Electronic Supplementary Information (ESI)

Chirality control of self-assembled achiral nanofibers using amines in their solid state

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Detailed Experimental :

Characterization. Using a Shimadzu Fourier transform infrared 8400S instrument, the IR spectra of samples from KBr pellets were observed over the range of 400 – 4000 cm^{-1}. In addition, the ^{1}H and ^{13}C NMR spectra were taken on a Bruker DRX 300, and mass spectroscopy samples were analyzed on a JEOL JMS-700 mass spectrometer. The elemental analysis was performed with a Perkin Elmer 2400 series II instrument.

Preparation of the Nanofiber Gels. A solution of 100 μL of amines (**2R**, **2S**, **3**, **4D**, **4L**, **5D**, **5L**, **6D**, **6L**, **7R**, and **7S**, 0-3.0 equiv.) in water was added into a vial containing 300 μL of a solution of gelator **1** (2.0 wt.% in DMSO) during a typical gelation experiment. Heating of the mixtures was then carried out at 60–70 °C, and the samples were sonicated in a bath sonicator for 3 minutes in order to obtain a homogenous solution. This solution was then cooled to ambient temperature gradually to afford the nanofiber gel.

Preparation of Electrospun Film. Homogeneous solutions were employed for electrospinning and were prepared by dissolving PMMA (Mw: 996,000 g mol^{-1}) with gelator **1** in DMSO for 3 hours under stirring conditions at room temperature using a 2.0 wt.% concentration of gelator **1** and 4.0 wt.% of PMMA with respect to gelator **1**. Next, homogeneous gelator **1** and PMMA solutions were loaded into a 10 mL plastic syringe housed with a metal needle (size 25 GA). The syringe was fixed horizontally within a syringe pump (KDS 200, KD Scientific, USA), and after the electrode of a high voltage power supply (Nano NC, Korea) was connected to the metal needle tip, the working distance between the needle tip and the ground electrode was set to 15 cm. The solution flow rate was then set to 20 μL/min and at the same time the electrospinning voltage was set to 17 kV. In these experiments, the temperature and relative humidity were maintained at 25 °C and 50 %, respectively.

Electrospun Film Inversion Experiments. After preparation of the electrospun films, they were submerged in solutions containing 0.1M of **2R** or **2S** and allowed to incubated at 25 °C for 1 minute followed by recording of the CD signal. The films were then placed in 0.1M HCl for 1 minute after which the CD signal arising from the films was again recorded. This process was repeated five time for both the case of **2R** and **2S** exposure to show the reversible nature of the helical transformation in the solid state films.

Microscopy Studies. The SEM images were taken with a field emission scanning electron microscope (FE-SEM, Philips XL30 S FEG) using an acceleration voltage of 10–15 kV and an emission current of 10 μA.

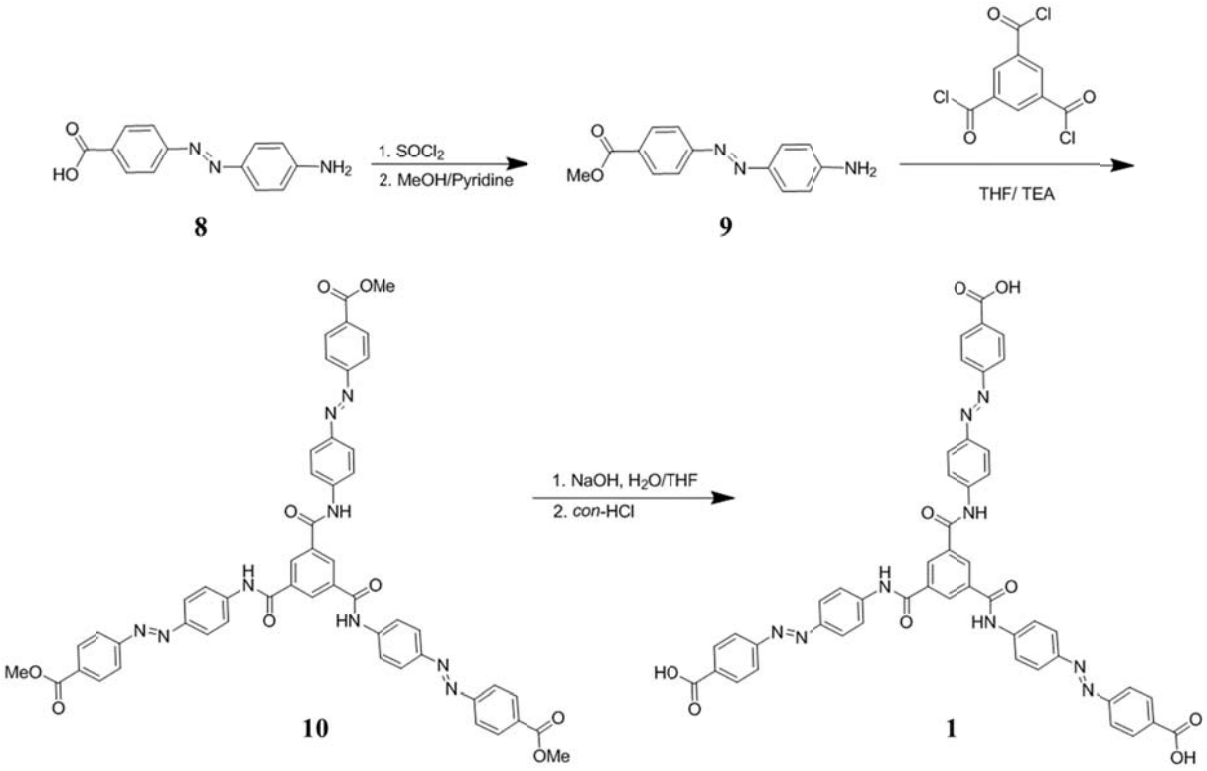
Photophysical and Circular Dichroism Studies. A UV-vis spectrophotometer (Thermo Evolution 600) was used to obtain the absorption spectra of the samples over the range of 200-800 nm. The spectra were acquired for both the gel directly at room temperature and also dispersed in 3:1 DMSO/H_2O. The UV-vis absorption spectra of **1** (5.0 x10^{-5} M) were observed in the presence of amines (**2R**, **2S**, **3**, **4D**, **4L**, **5D**, **5L**, **6D**, **6L**, **7R**, and **7S**, 0-3.0 equiv.). A quartz cell with 0.1 mm path length was loaded with samples for CD spectra analysis as recorded on a Jasco J-815 CD spectrophotometer over the range of 240-700 nm. In these experiments, scans were performed with a rate of 100 nm/min, with a sampling interval of 1.0 nm, and with a response time of 1s. The scans were acquired for the gel directly at room temperature in DMSO/H_2O (3/1 *v*/*v*). We also obtained the CD spectra of **1** (5.0 mM) in the presence of amines (**2R**, **2S**, **3**, **4D**, **4L**, **5D**, **5L**, **6D**, **6L**, **7R**, and **7S**, 0-3.0 equiv.).

NMR Studies. Stock solutions of cyclohexanediamine, gelator **1**, as well as an internal standard DPM in DMSO-d_6/D_2O (3/1, *v*/*v*) were mixed in an NMR tube. Using a heat gun, the mixtures were heated unitl a clear solution was formed that flowed freely, and at this point the sample was left to cool and equilibrate overnight during which time gelation occurred. The ^{1}H NMR spectra of the sample was then recorded at 5°C intervals, as the temperature was increased from 25-80°C. The relevant peaks at each temperature were integrated to then convert the data to concentrations by reference with the internal standard. The van't Hoff plots were produced using Equation 1 by a method that has been proposed in previous literature.[1] The gradient of the plots is equal to

$-\Delta H_{diss}$ and the intercept equal to ΔS_{diss}. The calculated values of ΔH_{diss} and ΔS_{diss} were used to predict the concentration of solubilized gelator at each 5°C temperature interval.

$$\ln(Sol) = -\frac{\Delta H_{diss}}{RT} + \frac{\Delta S_{diss}}{R} \qquad (1)$$

Computational details for supporting information. We performed the density functional theory (DFT) calculation to understand the origin of helical structure of nanofiber. Structures and energies of this work are predicted by applying the M06-2X functional [2] with the LACVP basis set,[3] implemented in Jaguar 8.0 program package.[4]



Scheme S1. Synthesis of gelator **1**

Synthesis of Compound **8**

8.35 g (0.05 mol) 4-Nitrobenzoic acid and 10.0 g (0.09 mol) *p*-phenylenediamine were suspended in 250 ml 3 % aqueous NaOH and heat up to 120℃ for 24 hours reaction time, the reaction was allowed to cool to room temperature before filtration. Once cooled to ~ 5℃, a red precipitate was collected (6.27 g, 52%); ^{1}H NMR (DMSO-d_6, 300MHz): 7.92 (d, J = 8.4 Hz, 2H), 7.65 (d, J = 8.7 Hz, 2H), 7.60 (d, J = 8.4 Hz, 2H), 6.67 (d, J = 8.7 Hz, 2H), 6.05 (s, 2H, NH_2); ^{13}C NMR (DMSO-d_6 125MHz): 168.8, 152.6, 152.4, 142.9, 141.5, 129.7, 124.9, 120.5, 113.3; ESI-MS: *m/z* 240.2 $[M-H]^-$; Anal. Calcd for $C_{13}H_{11}N_3O_2$: C 64.72 %, H 4.60 %, N 17.42 %, O 13.26 %; Found: C 64.68 %, H 4.59 %, N 17.45 %, O 13.28 %.

Synthesis of Compound **9**

A stirred suspension of **8** (1g, 4.15 mmol) in $SOCl_2$ (7.2 ml) was refluxed for 3h. The volatile components were removed *in vacuo*. Methanol (2 ml) and pyridine (6 ml) were then added and the mixture was refluxed for 3 h. It was then allowed to cool to room temperature. Water (40 ml) was added and the precipitate was isolated by centrifugation. The solid was dried on a clay plate. The product crystallized from the concentrated extract (0.64g , 60.7 %); ^{1}H NMR (DMSO-d_6, 300MHz): 8.08 (d, J = 8.7 Hz, 2H), 7.82 (d, J = 8.4Hz, 2H), 7.71 (d, J = 8.7Hz, 2H), 6.68 (d, J = 8.7Hz, 2H), 6.34 (s, 2H, NH_2), 3.88 (s, 3H, CH_3). ^{13}C NMR (DMSO-d_6 125MHz): 165.7, 155.3, 153.7, 142.9, 130.3, 129.3, 125.8, 121.7, 121.7, 113.4, 52.1; ESI-MS *m/z* 256.0 $[M+H]^+$; Anal. Calcd for $C_{14}H_{13}N_3O_2$: C 65.87 %, H 5.13 %, N 16.48 %, O 12.53 %; Found: C 65.91 %, H 5.10 %, N 16.49 %, O 12.49 %.

Synthesis of Compound **10**

A solution of **9** (0.53 g, 2.08 mmol) and triethylamine (2.9 ml, 20.72 mol) in THF was allowed to cool in an

acetone/ice bath for 15 minutes before adding 1,3,5-benzenetricarbonyl trichloride (0.183 g, 0.69 mmol). The resulting mixture was stirred at room temperature for 24h and filtered. The filtrate was concentrated in vacuo and MeOH was added to the residue. The precipitates were collected and re-crystallization was carried out from THF/MeOH (0.45 g, 71 %); ^{1}H NMR (DMSO-d_6, 300MHz): 11.03 (s, 3H), 8.82 (s, 3H), 8.18-8.12 (m, 12H), 8.05-7.97 (m, 12H), 3.90 (s, 9H); ^{13}C NMR (DMSO-d_6 125MHz): 165.5, 165.7, 155.5, 148.9, 143.6, 136.1, 132.1, 131.4, 124.9, 123.4, 121.5, 116.2, 53.3; ESI-MS: *m/z* 920.4 $[M-H]^-$; Anal. Calcd for $C_{51}H_{39}N_9O_9$: C 66.44 %, H 4.26 %, N 13.67 %, O 15.62 %; Found: C 66.50 %, H 4.19 %, N 13.62 %, O 15.68 %.

Synthesis of Compound **1** (gelator **1**)

A mixture of **10** (0.50 g, 0.543 mmol) and NaOH (0.22 g, 5.50 mol) in THF and H_2O was stirred for 24h at room temperature. The solution was then concentrated *in vacuo*, and acidified with *con*-HCl solution. The precipitate was filtered and dried *in vacuo* (0.42 g, 88 %).^{1}H NMR (DMSO-d_6, 300MHz): 13.27 (br, 3H), 11.08 (s, 3H), 8.84 (s, 3H), 8.18-8.14 (m, 12H), 8.05-7.95 (m, 12H); ^{13}C NMR (DMSO-d_6 125MHz): 167.2, 165.3, 155.0, 148.6, 143.2, 135.6, 133.0, 131.1, 131.0, 124.4, 122.9, 121.1; ESI-MS: *m/z* 878.5 $[M-H]^-$; Anal. Calcd for $C_{48}H_{33}N_9O_9$: C 65.53 %, H 3.78 %, N 14.33 %, O 16.37 %; Found: C 65.46 %, H 3.75 %, N 14.19 %, O 16.41 %.

Table S1 Gelation Properties of Gelator **1**[a]

Solvent	Gelator **1**	Solvent	Gelator **1**
DMSO/water (3/1 v/v)	G	EtOAc	I
Water	I	Acetonitrile	I
DMSO	S	$CHCl_3$	I
DMF	S	CH_2Cl_2	I
THF	I	Toluene	I
MeOH	I	*n*-Hexane	I

[a] G=gelation, I=insoluble, S=solution.

Table S2 Thermodynamic Parameters Associated with the Gel-Sol Transition from Van't Hoff Analysis of Variable Temperature NMR Data.

Sample	ΔH_{diss} / kJ mol^{-1}	ΔS_{diss} / J $mol^{-1}K^{-1}$
1	15.65	3.65
1 + **2R**	27.03	47.47

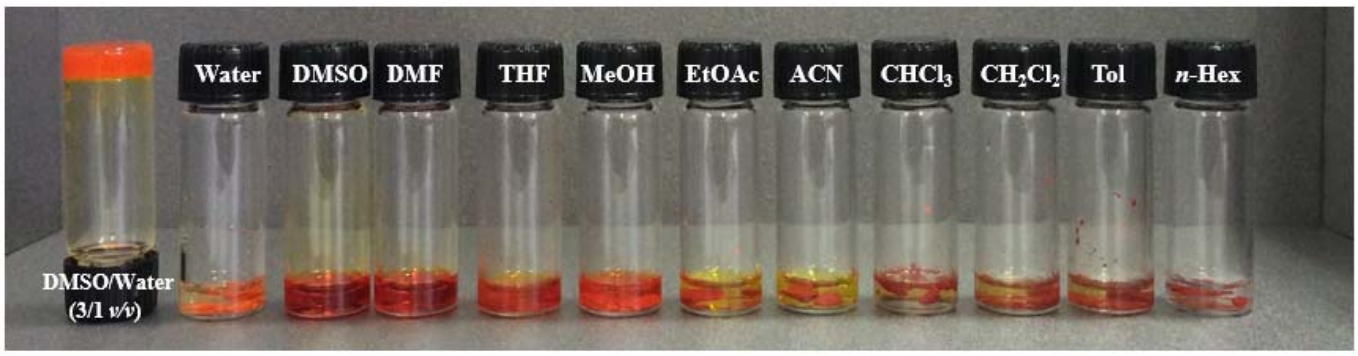


Fig. S1 Photograph of gelation test in different solvents (2 wt% gelator **1**).

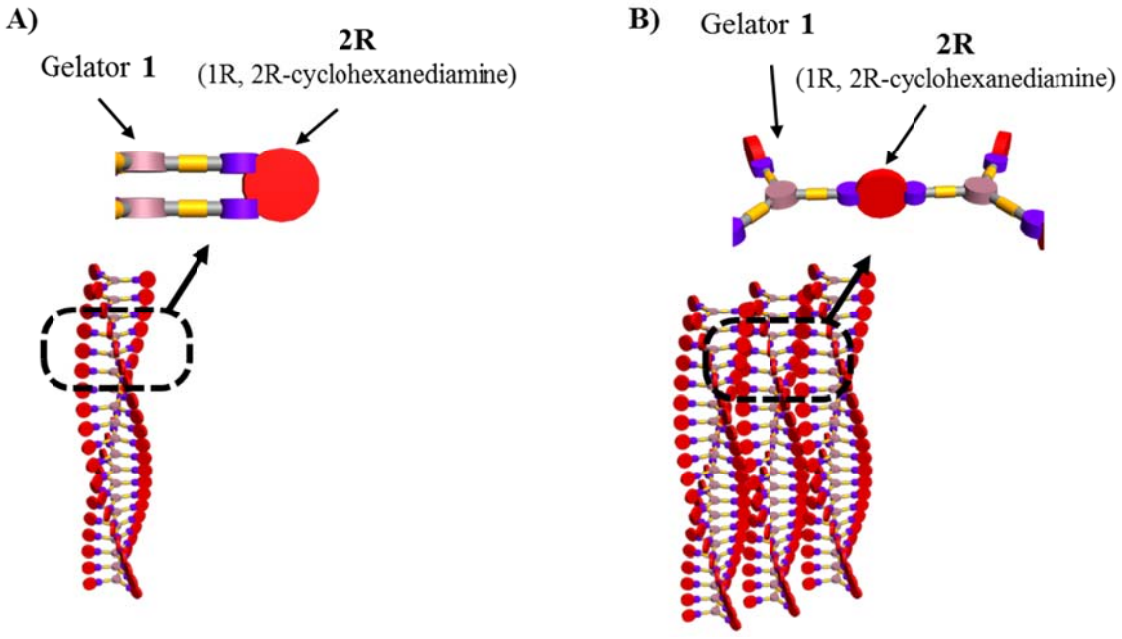


Fig. S2 Schematic illustration of possible gelation process of gelator **1** with A) small amount of **2R** and B) large amount of **2R**; We suspect this characteristic of our system results from increased amount of analyte providing a means for fiber aggregation as a growing proportion of analyte present on the surface of the fibers may facilitate inter-fiber interactions.

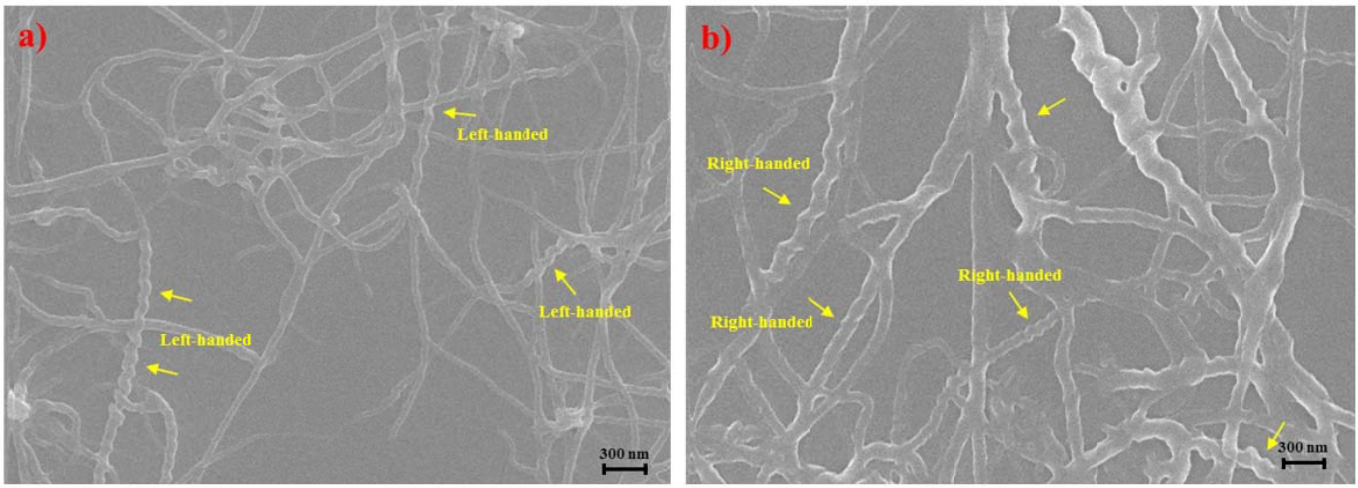


Fig. S3 SEM images of nanofibers prepared from of gelator **1** containing (a) 2 equiv. of **2R** , and (b) 2 equiv. of **2S.**

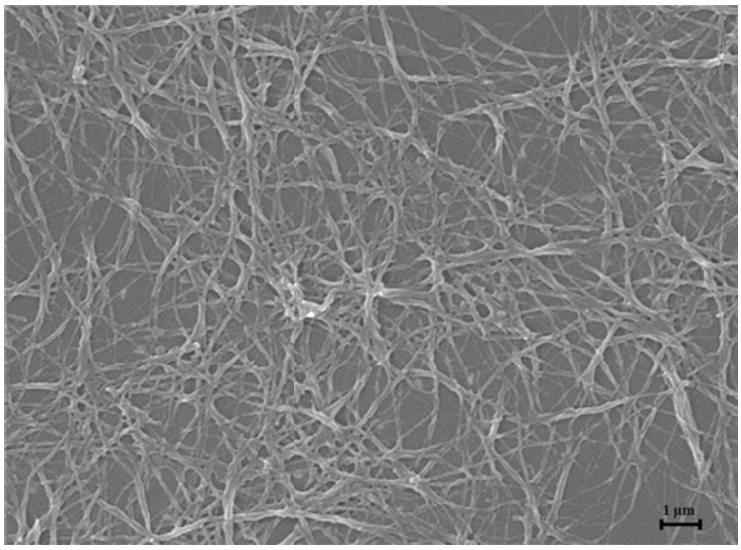


Fig. S4 SEM image of nanofibers prepared from gelator **1** after addition of 2.0 equiv. of **3**.

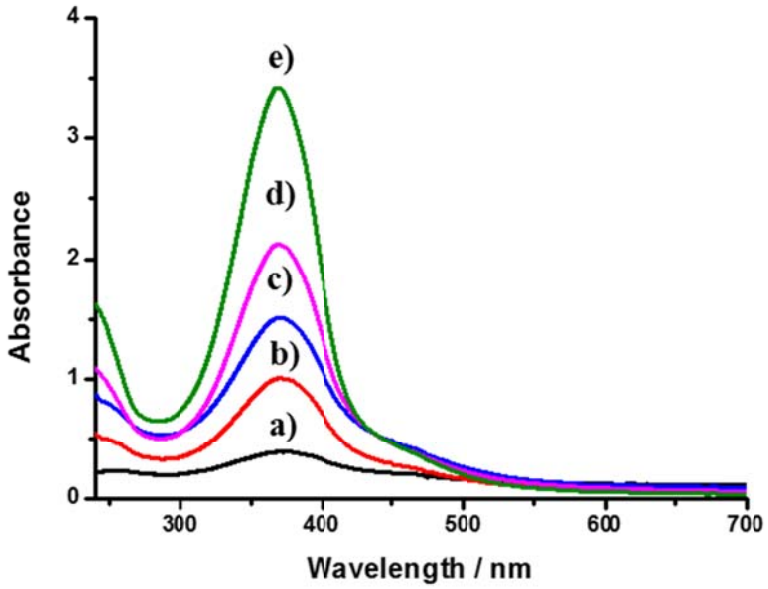


Fig. S5 UV/Vis spectra of gelator **1** (5.0×10^{-5} M) without (a) **2R** and with (b) 1.0 equiv., (c) 1.5 equiv., (d) 2.0 equiv., and (e) 2.5 equiv. of **2R** in DMSO/water.

Fig. S6 Photograph of gelation test of gelator **1** (2 wt%) without and with **2R** (1.0 equiv.- 4.0 equiv.).

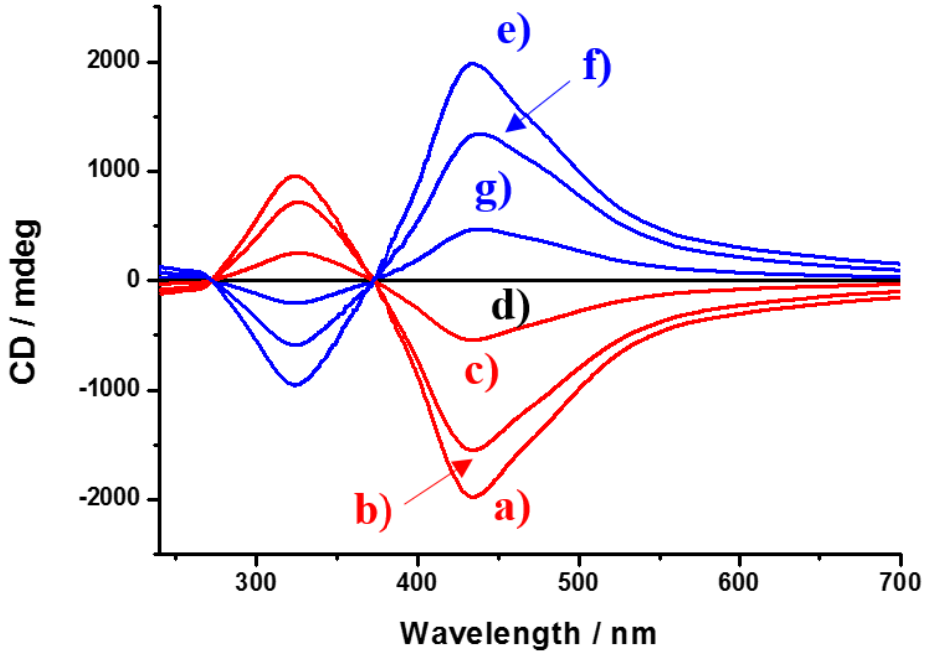


Fig. S7 CD spectra of gelator **1** nanofibers having (a) 2.0 equiv., (b) 2.5 equiv., (c) 3.0 equiv., and (d) 4.0 equiv. of **2R** (red lines) or **2S** (blue lines) in DMSO/water.

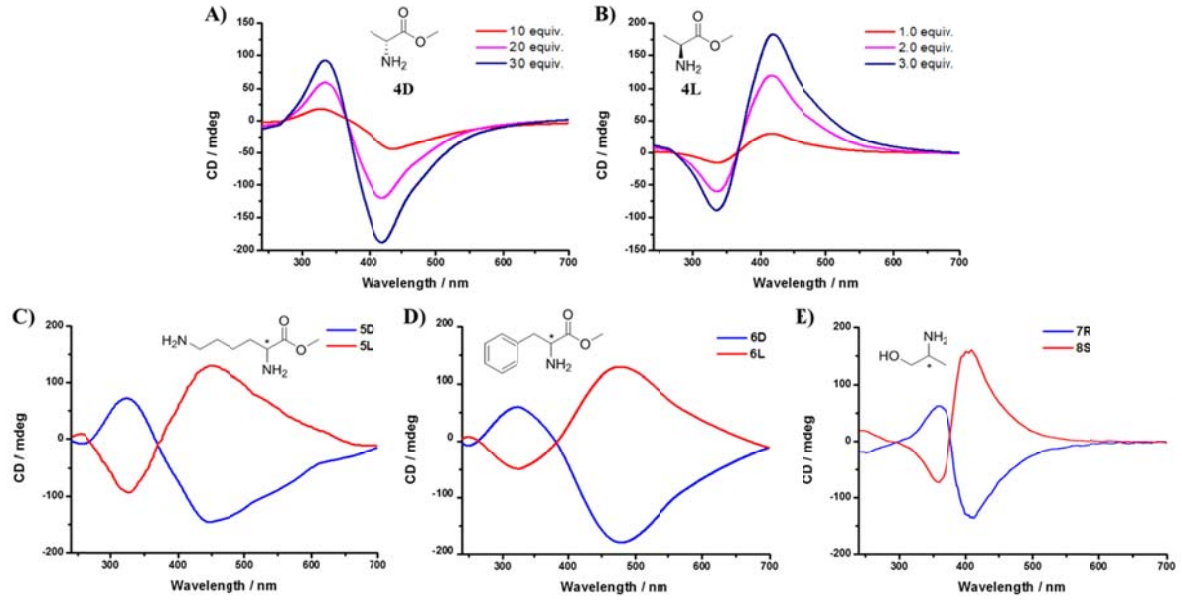


Fig. S8 CD spectra of gelator **1** (5.0 mM) nanofibers having 1.0 equiv., 2.0 equiv. and 3.0 equiv. of (A) **4D** and (B) **4L** in DMSO/water. (C) CD spectra of gelator **1** (5.0 mM) nanofibers having 3.0 equiv. of **5D** and **5L** in DMSO/water. (D) CD spectra of gelator **1** (5.0 mM) nanofibers having 3.0 equiv. of **6D** and **6L** in DMSO/water. (E) CD spectra of gelator **1** (5.0 mM) nanofibers having 3.0 equiv. of **7R** and **7S** in DMSO/water.

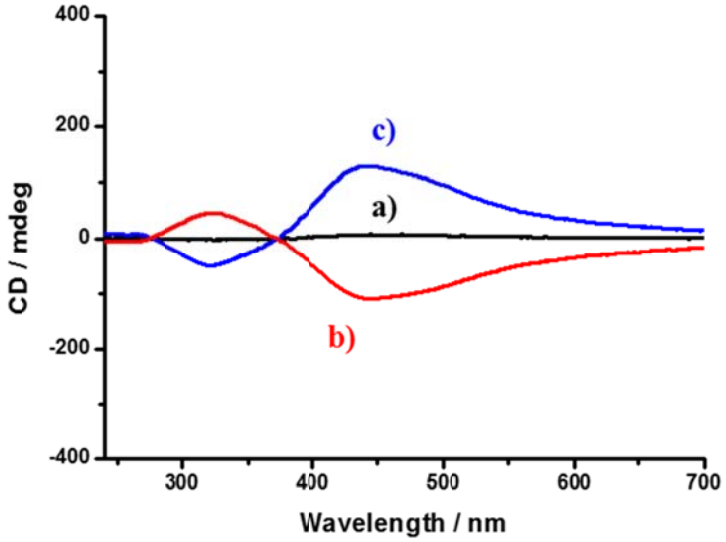


Fig. S9 CD spectra of gelator **1** (5.0 mM) nanofibers with different composition of cyclohexanediamine (2.0 equiv.) at a molar ratio of (a) 1:1 (**2R** : **2S**), (b) 2:1 (**2R** : **2S**), and (c) 1:2 (**2R** : **2S**).

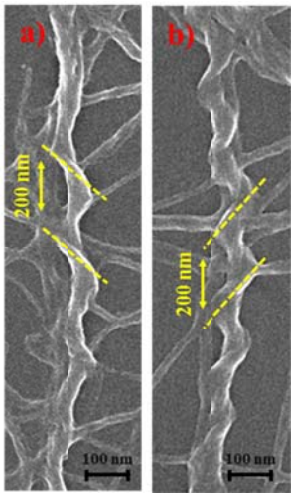


Fig. S10 SEM images of (a) left- and (b) right-handed helical nanofibers formed in the presence of cyclohexanediamine (2 equiv.) as a racemic mixture having a 1:1 molar ratio of **2R** : **2S**.

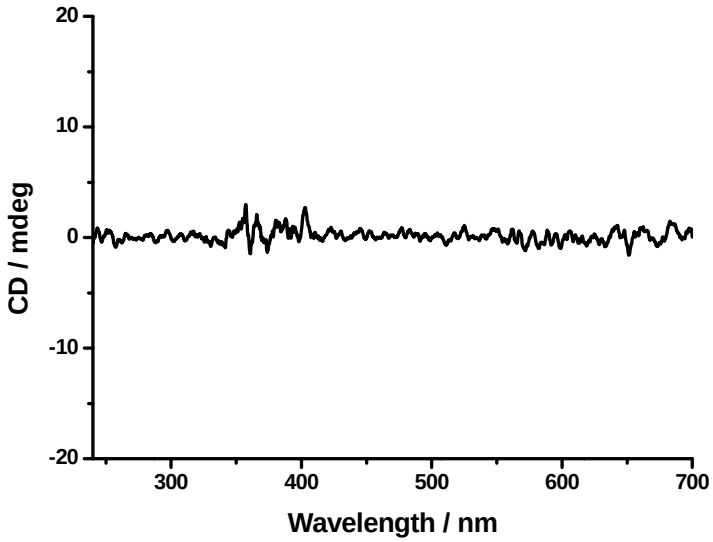


Fig. S11 CD spectrum of gelator **1** (5.0 mM) nanofibers with cis-1,2-cyclohexanediamine **3** (2.0 equiv.) in DMSO/water.

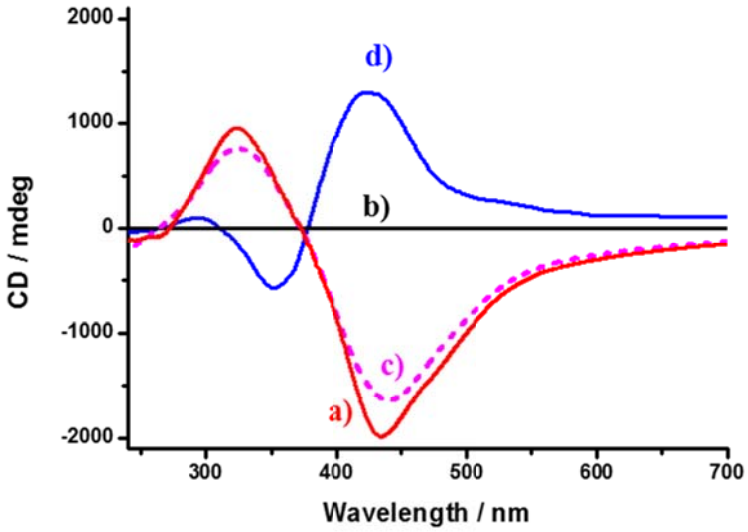


Fig. S12 CD spectra of gelator **1** (5.0 mM) nanofibers with (a) **2R** (2.0 equiv.), (b) after washing with HCl for nanofibers previously exposed to **2R**; and after re-exposure of xerogel **1** to either (c) **2R** or (d) **2S** in DMSO/water.

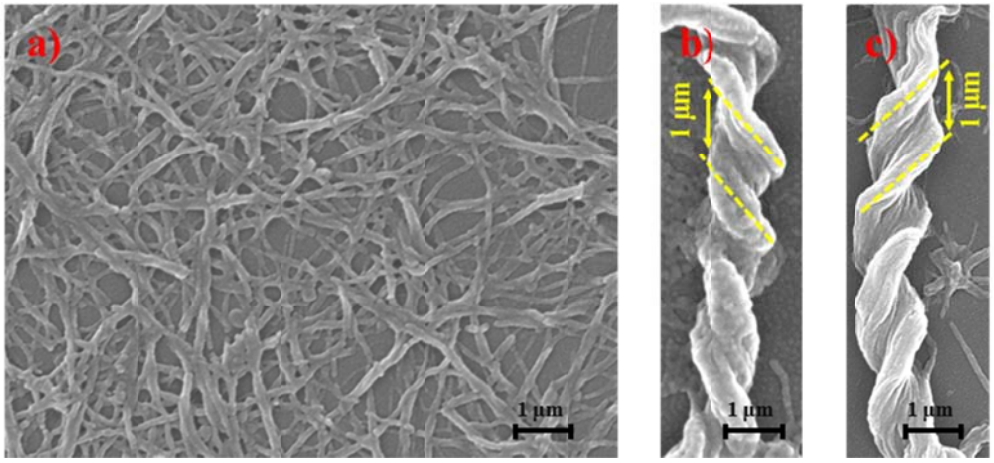


Fig. S13 SEM images of (a) xerogel **1** with **2R** after washing with HCl solution; and after re-exposure of xerogel **1** to either (b) **2R** or (c) **2S** in DMSO/water.

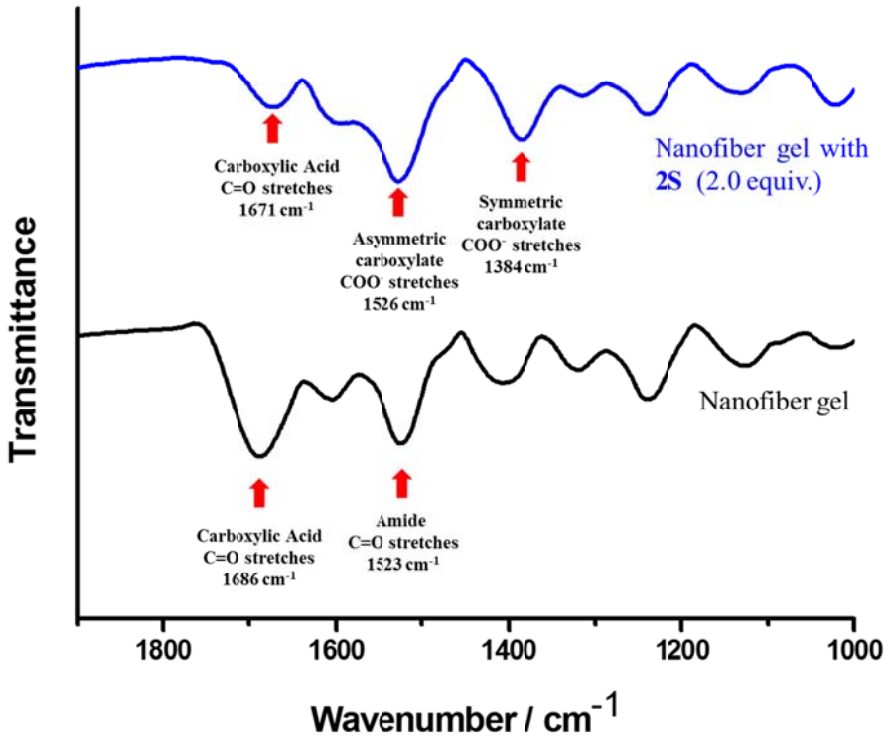


Fig. S14 IR spectra of nanofibers gel before and after mixture with **2S** (2.0 equiv.).

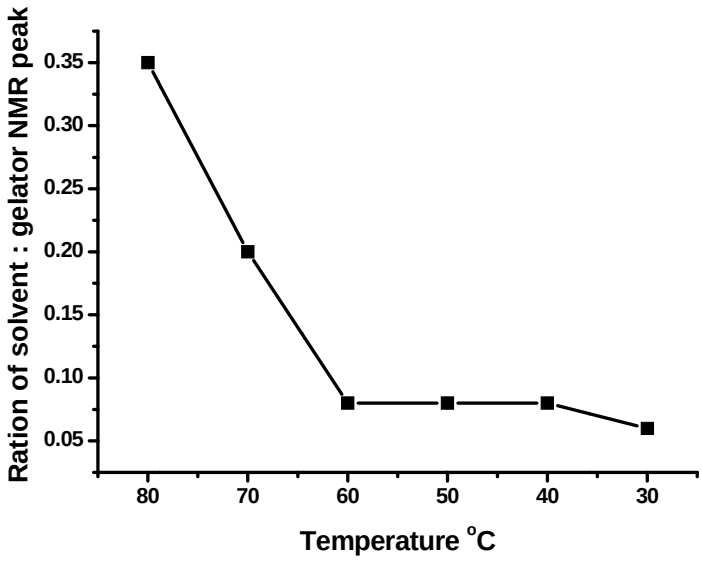


Fig. S15 Variable temperature (VT) ^{1}H NMR experiment demonstrating the immobilization of nanofibers gel with **2R** (20 mM) as temperature decreases; squares represent data of gelator **1** (10 mM).

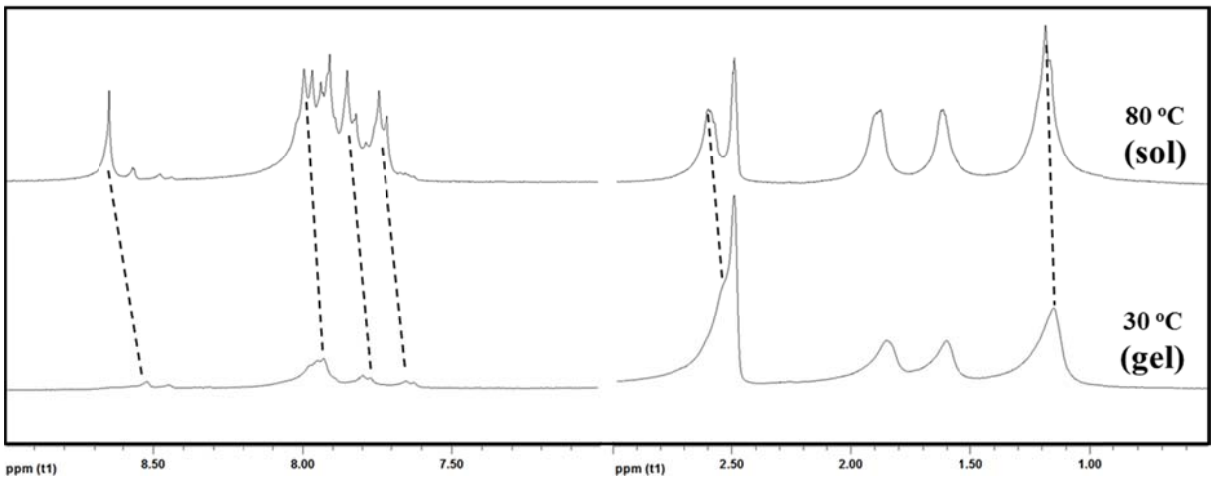


Fig. S16 Variable temperature (VT) ^{1}H NMR spectra of nanofiber gel with **2R** (2.0 equiv.) as temperature decreases.

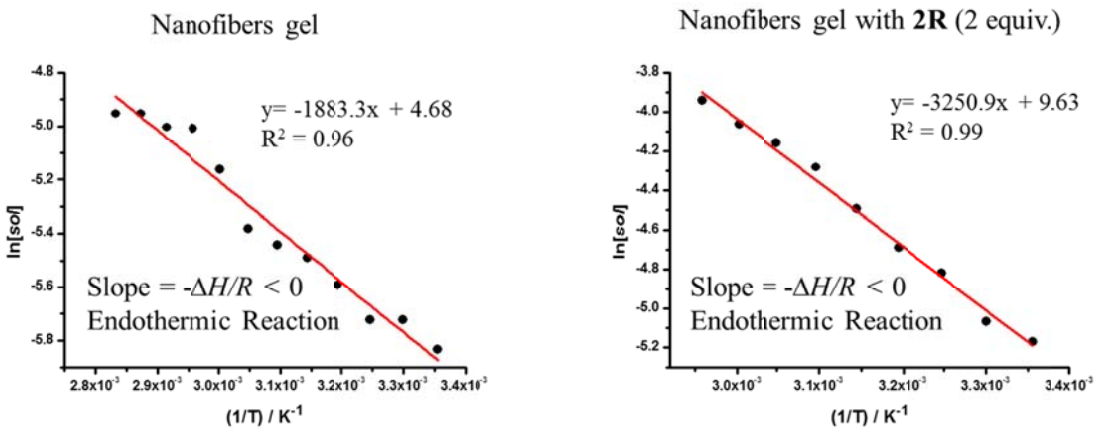


Fig. S17 Van 't Hoff plots of nanofibers gel formed form nanofiber gel and also nanofiber gel with **2R** (2 equiv.)

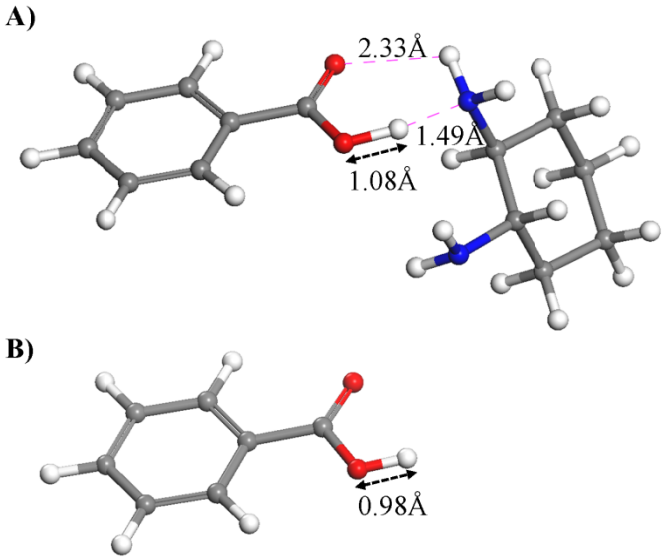


Fig. S18 Optimized structures from density functional theory (DFT) calculations. (A) DFT optimized structure of the benzoic acid (modeling the terminal part of gelator **1**) associated with the 1S, 2S-cyclohexanediamine (**2S**). The binding energy is 0.99 eV. **(**B) DFT optimized structure of the benzoic acid. Development of COO^--NH_3^+ interaction elongates OH bond of the carboxylic acid groups by 0.1 Å (~10%). The magenta dotted line represents hydrogen bonding.

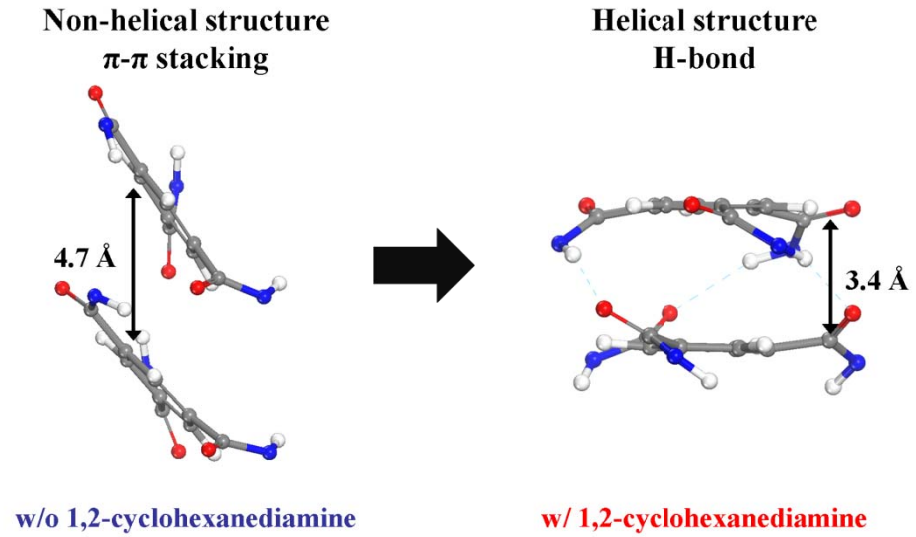


Fig. S19 Central phenyl rings in non-helical (left) and helical (right) structures from density functional theory (DFT) calculation.

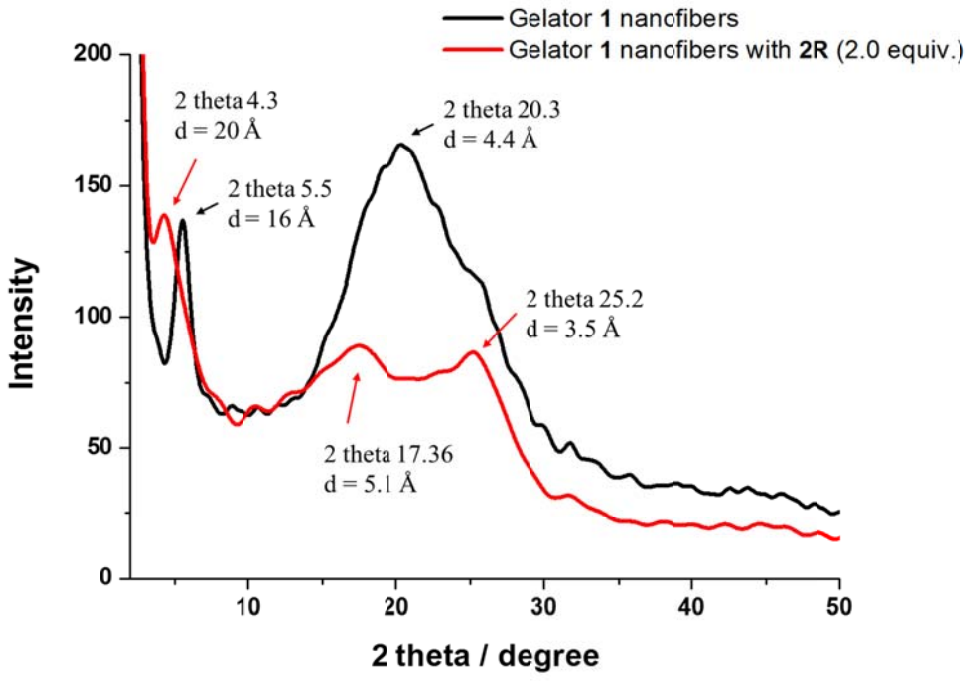


Fig. S20 Powder X-ray diffraction analysis of gelator **1** nanofibers with and without exposure to 2 equiv. of **2R**.

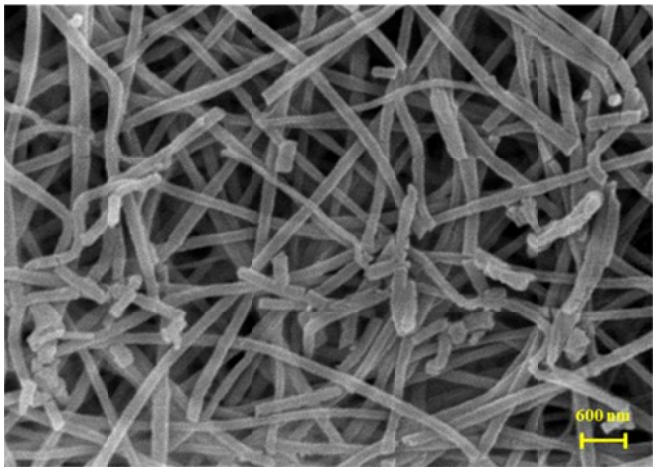


Fig. S21 SEM images of film produced by electrospinning process of gelator **1** (2.0 wt%) with PMMA (4.0 wt%).

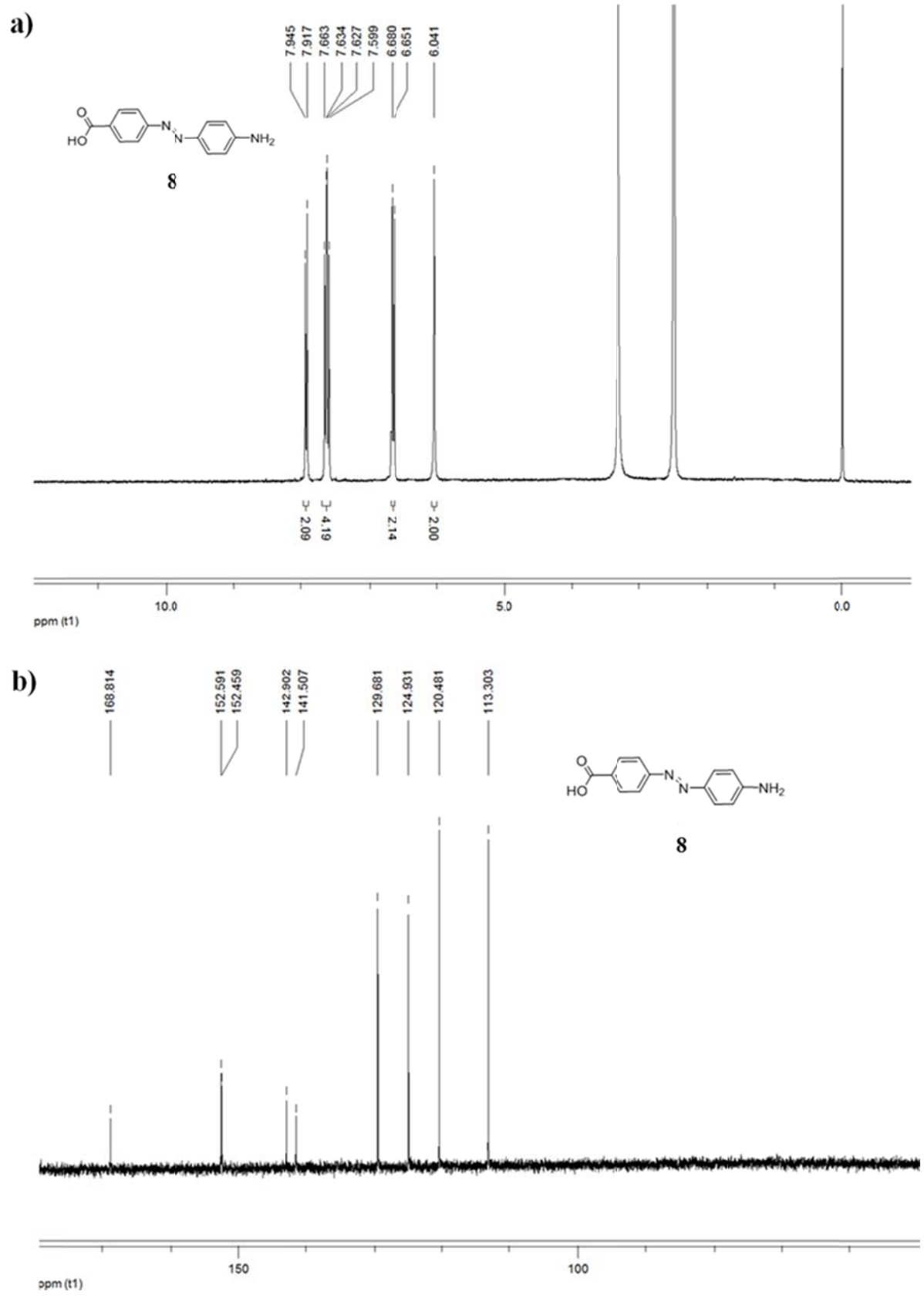


Fig. S22 (a) ^{1}H NMR spectrum of **8** (300 MHz, DMSO-d_6). (b) ^{13}C NMR spectrum of **8** (125 MHz, DMSO-d_6).

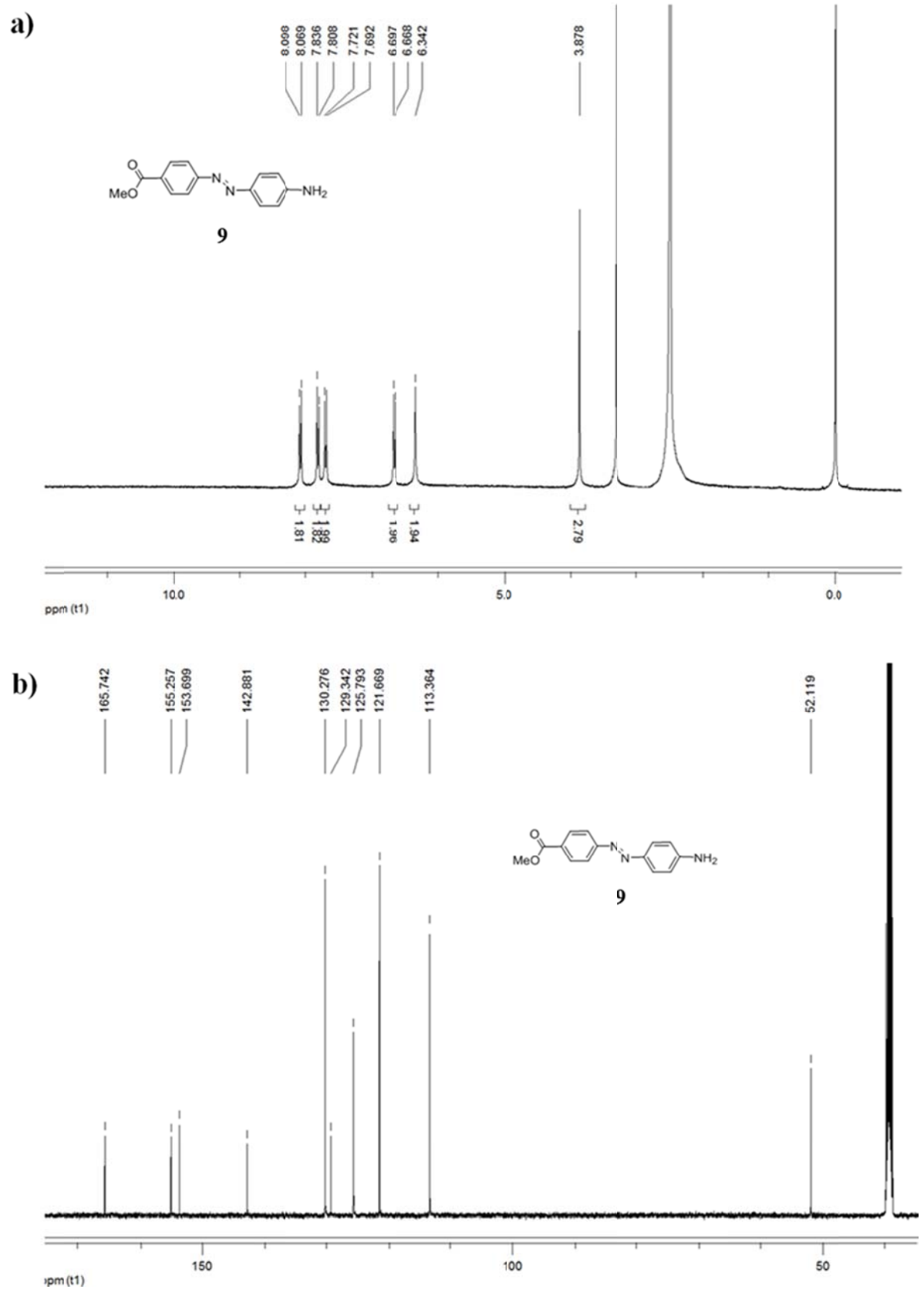


Fig. S23 (a) ^{1}H NMR spectrum of **9** (300 MHz, DMSO-d_6). (b) ^{13}C NMR spectrum of **9** (125 MHz, DMSO-d_6).

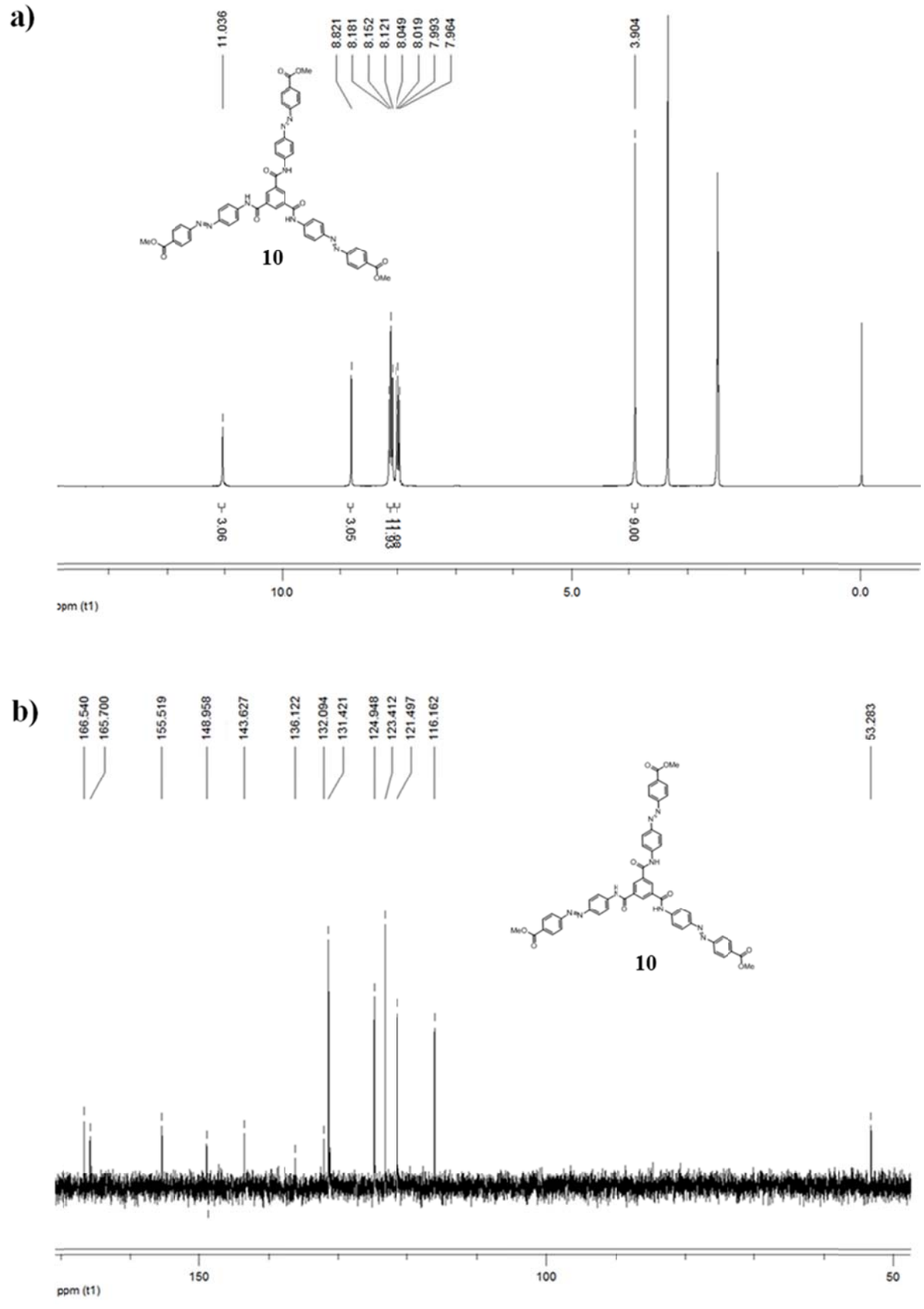


Fig. S24 (a) ^{1}H NMR spectrum of **10** (300 MHz, DMSO-d_6). (b) ^{13}C NMR spectrum of **10** (125 MHz, DMSO-d_6).

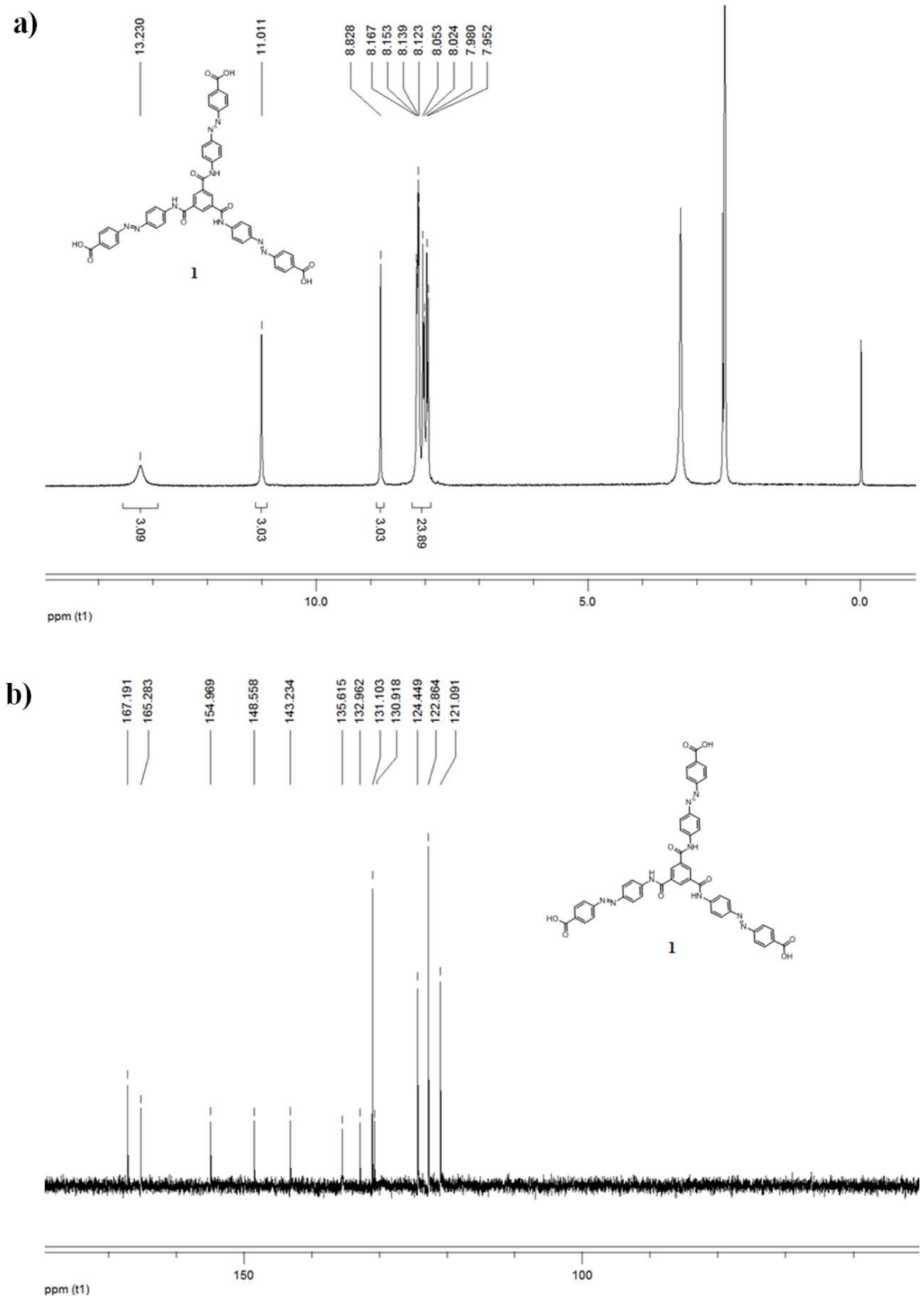


Fig. S25 (a) ^{1}H NMR spectrum of **1** (300 MHz, DMSO-d_6). (b) ^{13}C NMR spectrum of **1** (125 MHz, DMSO-d_6).

References

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