time. Adhesion strength and work of adhesion were characterized by a Shimadzu tensile-compression tester (Model: EZ-LX) equipped with a 200 N force transducer (Interface Ltd. model: SM-200 N-168).

Lap Shear Adhesion Testing. Adhesion strength and work of adhesion were measured by lap shear test. Firstly, adhesives (20.00 mg) were swollen by a DI water (0.02 mL) for a few hours. The solid terpolymer became viscous gel-like material after having been swollen in ultra-pure deionized water as shown in the lower-right image of Fig. 2 and the shape of swollen adhesive was well deformed when the force is given to swollen adhesive. Then, swollen adhesives were applied on 1.25 cm x 0.80 cm rectangle area of 1.25 cm x 8.5 cm sized Mylar film. After that, another Mylar film was overlaid on the adhesive applied part and then overlaid part was pressed using an aluminum block (~130 g) for 10 min. As shown in the Fig. 6a, it was confirmed that swollen adhesive was just right in the square and there was no adhesive to be trimmed off. Then, prepared samples were kept in sealed aluminum foil for 24h. After that, the samples were placed into the Luzchem LCZ-4X photoreactor and UV was irradiated to samples for different periods of time. Then, UV irradiated samples were mounted on a lap shear tensile testing apparatus, pulled to failure using a crosshead speed of 1 mm/min, and then force-displacement curves of samples were obtained. The adhesion strength (kPa) and work of adhesion (J/m^2) were calculated by dividing maximum force (N) by the overlapping contact area of Mylar film (m^2) and dividing total adhesion energy (J, integration of force-displacement curve) by the overlapping contact area of Mylar film (m^2), respectively. The test was repeated five times for each sample with a certain UV exposure time, and the mean adhesion strength and work of adhesion with standard deviation for each sample with a certain UV exposure time was calculated by using obtained five curves.

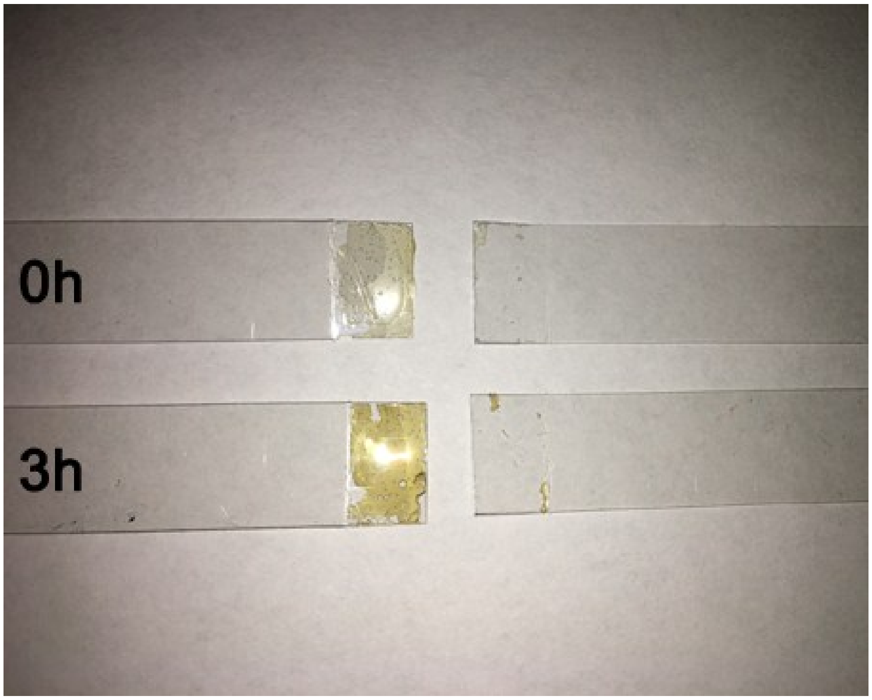


Fig. S1 Photo of terpolymer **8** on Mylar films after lap shear tensile testing: 0 hour UV treatment (top) and 3 hour UV treatment (bottom).

Fig. S1 depicts the photos of terpolymer **8** on Mylar films after lap shear tensile testing (top: 0 hour UV treatment and bottom: 3 hour UV treatment). Both samples show adhesive failure. The residue adhesive was found only one side of strap. This phenomenon implies that adhesive attraction to substrate (Mylar film) was failed primarily without visual trace of cohesive failure (failure within the matrix of polymer adhesives). Although the decreased adhesion strength was 56% (from 341 kPa to 150 kPa) in Fig 6c, it seems that the diminished adhesion strength did not generate failure morphology difference of the used terpolymer, poly(MDOPA-*co*-SBMA-*co*-NBDM) **8**. The work of adhesion also decreased from 144 J/m^2 to 46 J/m^2 (Fig. 6d). The result presents that 56% of adhesion property change does not effect on failure morphology in lap shear strength test.

2. Synthetic procedures

Synthesis of 2-nitro-1,3-benzenedimethanol dimethacrylate (5). Firstly, 2-Nitro-1,3-benzenedicarboxylic acid **2** and 2-nitro-1,3-benzenedimethanol **3** were synthesized sequentially according to a method reported in the literature.[1] The mixed solution of 1,3-dimethyl-2-

nitrobenzene **1** (1.50 g, 9.92 mmol, 1.00 equiv.), sodium hydroxide (0.60 g, 15.00 mmol, 1.51 equiv.), and ultra-purified deionized water (DI water) (75.00 mL) was firstly heated to 105 ºC. Then, $KMnO_4$ (6.00 g, 37.97 mmol, 3.83 equiv.) was slowly added to this mixture over a period of 3 hr. The resulting solution was refluxed for 20 h, cooled to room temperature, and then filtered. Next, the filtrate was acidified with concentrated HCl and white solid precipitate **2** was filtered, collected, and dried under vacuum, yielding a dry white solid powder **2** (1.51 g, 72 %). ^1H NMR (400 MHz, DMSO-d_6, δ ppm): 3.36 (s (broad, H_2O + COOH), 7.80 (t, 1H, *J* = 8 Hz), and 8.16 (d, 2H, *J* = 8 Hz).

Then, **2** (1.50 g, 7.10 mmol, 1.00 equiv.) was added to 9.38 mL anhydrous THF solvent and the solution was cooled down to 0 ºC with dry N_2 gas bubbling. To this solution, BH_3•THF (1.00 M in THF. 0.52 g, 37.60 mmol, 5.30 equiv., 37.50 mL) was added slowly over 10 min. The resulting solution was stirred at room temperature for 48 h in the dark. After the reaction, methanol (7.50 mL) was added to the solution followed by vacuum filtration to remove solid particles. From the obtained solution, solvents were removed by using a rotary evaporator. Then, ethyl acetate was poured into residue and the solution was washed with DI water (3×18.75 mL). The resulting organic layer was dried over anhydrous $MgSO_4$ and the solvent was removed under vacuum by using a rotary evaporator. The resulting crude product was further purified by silica gel column chromatography (hexane:ethyl acetate=1:1, TLC $R_f = 0.40$) to obtain white solid **3** (1.15 g, 88 % yield). ^1H NMR (400 MHz, DMSO-d_6, δ ppm): 4.53 (d, 4H, *J* = 5.6 Hz), 5.50 (t, 2H, *J* = 5.6 Hz), and 7.52-7.60 (m, 3H).

Then, EDC•HCl (3.45 g, 18.00 mmol, 3.30 equiv.), DMAP (0.50 g, 4.10 mmol, 0.75 equiv.), **3** (1.00 g, 5.46 mmol, 1.0 equiv.), and methacrylic acid **4** (1.02 mL, 1.03 g, 12.00 mmol, 2.20 equiv.) were dissolved in DCM (950 mL) and the reaction mixture was stirred for 20 h at room temperature in the dark. Methacrylic acid was passed through basic alumina-packed glass columns to remove inhibitors before use. After the reaction, the solvent was removed under reduced pressure and crude product was purified by silica gel column chromatography (1% MeOH:DCM, TLC R_f = 0.75) to obtain light yellow solid **5** (1.30 g, 74 % yield). ^{1}H NMR (600 MHz, DMSO-d_6, δ ppm): 1.85 (t, 6H, *J* = 1.2 Hz), 5.28 (s, 4H), 5.73 (t, 2H, *J* = 1.8), 6.00 (t, 2H, *J* = 1.2), and 7.69 (s, 3H). ^{13}C NMR (150 MHz, DMSO-d_6, δ ppm): 17.79, 62.33, 126.71, 129.07, 130.66, 131.71, 135.12, 148.16, and 165.83. HRMS (ESI): calcd. for $C_{16}H_{17}N_1Na_1O_6$ $[M+Na]^+$ 342.09536, found 342.09517.

Synthesis of *N*-Methacryloyl 3,4-dihydroxyl-L-phenylalanine (6). First, L-DOPA **11** (3.42 g, 17.34 mmol, 1.00 equiv.) was added to a solution containing degassed DI water (175.00 mL) and $Na_2B_4O_7 \cdot 10H_2O$ (6.62 g, 17.36 mmol, 1.00 equiv.). Then, the pH of the solution was adjusted to 9−10 by adding Na_2CO_3 (3.68 g) to the solution, and the mixture was degassed for another 5 min with dry nitrogen gas under vigorous stirring conditions. After that, the solution was cooled down to 0 °C, and 2.21 mL (2.36 g, 22.58 mmol, 1.30 equiv.) of methacryloyl chloride **12** was added to the mixture in a dropwise fashion, and again the pH of the solution was adjusted to 9−10 by adding Na_2CO_3 (1.84 g). Then, reaction mixture was degassed for 10 min with dry nitrogen gas under vigorous stirring conditions while kept in ice bath, then allowed to warm to room temperature, and stirred for 3 h at room temperature. After the reaction, the solution was acidified with concentrated HCl (~10 mL) until a pH of ~2.0 and then extracted with ethyl acetate (4 x 50.00 mL). The combined organic layers were washed with 0.1 M HCl (2 x 50 mL) and with brine (2 x 50 mL). The resulting organic layer was dried over anhydrous $MgSO_4$ and the solvent was removed under vacuum. The brown color crude product was purified by silica gel column chromatography (5% MeOH: $CHCl_3$, TLC R_f = 0.30) to obtain brown, sticky, viscous liquid **6** (3.51 g, 76 % yield). ^{1}H

NMR (600 MHz, D_2O, δ ppm): 1.80 (s, 3H), 2.90 (dd, 1H, J_1 = 9.0 Hz, J_2 = 13.8 Hz), 3.13 (dd, 1H, J_1 = 5.4 Hz, J_2 = 14.4 Hz), 4.60 (dd, 1H, J_1 = 5.4 Hz, J_2 = 8.4 Hz), 5.37 (s, 1H), 5.52 (s, 1H), and 6.66-6.81 (m, 3H).

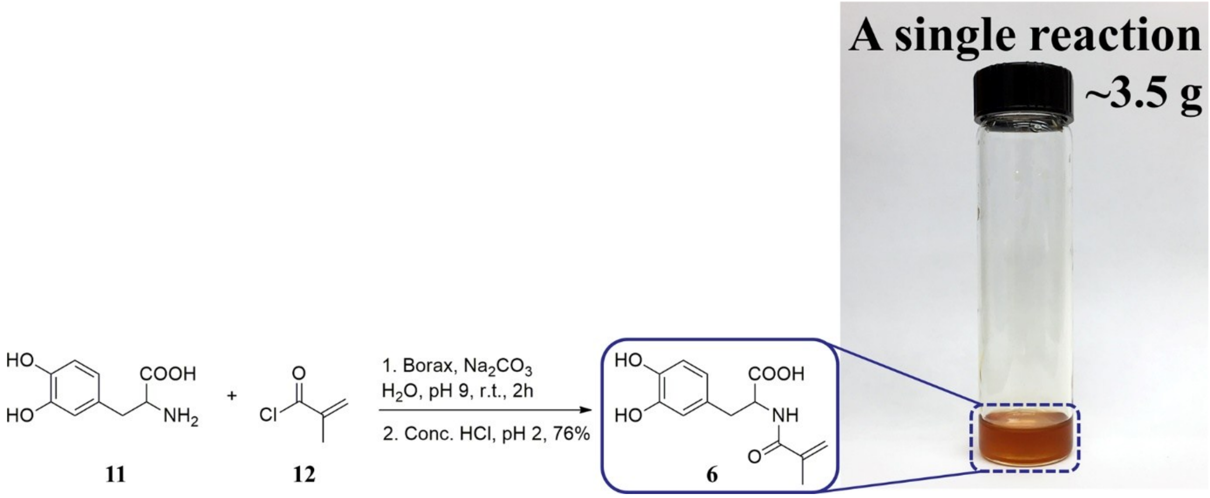


Fig. S2 Synthetic scheme and photograph of MDOPA **6**.

Fig. S2 illustrates the synthetic scheme and photograph of polymerizable DOPA monomer MDOPA **6**. This one-pot synthetic procedure (detailed synthetic procedure is described in materials and methods section) is simple and efficient, and can be scaled easily to multi-gram quantities (~3.5 g).

Synthesis of Poly(MDOPA-*co*-SBMA-*co*-NBDM) (8) Firstly, 1,4 dioxane/DI water co-solvent (15.00 mL; the volume ratio of 1,4 dioxane: DI water = 1:1) was round-bottom flask containing **6** (0.19 g, 0.72 mmol, 0.15 equiv.), **7** (1.13 g, 4.10 mmol, 0.85 equiv.), **5** (0.08 g, 0.25 mmol, 0.05 equiv.), and AIBN (0.02 g, 0.12 mmol, 0.03 equiv.). The solution was then degassed with dry nitrogen gas for 20 min. Then, the solution was stirred for 16h at 65 °C in the dark, yielding a terpolymer **8**. After polymerization process, **8** was dialysed in DI water for 24h using a Spectra/Por dialysis membrane tube (molecular weight cutoff: 1kDa). After the dialysis, the polymer solution was lyophilized and dry powder **8** (1.10 g, 77 %) was obtained. The structure of **8** was verified by ^1H NMR (600 MHz, D_2O) spectroscopy as shown in Fig. 3b. The synthetic procedure of the poly(MDOPA-*co*-SBMA) **9** was identical to that of the **8** except incorporation of the photocleavable cross-linker **5**. The structure of **9** was also verified by ^{1}H NMR (600 MHz, D_2O) spectroscopy as shown in Fig. 3b.

3. Calculation of conversion of 5 to 10 and 4 over UV irradiation time

The conversion of **5** to **10** and **4** over UV irradiation time was calculated by using equation (S2). At time 0 s, the initial molecular number of **5** can be set as $\mathbf{N_{5,\,int}}$ and molecular number of **10** and **4** are 0, respectively. When $\mathbf{N_{cnv}}$ molecules are converted from **5** to **10** and **4** at UV irradiation time *t* (s), the molecular number of **5, 10,** and **4** are ($\mathbf{N_{5,\,int}}$-$\mathbf{N_{cnv,\,\mathit{t}}}$), $\mathbf{N_{cnv,\,\mathit{t}}}$, and $\mathbf{N_{cnv,\,\mathit{t}}}$ at *t* (s), respectively. Then, integration ratio between a characteristic signal at **c** ($I_{Hc,\,t}$) and a characteristic signal at a′ ($I_{Ha',\,t}$) at *t* (s) in the ^{1}H NMR spectrum (Fig. 4b) can be expressed as equation (**S1**).

$$I_{Hc,\,t}\colon I_{Ha',\,t} = \{2(N_{5,\,int} - N_{cnv,t}) + N_{cnv,t}\} : N_{4,\,t} = (2N_{5,int} - N_{cnv,t})\colon N_{cnv,t} \qquad \textbf{(S1)}$$

The conversion of **5** into **4** at *t* (s) (converion$_t$) is given as equation (**S2**) by using equation (**S1**). Finally, conversion$_t$ for each irradiation time was calculated by substituting the measured integration $I_{Hc,\,t}$ and $I_{Ha',\,t}$ into equation (**S2**) and the conversion at *t* = 0, 0.5, 1, 1.5, 2, 2.5, and 3 h were calculated as 0.00, 0.37, 0.55, 0.68, 0.80, 0.90, and 1.00, respectively.

$$Conversion_t = \frac{N_{cnv,\,t}}{N_{5,\,int}} = \frac{2I_{Ha',t}}{I_{Hc,t} + I_{Ha',t}}$$

(S2)

4. Spectral data

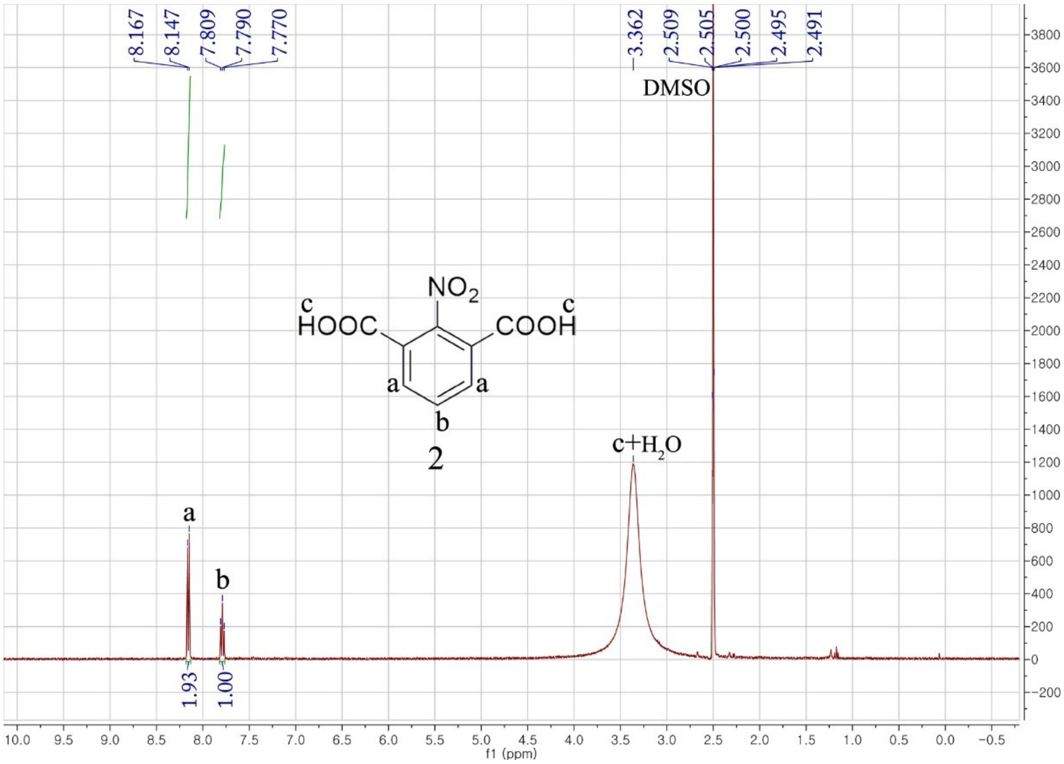


Fig. S3 ^{1}H NMR spectrum of compound **2**.

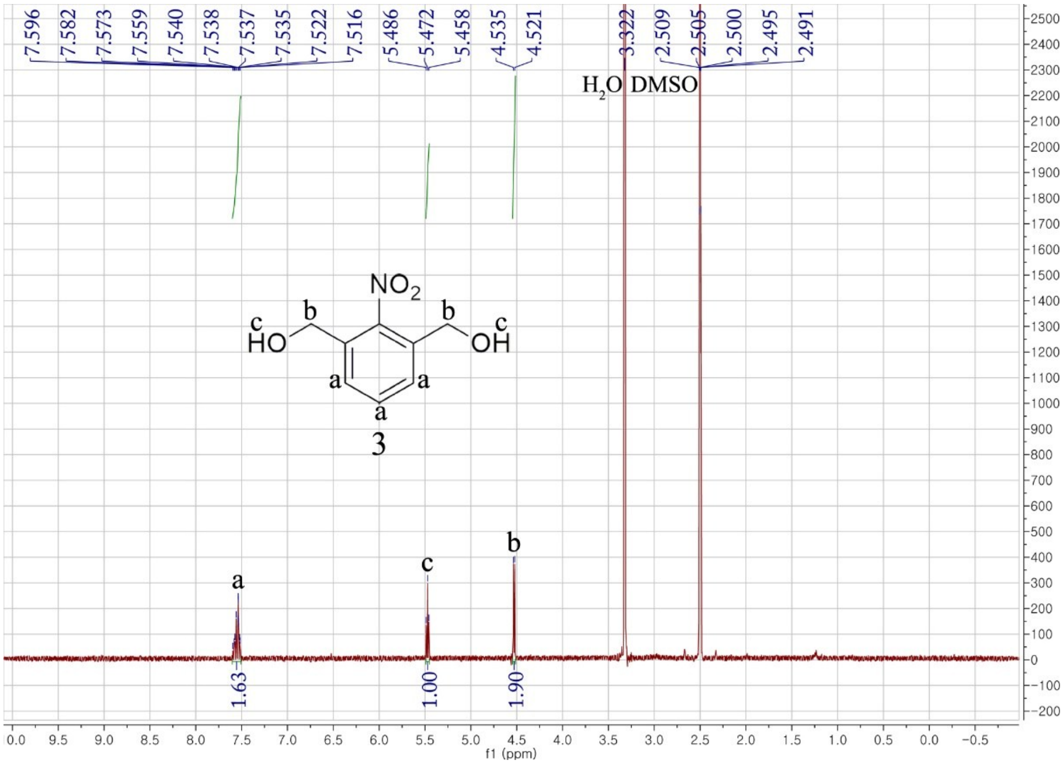


Fig. S4 ^{1}H NMR spectrum of compound **3**.

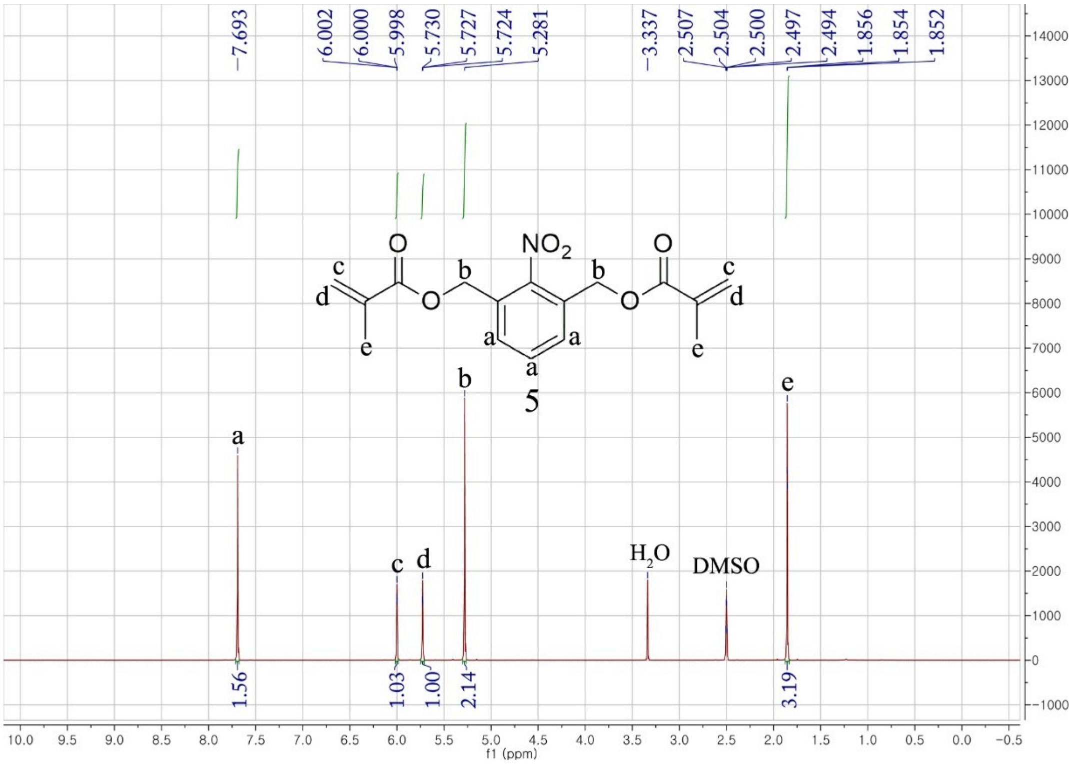


Fig. S5 ^{1}H NMR spectrum of compound **5**.

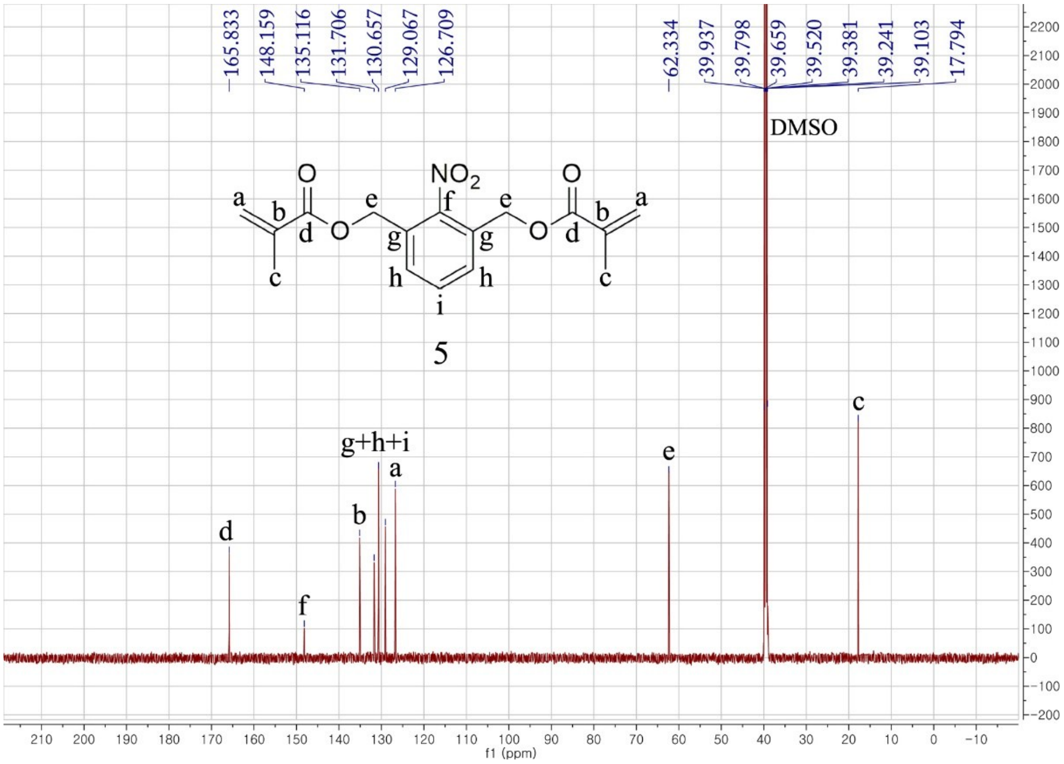


Fig. S6 ^{13}C NMR spectrum of compound **5**.

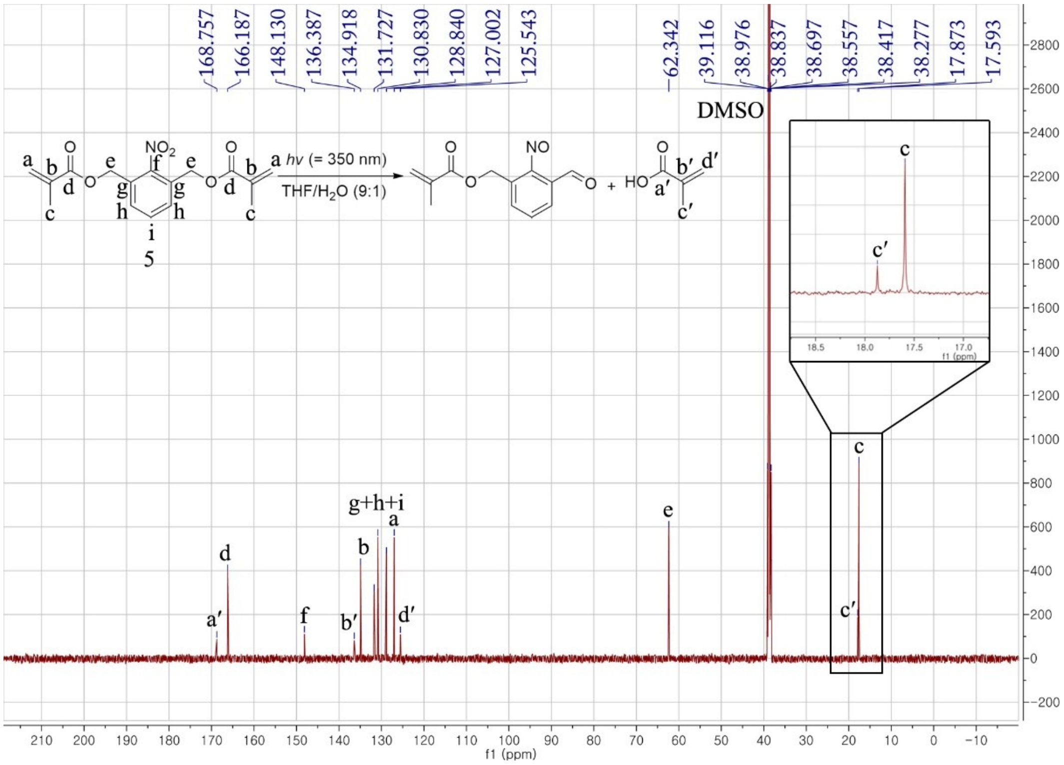
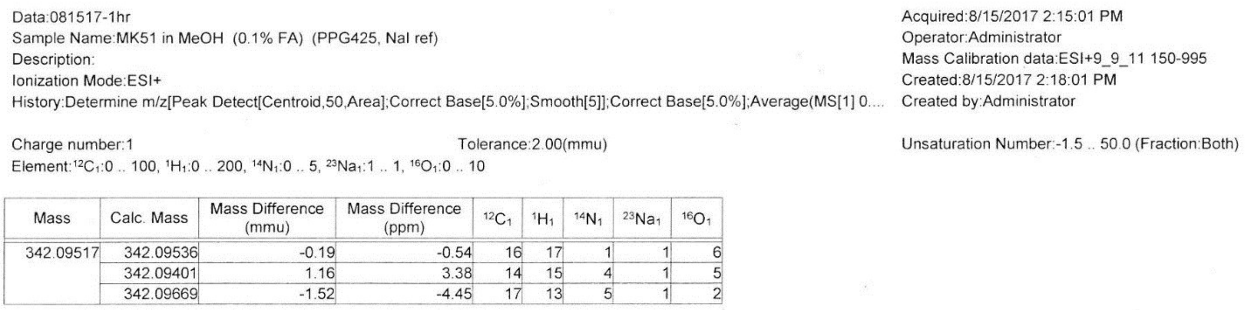


Fig. S7 ^{13}C NMR spectrum of photo-irradiated compound **5** (4 hour UV treatment). The spectrum does not show resonances from aldehyde presumably due to a secondary photoinduced dimerization during the extended photo-irradiation time.[2-5]



Data:081517-1hr
Sample Name:MK51 in MeOH (0.1% FA) (PPG425, NaI ref)
Description:
Ionization Mode:ESI+
History:Determine m/z[Peak Detect[Centroid,50,Area];Correct Base[5.0%];Smooth[5]];Correct Base[5.0%];Average(MS[1] 0....

Acquired:8/15/2017 2:15:01 PM
Operator:Administrator
Mass Calibration data:ESI+9_9_11 150-995
Created:8/15/2017 2:18:01 PM
Created by:Administrator

Charge number:1
Tolerance:2.00(mmu)
Unsaturation Number:-1.5 .. 50.0 (Fraction:Both)
Element:$^{12}C_1$:0 .. 100, $^{1}H_1$:0 .. 200, $^{14}N_1$:0 .. 5, $^{23}Na_1$:1 .. 1, $^{16}O_1$:0 .. 10

Mass	Calc. Mass	Mass Difference (mmu)	Mass Difference (ppm)	$^{12}C_1$	$^{1}H_1$	$^{14}N_1$	$^{23}Na_1$	$^{16}O_1$
342.09517	342.09536	-0.19	-0.54	16	17	1	1	6
	342.09401	1.16	3.38	14	15	4	1	5
	342.09669	-1.52	-4.45	17	13	5	1	2

Acq. Data Name: 081517-1lr
Internal Sample Id: MK51 in MeOH (0.1% FA)
Ionization Mode: ESI+
MS Calibration Name: ESI+9_9_11 150-995
Creation Parameters: Average(MS[1] Time:0.412..1.017)

Orifice1 Volt Sweep: 89.9853444064485V
Acquired m/z Range: 200.0..900.0

Experiment Date/Time: 8/15/2017 2:01:56 PM
Spec. Record Interval: 1.0[s]
Ring Lens Volt: 13[V]

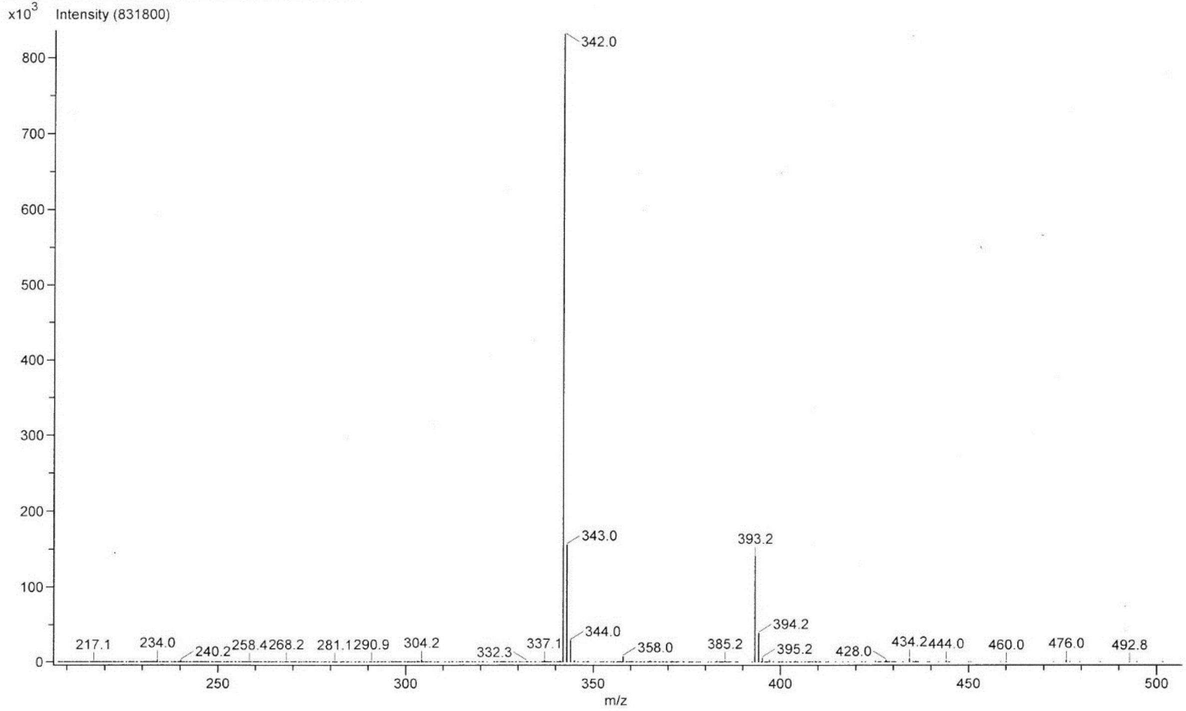


Fig. S8 High resolution mass spectrum of compound **5**.

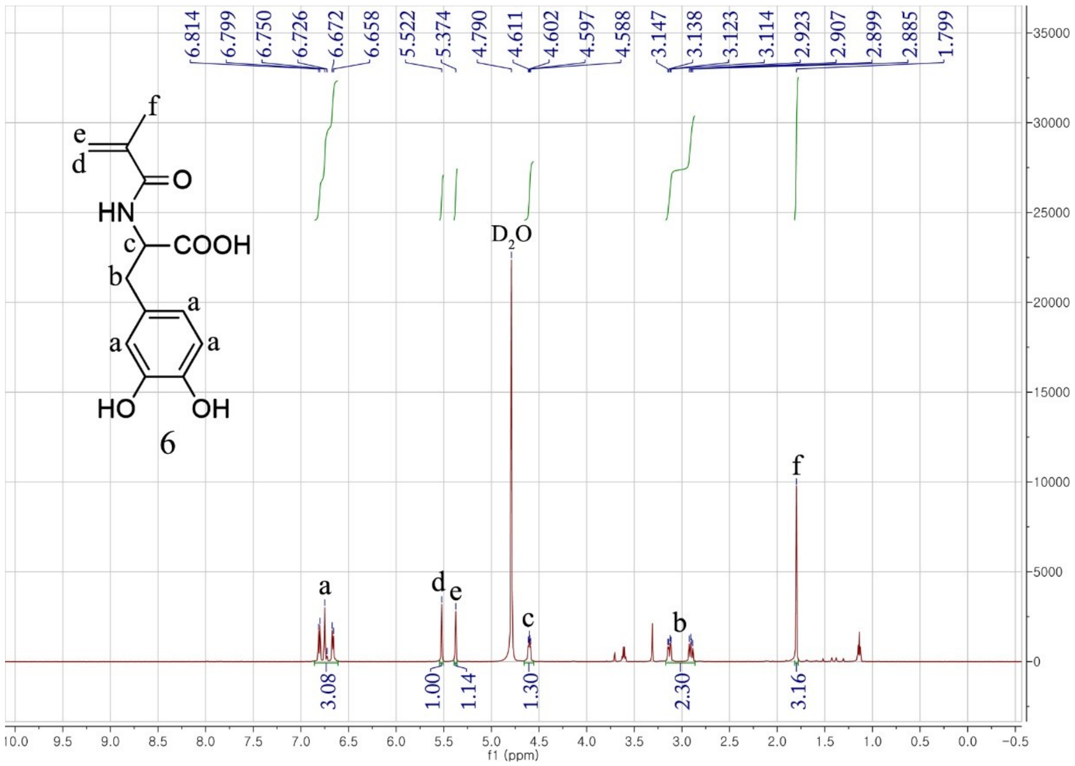


Fig. S9 ^{1}H NMR spectrum of compound **6**.

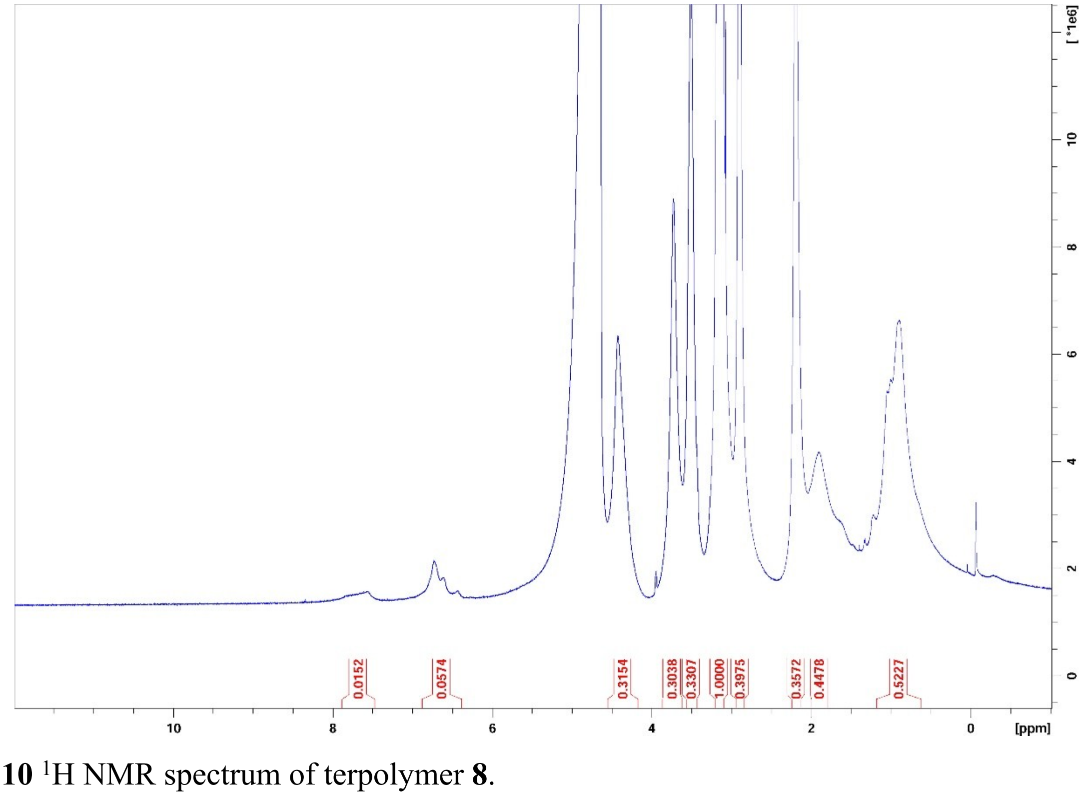


Fig. S10 ^{1}H NMR spectrum of terpolymer **8**.

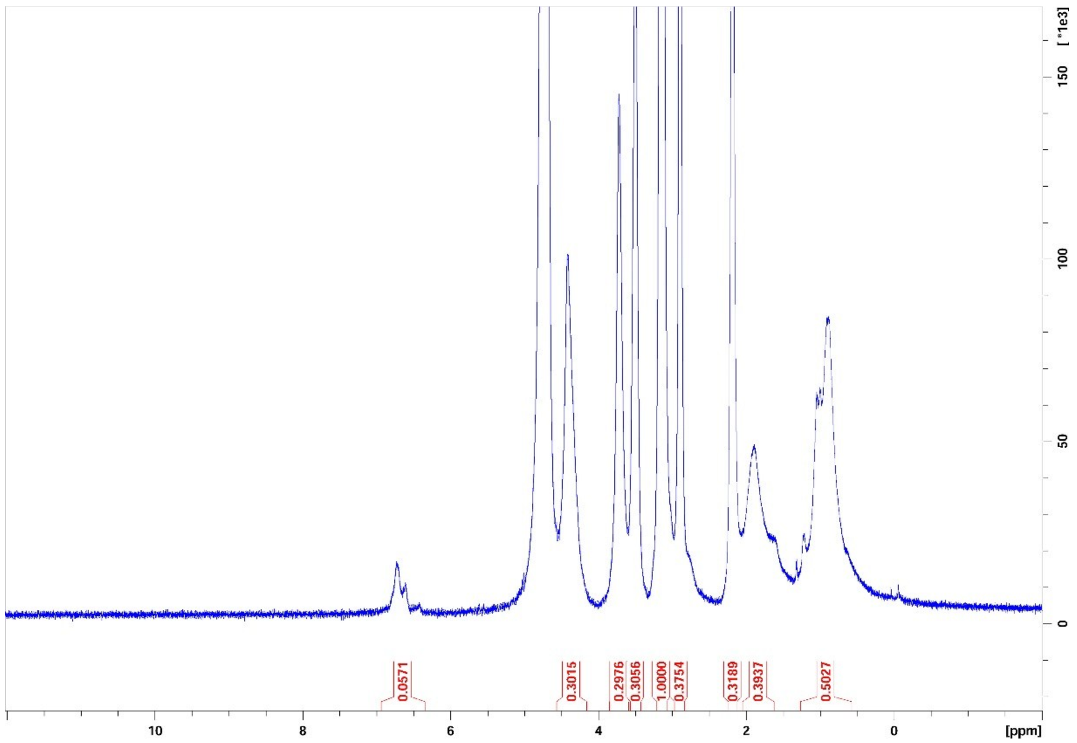


Fig. S11 ^{1}H NMR spectrum of bipolymer **9**.

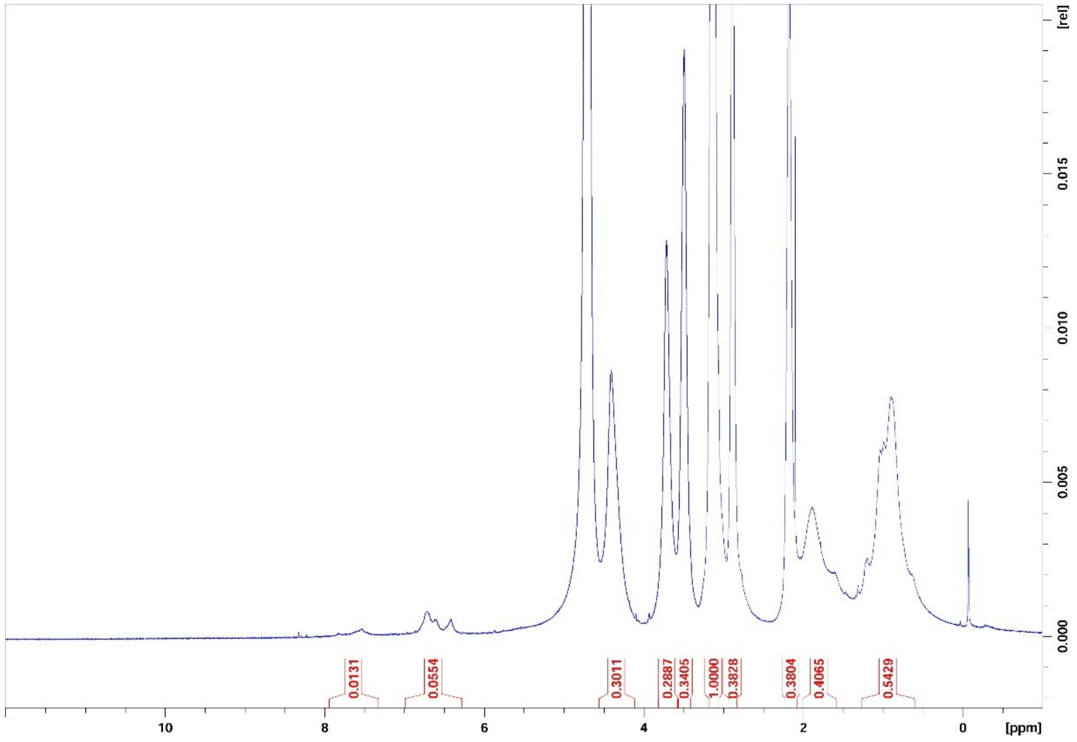


Fig. S12 ^{1}H NMR spectrum of terpolymer **8** obtained after 3 hours of UV irradiation.

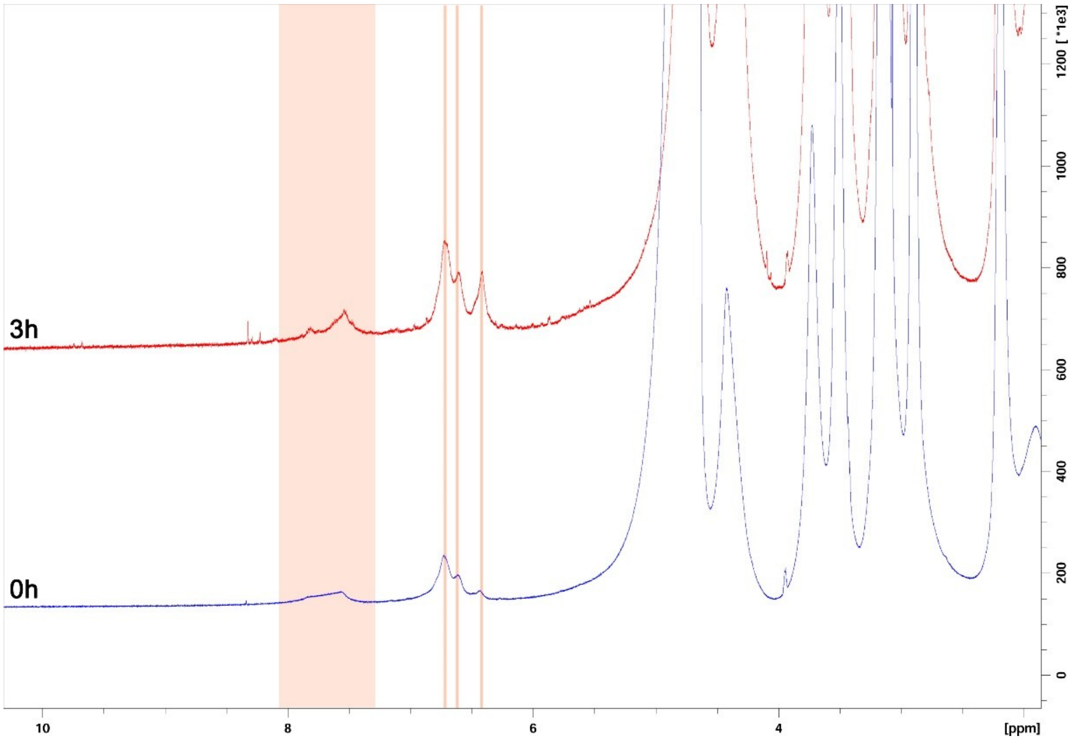


Fig. S13 ^{1}H NMR spectrum of terpolymer **8** without UV irradiation (blue) and obtained after 3 hours of UV irradiation (red).

5. References

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