

Electronic Supplementary Information

Gelation of Amino acid-Based Amphiphiles in Water-Based Mixed Solvent Systems: Reusable Catalytic Templates for Nanostructured Silica and Silica-Zirconia Photocatalyst

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Synthesis of amino acid based amphiphiles. A series of different amino acid-based amphiphiles (conjugates of different chain length of fatty acids and tyrosine/phenylalanine/leucine) such as (C₁₇H₃₅-Tyr-OH/ C₁₃H₂₇-Tyr-OH/ C₉H₁₉-Tyr-OH/ C₁₇H₃₅-Phe-OH or C₁₇H₃₅-Leu-OH) are synthesized. The preparation of these amphiphiles involves the synthesis of their methyl ester (C₁₇H₃₅-Tyr-OMe/ C₁₃H₂₇-Tyr-OMe/ C₉H₁₉-Tyr-OMe/ C₁₇H₃₅-Phe-OMe or C₁₇H₃₅-Leu-OMe) followed by their saponification. The methyl esters of these amphiphiles are synthesized by conventional solution-phase method using a racemization-free fragmentation/condensation strategy. In general, the C terminus of amino acid is first protected via esterification with a methyl group, followed by coupling with a fatty acid by using DCC and HOBT. These esters were finally saponified to obtain the actual amphiphiles.

Synthesis of methyl ester of tyrosine (H₂N-Tyr-OMe), phenylalanine (H₂N-Phe-OMe) and leucine (H₂N-Leu-OMe). First, 20 mmol of either tyrosine (3.62 gm)/ phenylalanine (3.3 gm)/ leucine (2.62) is dissolved in of 20 ml ice cold dry methanol containing 2 ml SOCl₂ and allowed to stand for 8h to obtain the chloride salt of methyl ester of different amino acid (Cl⁻H₃N⁺-Tyr-OMe/ Cl⁻H₃N⁺-Phe-OMe/ Cl⁻H₃N⁺-Leu-OMe respectively). The subsequent neutralization of these compounds with saturated Na₂CO₃ solution and extraction with ethyl acetate results the required H₂N-Tyr-OMe/ H₂N-Phe-OMe/ H₂N-Leu-OMe. Using these purified esters, the following methyl esters of amphiphiles were synthesized.

Synthesis of methyl ester of amphiphiles (C₁₇H₃₅-Tyr-OMe/ C₁₃H₂₇-Tyr-OMe/ C₉H₁₉-Tyr-OMe/ C₁₇H₃₅-Phe-OMe or C₁₇H₃₅-Leu-OMe): 12 mmol of different fatty acid [capric acid (2.06 g)/myristic acid (2.73 g)/ stearic acid (3.5 g)] is taken in DCM (10 ml) and cooled in an ice-water bath. DCM solution of purified methyl ester of amino acid (10 mmol) is then added separately to this fatty acid solution. Finally, DCC (2.06 g, 10 mmol) and HOBT (0.135 g, 1 mmol) are added consecutively to each of above reaction mixture and stirred magnetically for 3 days. Final reaction mixture taken in ethyl acetate (30 ml) was filtered through sintered funnel to remove the formed dicyclohexyl urea (DCU). The filtrate containing the actual compound is washed with 2N HCl (3 × 20 ml), brine (1 × 20 ml), saturated sodium carbonate (3 × 20 ml), water (1 × 20 ml) and dried over anhydrous sodium sulfate. The crude compound is isolated by evaporating the solvent in rotary evaporator and finally dried under vacuum. Final purification was done on a silica gel column (100-200 mesh) using mixture of ethyl acetate and toluene as eluent. Methyl ester of these amino acid based amphiphile (C₁₇H₃₅-Tyr-OMe/ C₁₃H₂₇-Tyr-OMe/ C₉H₁₉-Tyr-OMe/ C₁₇H₃₅-Phe-OMe or C₁₇H₃₅-Leu-OMe) is finally characterized through ESI mass spectroscopy, 300 MHz ¹H NMR spectroscopy, the details of which are given below.

C₁₇H₃₅-Tyr-OMe: ¹H NMR (300 MHz, CDCl₃, TMS): δ = 6.96-6.93 (d, 2H, J = 9, Tyr ring H), 6.76-6.73 (d, 2H, J = 9, Tyr ring H), 5.89-5.86 (d, 1H, J = 9, amide H), 4.90-4.83 (q, 1H, J = 3, Tyr C^α Hs), 3.73 (s, 3H, -OCH₃), 3.12-2.97 (m, 2H, Tyr C^β Hs), 2.20-2.14 (t, 2H, J = 7.5, -CO-CH₂), 1.61 (br., 8H, -(CH₂)₂-), 1.25 (br., 22H, -(CH₂)₂-), 0.89-0.85 (t, 3H, J = 6.5, -CH₃).

MS (35eV): m/z (%): 484 [M + Na⁺]

C₁₃H₂₇-Tyr-OMe: ¹H NMR (300 MHz, CDCl₃, TMS): δ = 6.96-6.93 (d, 2H, J = 9, Tyr ring H), 6.76-6.73 (d, 2H, J = 9, Tyr ring H), 5.89-5.86 (d, 1H, J = 9, amide H), 4.90-4.83 (q, 1H, J = 3, Tyr C^α), 3.73 (s, 3H, OCH₃), 3.12-2.97 (m, 2H, J = 5.16, Tyr C^β), 2.20-2.14 (t, 2H, J = 7.5, -CO-CH₂), 1.61 (br., 8H, -(CH₂)₂-), 1.25 (br., 14H, -(CH₂)₂-), 0.89-0.85 (t, 3H, J = 6.5, -CH₃).

MS (35eV): m/z (%): 428 [M + Na⁺]

C₉H₁₉-Tyr-OMe: ¹H NMR (300 MHz, CDCl₃, TMS): δ = 6.95-6.92 (d, 2H, J = 9, Tyr ring H), 6.75-6.72 (d, 2H, J = 9, Tyr ring H), 5.89-5.86 (d, 1H, J = 9, amide H), 4.89-4.83 (m, 1H,

Tyr C^α Hs), 3.73 (s, 3H, -OCH₃), 3.06-2.98 (m, 2H, Tyr C^β Hs), 2.19-2.14 (t, 2H, J = 7.5, -CO-CH₂), 1.91-1.80 (m, 14H, -(CH₂)₂-), 0.89-0.84 (t, 3H, J = 6.5, -CH₃).

MS (35 eV): m/z (%): 372 [M+Na⁺]

C₁₇H₃₅-Phe-OMe: ¹HNMR (300 MHz, CDCl₃, TMS): δ = 7.099 (br, 5H, Phe ring H), 5.82 (s, 1H, amide H), 4.90-4.83 (m, 1H, Phe C^α), 3.73 (s, 3H, -OCH₃), 3.139 (br, 2H, Phe C^β), 2.18 (br, 2H, -CO-CH₂-), 1.60 (br., 8H, -(CH₂)₂-), 1.25 (br., 24H, -(CH₂)₂-), 0.89-0.85 (t, 3H, J = 6.5, -CH₃).

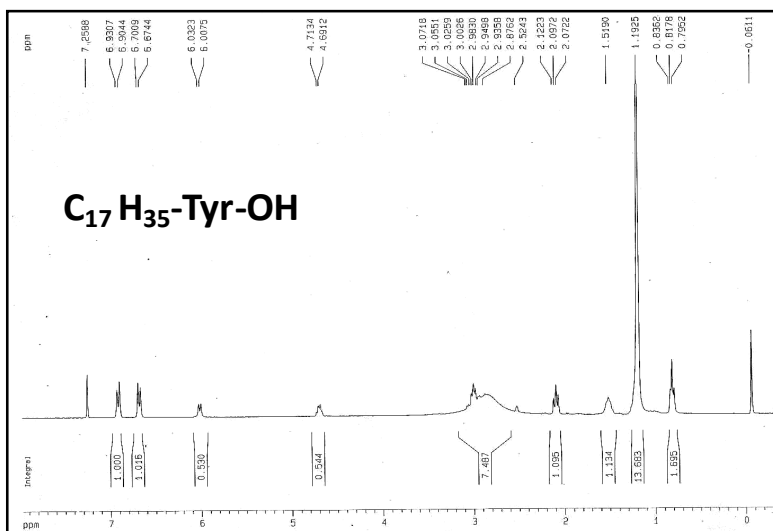
MS (35 eV): m/z (%): 468 [M + Na⁺]

C₁₇H₃₅-Leu-OMe: ¹HNMR (300 MHz, CDCl₃, TMS): δ = 0.96-0.95 (d, 6H, J = 9, Leu C^δ), 5.9-5.88 (d, 1H, J = 9, amide -NH), 4.62-4.58 (m, 1H, Leu C^αH), 1.63 (m, 2H, Leu C^βH), 1.70 (m, 1H, Leu C^γ), 3.73 (s, 3H, -OCH₃), 2.18-2.13 (t, 2H, J = 9, -CO-CH₂-), 1.55 (br., 2H, -CH₂-), 1.26 (br., 28H, -(CH₂)₁₄-), 0.89-0.85 (t, 3H, J = 6, -CH₃).

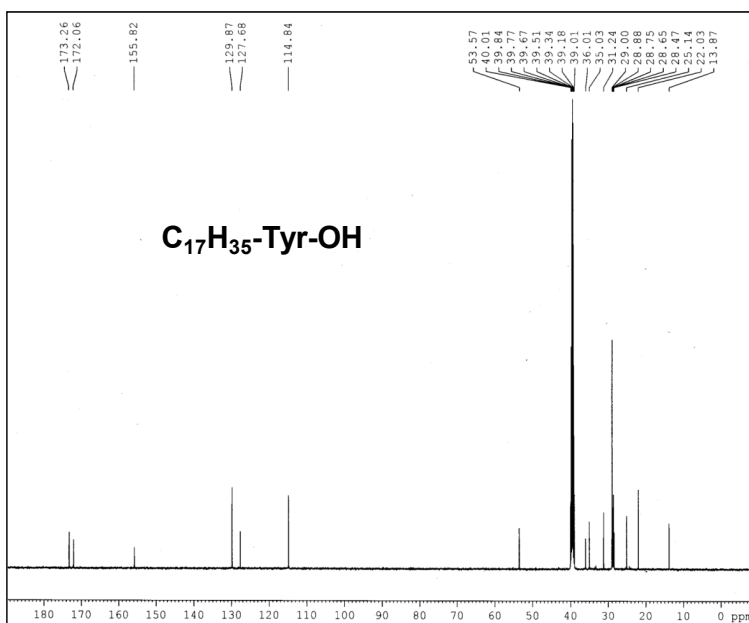
MS (35 eV): m/z (%): 444 [M + Na⁺]

Synthesis of amphiphiles (C₁₇H₃₅-Tyr-OH/ C₁₃H₂₇-Tyr-OH/ C₉H₁₉-Tyr-OH/ C₁₇H₃₅-Phe-OH or C₁₇H₃₅-Leu-OH). Typically, for the synthesis of amino acid based amphiphile (C₁₇H₃₅-Tyr-OH), an aqueous NaOH (10 ml, 2N) solution is added dropwise to the methanolic solution (25 ml) of purified ester of amphiphile (C₁₇H₃₅-Tyr-OMe) and the progress of this basic hydrolysis is monitored via thin layer chromatography (TLC). The reaction mixture is then stirred (magnetically) further for 12 h and subsequently methanol is removed. The rest alkaline aqueous part containing sodium salt of amphiphiles is mixed with 30 ml of water followed by washing with diethyl ether (2 × 20 ml) to remove any unreacted ester. Then the pH of the aqueous layer was adjusted to 2 using 2N HCl and organic compound (amphiphile) was further extracted with ethyl acetate (3 × 20 ml). The extract was dried over anhydrous sodium sulphate, and evaporated by rotary evaporator and finally dried under vacuum to isolate the amphiphile. Other amphiphiles (C₁₃H₂₇-Tyr-OH, C₉H₁₉-Tyr-OH, C₁₇H₃₅-Phe-OH and C₁₇H₃₅-Leu-OH) are prepared by similar procedure. ¹H NMR spectroscopy, ESI mass spectroscopy are used to characterize the resultant amphiphiles, the details of which are mentioned below.

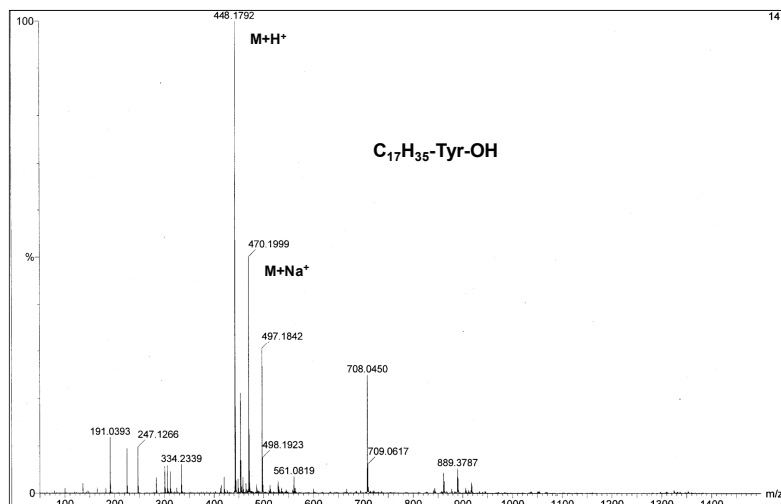
C₁₇H₃₅-Tyr-OH: Yield = (79%); ¹HNMR (300MHz, CDCl₃ + (D₆)DMSO, TMS): δ = 6.93-6.90 (d, 2H, J = 9, Tyr ring-Hs), 6.70-6.67 (d, 2H, J = 9, Tyr ring Hs), 6.03-6.00 (d, 1H, J = 9, amide -NH), 4.71-4.69 (m, 1H, Tyr C ^{α} H), 3.07-3.05 (d, 2H, J = 6, Tyr C ^{β} H), 2.12-2.07 (t, 2H, J = 9, -CO-CH₂), 1.52 (br., 2H, -CH₂), 1.21 (br., 28H, -(CH₂)₄-), 0.83-0.79 (t, 3H, J = 6, -CH₃).



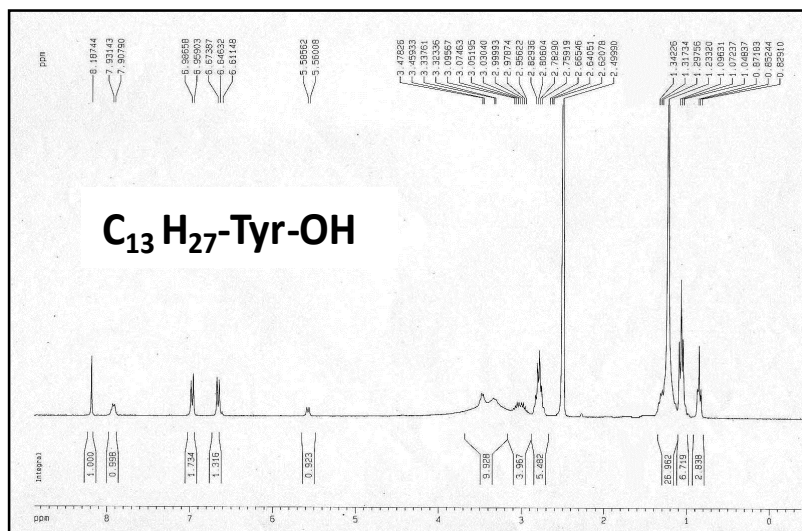
¹³CNMR (500MHz, (D₆)DMSO, TMS): δ = 129.87 (d, 2C,Tyr ortho), 114.84 (d,2C,Tyr meta),127.68 (s,1C,ipso),155.02 (s,1C,Tyr para),173.26(s,1C,CO₂H),172.06 (s,1C, -CONH-), 53.57(s,1C,Tyr C ^{α}),36.01(s,1C,Tyr C ^{β}),35.03(s,1C,Acid C ^{α}),29-28.47(m,12C,Alkyl chain), 25.14 (s,1C, Acid C ^{β}), 22.03(s,1C, Acid C¹⁷), 31.24 (s, 1C,Acid C¹⁶), 13.87(s,1C,C¹⁸)



MS (35eV): m/z (%): 448[M+H⁺], 470 [M+Na⁺]

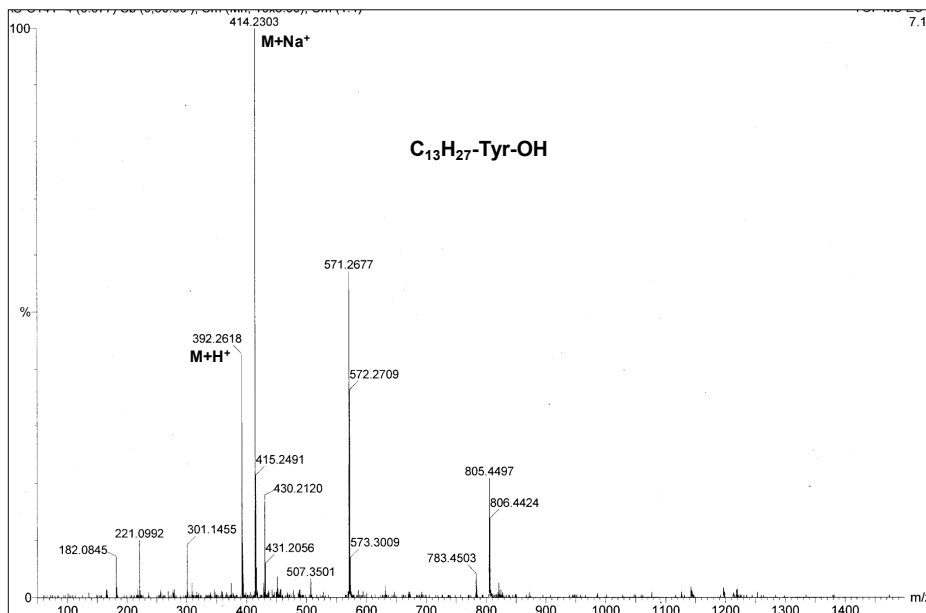


C₁₃H₂₇-Tyr-OH: Yield = (81%); ¹HNMR (300MHz, CDCl₃ + (D₆)DMSO, TMS): δ = 6.93-6.90 (d, 2H, J = 9, Tyr ring-Hs), 6.70-6.67 (d, 2H, J = 9, Tyr ring Hs), 6.03-6.00 (d, 1H, J = 9, amide -NH), 4.71-4.69 (m, 1H, Tyr C^αH), 3.07-3.05 (d, 2H, J = 6, Tyr C^β), 2.12-2.07 (t, 2H, J = 9, -CO-CH₂), 1.52 (br., 2H, -CH₂), 1.21 (br., 28H, -(CH₂)₄-), 0.83-0.79 (t, 3H, J = 6, -CH₃).



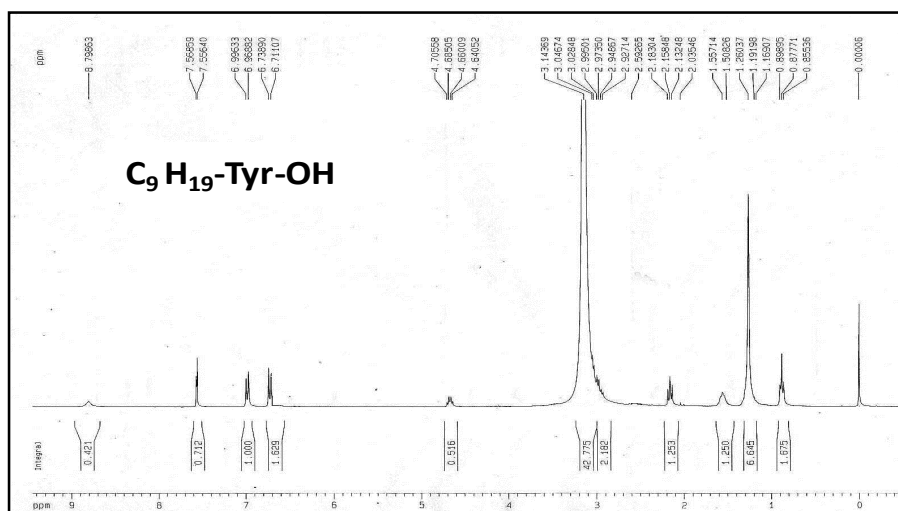
¹³CNMR (300MHz, CDCl₃ + (D₆)DMSO, TMS): δ = 128.44 (d, 2C,ortho), 113.45 (d,2C, meta),126.04 (s,1C,ipso),154.45 (s,1C,para),171.83(s,1C,CO₂H),170.98 (s,1C, -CONH-),

52.04 (s,1C,Tyr C^α),34.04(s,1C,Tyr C^β),33.96(s,1C,Acid C^α),27.75-27.33(m,8C,Alkyl chain),
23.85 (s,1C, Acid C^β), 20.77(s,1C, Acid C¹³), 29.99 (s, 1C,Acid C¹²), 12.47(s,1C,C¹⁴)

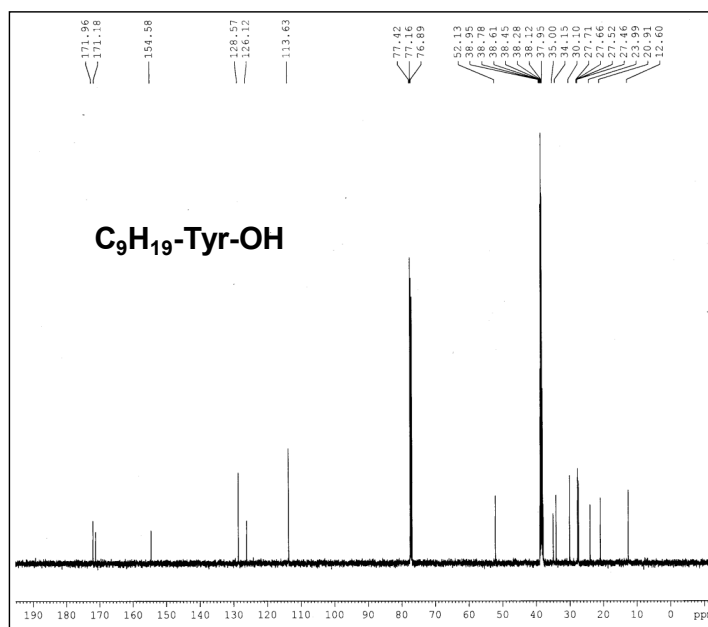


MS (35eV): m/z (%):392 [M+H⁺],414 [M+Na⁺]

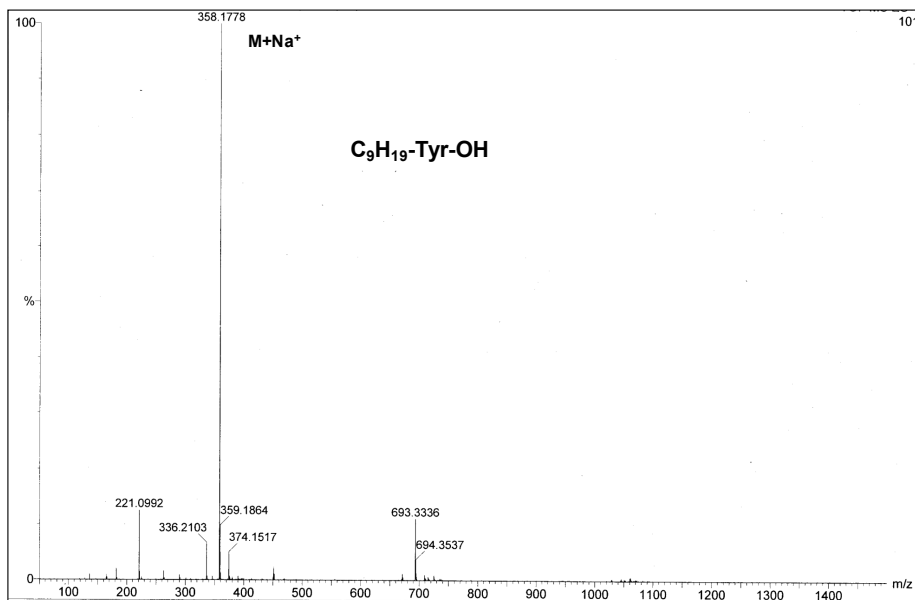
C₉H₁₉-Tyr-OH: Yield = (74%); ¹HNMR (300MHZ, CDCl₃ + (D₆)DMSO, TMS): δ = 6.99-6.96 (d, 2H, J = 9, Tyr ring-Hs), 6.73-6.71 (d, 2H, J = 6, Tyr ring Hs), 6.66-6.65 (d, 1H, J = 9, amide -NH), 4.71-4.64 (m, 1H, Tyr C^αH), 3.07-3.05 (d, 2H, J = 6, Tyr C^β), 2.18-2.13 (t, 2H, J = 9, -CO-CH₂), 1.55 (br., 2H, -CH₂), 1.26 (br., 12H, -(CH₂)₄-), 0.89-0.85 (t, 3H, J = 6, -CH₃).



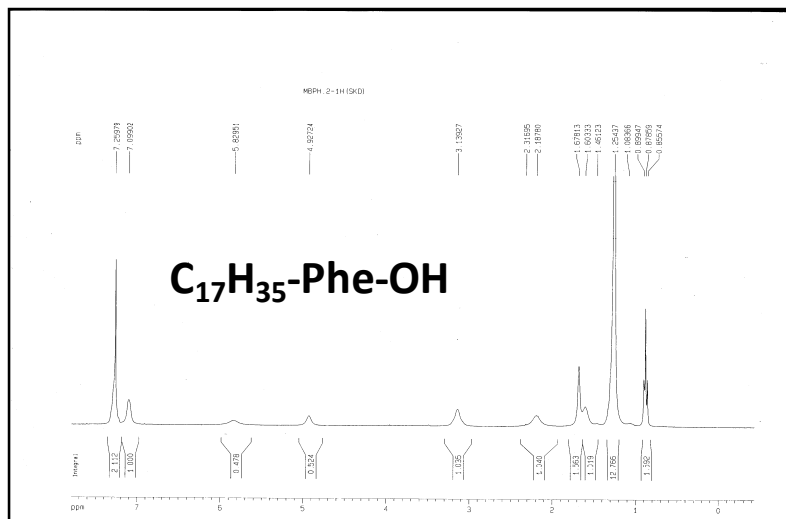
^{13}C NMR (300MHz, $\text{CDCl}_3 + (\text{D}_6)\text{DMSO}$, TMS): $\delta = 120.57$ (d, 2C,ortho), 113.63 (d,2C, meta), 126.12 (s,1C,ipso), 154.58 (s,1C,para), 171.96(s,1C, CO_2H), 171.10 (s,1C, -CONH-), 52.13(s,1C,Tyr C^α), 35(s,1C,Tyr C^β), 34.15(s,1C,Acid C^α), 27.71-27.46(m,12C,Alkyl chain), 23.99 (s,1C, Acid C^β), 20.91(s,1C, Acid C^γ), 30.10 (s, 1C,Acid C^δ), 12.6(s,1C, C^{10}).



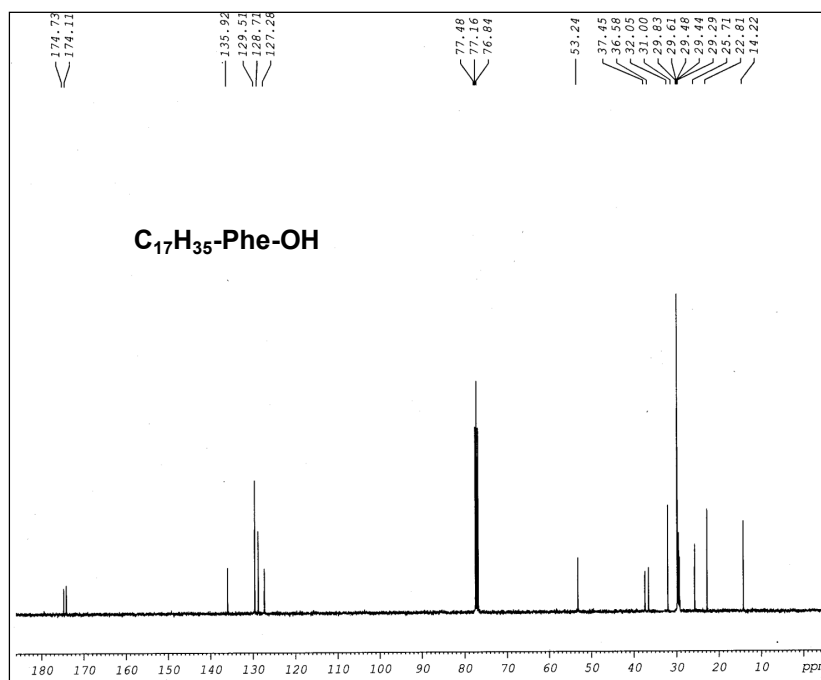
MS (35eV): m/z (%): 358 [$\text{M}+\text{Na}^+$]



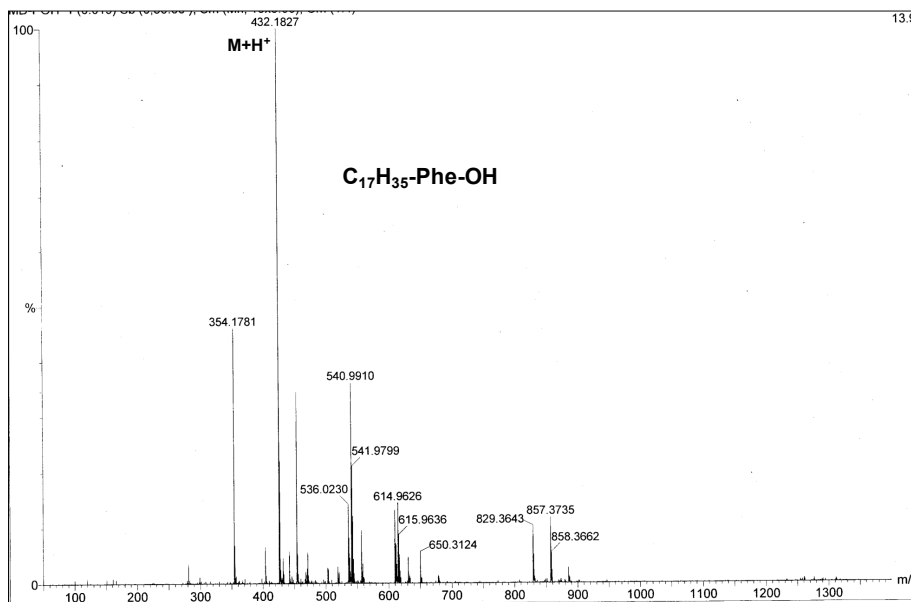
C₁₇H₃₅-Phe-OH: Yield = (82%); ¹HNMR (300 MHz, CDCl₃, TMS): δ = 7.099 (br, 5H, Phe ring H), 5.82 (s, 1H, amide H), 4.90-4.83 (m, 1H, Phe C^α), 3.139 (br, 2H, Phe C^β), 2.18 (br, 2H, -CO-CH₂-), 1.60 (br., 8H, -(CH₂)₂-), 1.25 (br., 24H, -(CH₂)₂-), 0.89-0.85 (t, 3H, J = 6.5, -CH₃).



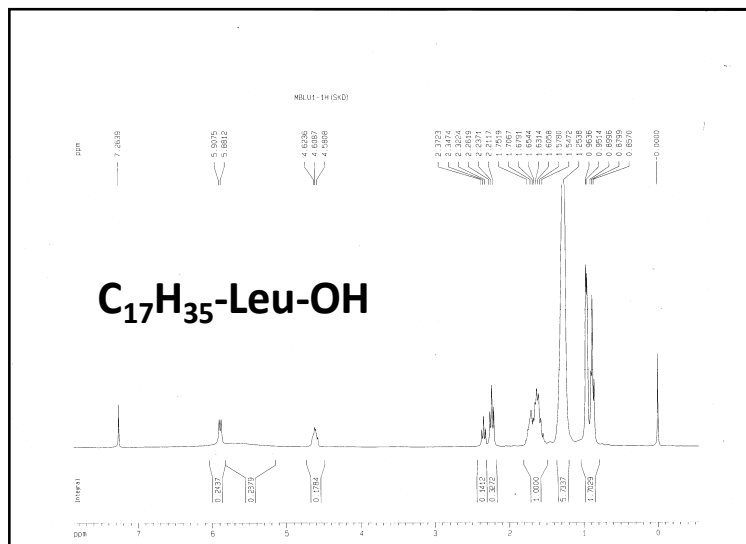
¹³CNMR (300MHz, CDCl₃, TMS): δ = 128.71 (d, 2C, ortho), 129.51 (d, 2C, meta), 135.92 (s, 1C, ipso), 127.26 (s, 1C, para), 174.73 (s, 1C, CO₂H), 174.11 (s, 1C, -CONH-), 53.24 (s, 1C, Phe C^α), 37.45 (s, 1C, Phe C^β), 36.58 (s, 1C, Acid C^α), 29.83-29.29 (m, 12C, Alkyl chain), 25.71 (s, 1C, Acid C^β), 22.81 (s, 1C, Acid C¹⁷), 32.05 (s, 1C, Acid C¹⁶), 14.22 (s, 1C, C¹⁸)



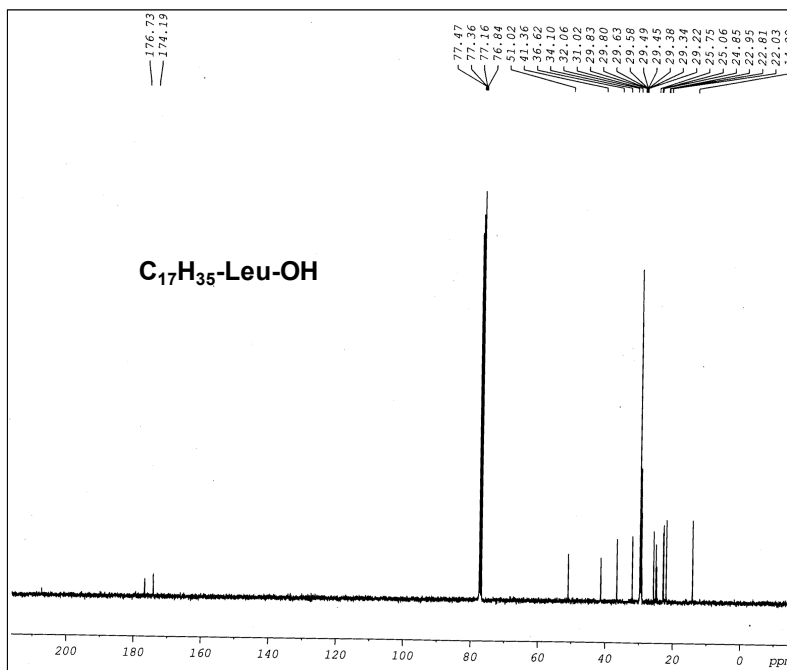
MS (35eV): m/z (%): 432 [M + H⁺]



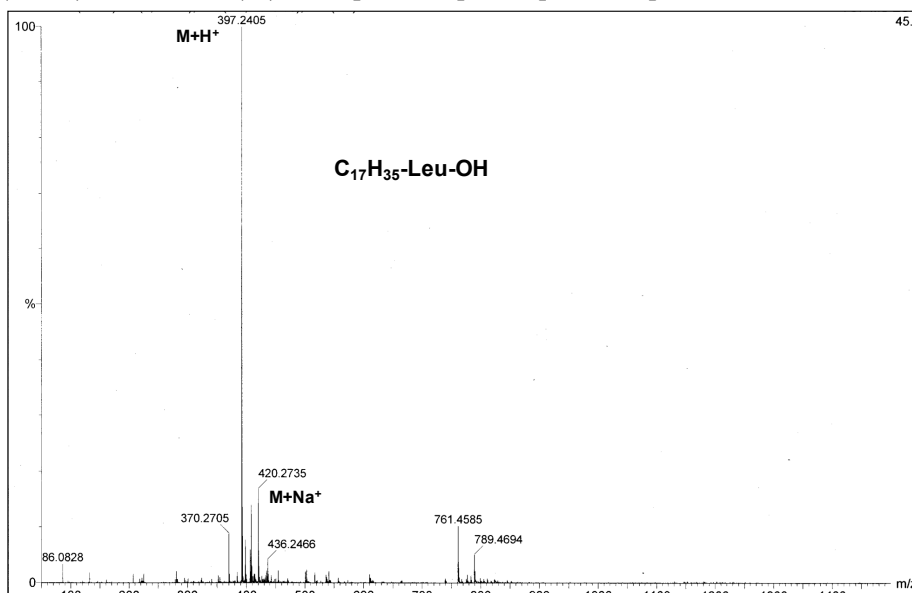
C₁₇H₃₅-Leu-OH: Yield = (75%); ¹HNMR (300MHZ, CDCl₃, TMS): δ = 0.96-0.95 (d, 6H, J = 9, Leu C^δ), 5.9-5.88 (d, 1H, J = 9, amide -NH), 4.62-4.58 (m, 1H, Leu C^αH), 1.63 (m, 2H, Leu C^βH), 1.70 (m, 1H, Leu C^γ), 2.18-2.13 (t, 2H, J = 9, -CO-CH₂-), 1.55 (br., 2H, -CH₂-), 1.26 (br., 28H, -(CH₂)₁₄-), 0.89-0.85 (t, 3H, J = 6, -CH₃).



^{13}C NMR (300MHz, CDCl_3 , TMS): $\delta = 22.95$ (d, 2C,Leu C^δ), 22.81 (d, 1C,Leu C^γ),127.68 (s,1C,ipso),155.02(s,1C,Tyr para),176.73(s,1C, CO_2H),174.19(s,1C,-CONH-), 51.02 (s,1C,Leu C^α), 41.36(s,1C,Leu C^β),36.62(s,1C,Acid C^α),31.02-29.22(m,12C,Alkyl chain), 25.75 (s,1C, Acid C^β), 22.03(s,1C, Acid C^{17}), 31.24 (s, 1C,Acid C^{16}), 14.22(s,1C, C^{18}).



MS (35eV): m/z (%): 397 [$\text{M} + \text{H}^+$], 420 [$\text{M} + \text{Na}^+$]



Preparation of salt of the amphiphile. Typically, 10 mg of C₁₇H₃₅-Tyr-OH was first dissolved in 3 mL of methanol in a small beaker; subsequently water (5 mL) was added with swirling. 0.025 N NaOH was added to it dropwise with subsequent pH measurement. At certain point, pH abruptly increases to 8.3. The salt of the amphiphile is collected after solvent removal under vacuum.

Table S1. Gelation study of the salts of the amphiphiles.

Amphiphile	Solvent	Solvent composition (v/v)	Concentration (wt %)	Appearance
C ₁₇ H ₃₅ -Tyr-ONa	Water/DMSO	4:1	0.5	TS
C ₁₃ H ₂₇ -Tyr-ONa				TS
C ₉ H ₁₉ -Tyr-ONa				OS
C ₁₇ H ₃₅ -Phe-ONa				OS
C ₁₇ H ₃₅ -Leu-ONa				OS

TS = transparent solution, OS = opaque solution.

Table S2: Reusability of gel in three cycles to prepare silica gel and its corresponding yield.

No. of cycles	%yield
1 st	96
2 nd	85.4
3 rd	76.8

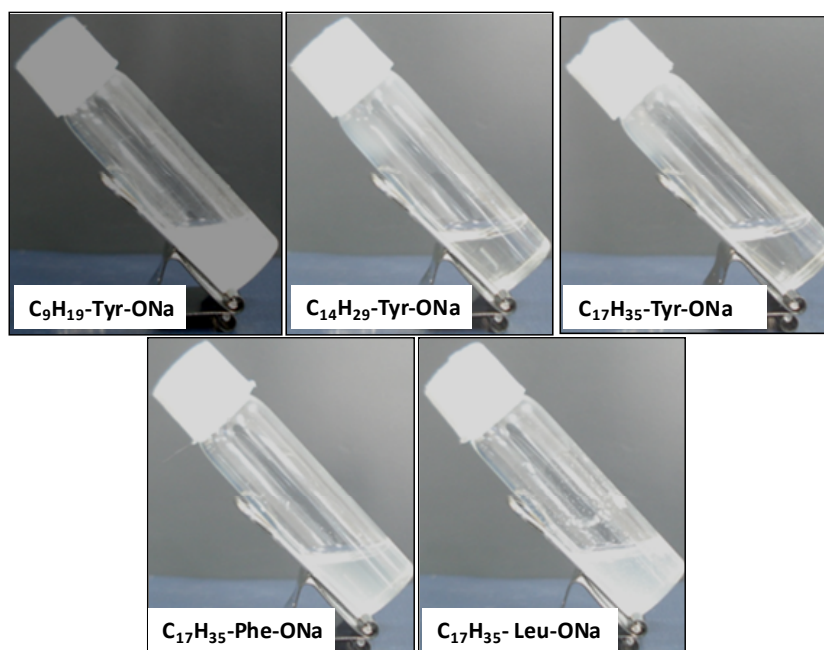


Figure S1. Photograph showing the solution of salts of amphiphiles in water/DMSO (4:1) mixed solvent.

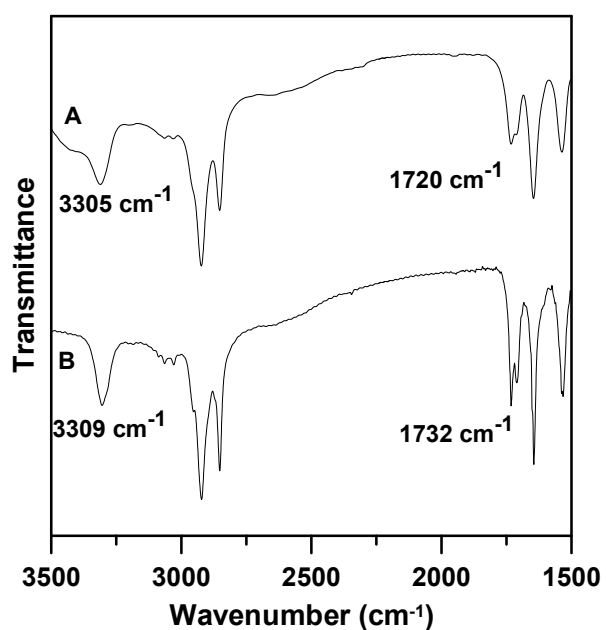


Figure S2. FTIR spectra of (A) $C_{17}H_{35}\text{-Phe-OH}$ xerogel obtained from water/DMSO and (B) $C_{17}H_{35}\text{-Phe-OH}$ in CHCl_3 solution.

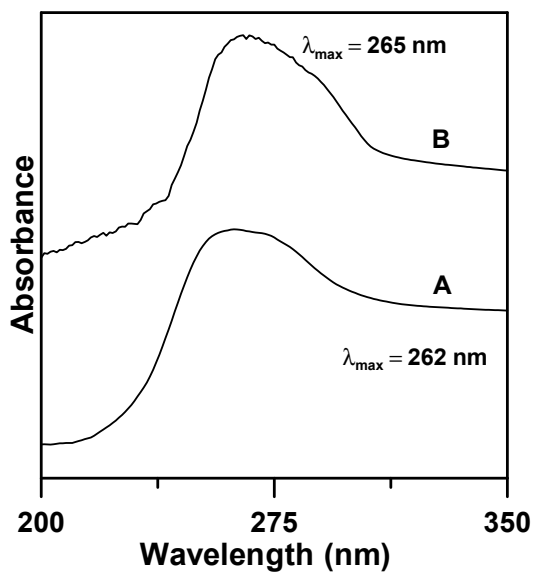


Figure S3. UV-vis spectra of (A) $\text{C}_{17}\text{H}_{35}\text{-Tyr-OH}$ gel in (4:1) water/DMSO and (B) its solution in (2:1) water/DMSO.

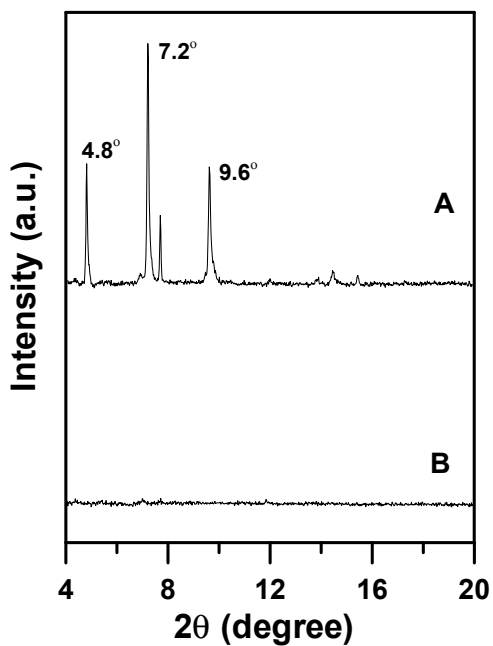


Figure S4. XRD patterns of (A) xerogel of $\text{C}_{17}\text{H}_{35}\text{-Tyr-OH}$ obtained from water/DMSO at 0.5%, (B) neat $\text{C}_{17}\text{H}_{35}\text{-Tyr-OH}$ obtained by casting from its DMSO solution.

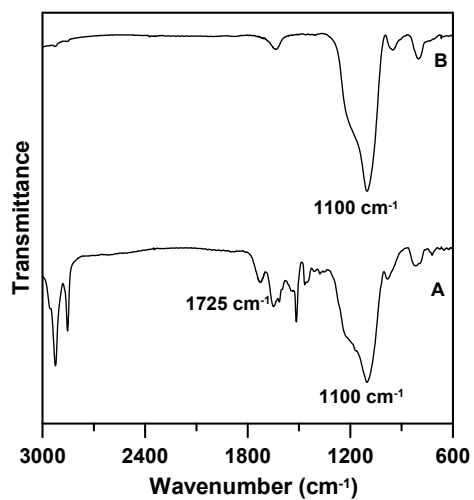


Figure S5. FTIR spectra of (A) composite gel and (B) silica aerogel obtained from C₁₇H₃₅-Tyr-OH gel in water/DMSO.

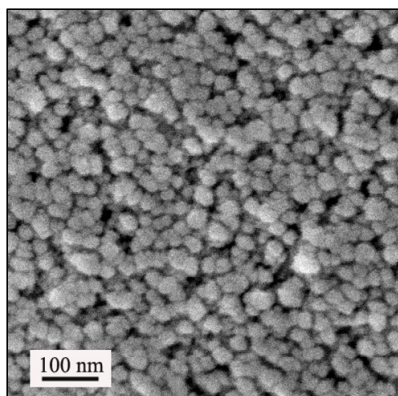


Figure S6. FESEM image of silica nanostructures obtained using C₉H₁₉-Tyr-OH gel as template in water/DMSO (4:1) mixed solvent.

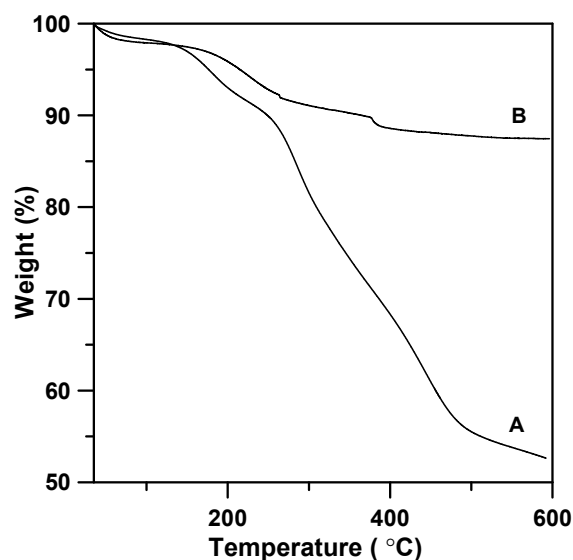


Figure S7: TGA thermograms of (A) dried composite gel and (B) silica aerogel.

Calculation of washable organic moiety present in the composite gel.

We assume that after heating to 600 °C, we obtain materials of similar nature for the dried silica gel and composite gel. We observe that 13% of physisorbed materials are removed after heating the dried silica gel at 600 °C. The remaining 87% material is silica. The weight loss of composite gel is 46%. Therefore, for the composite gel is the amount of physisorbed material is $(13/87 \times 54) = 8\%$. Therefore the total amount of organic moiety removed after methanol washing is 38%.

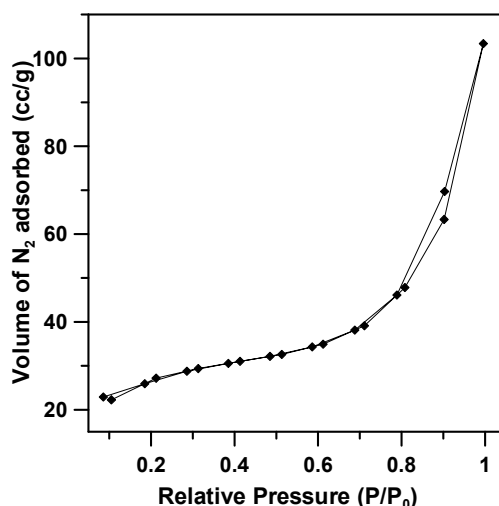


Figure S8: N₂ adsorption/desorption isotherm of silica aerogel.

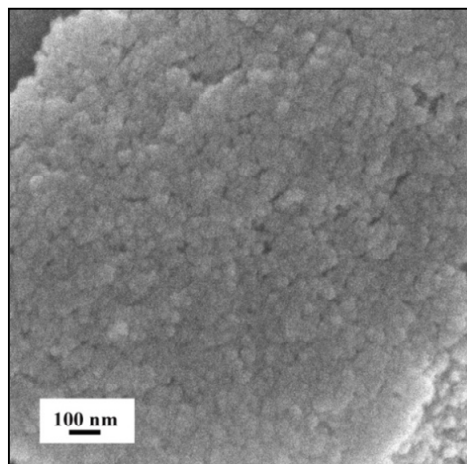


Figure S9. FESEM image of silica nanostructures obtained after using $C_{17}H_{35}-CO_2H$ as catalyst in water/DMSO (4:1) mixture as solvent.

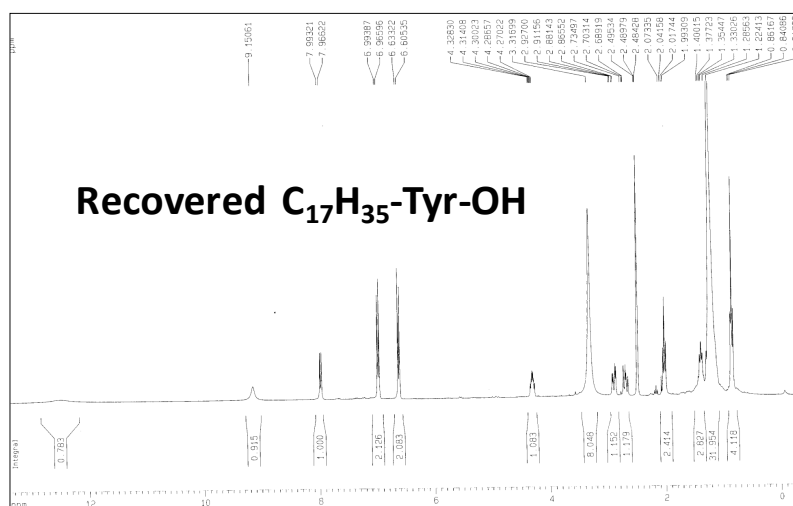


Figure S10: NMR spectrum of recovered $C_{17}H_{35}-Tyr-CO_2H$ after silica formation.

Recovered $C_{17}H_{35}-Tyr-OH$ after gel based catalysis: 1H NMR (300MHz, $CDCl_3$ + $(D_6)DMSO$, TMS): δ = 6.99-6.96 (d, 2H, J = 9, Tyr ring-Hs), 6.63-6.60 (d, 2H, J = 9, Tyr ring Hs), 9.15 (d, 1H, amide -NH), 4.32-4.27 (m, 1H, Tyr $C^{\alpha}H$), 2.92-2.86 (s, 2H, J = 6, Tyr C^{β}), 2.07-1.99 (t, 2H, J = 9, -CO- CH_2), 1.40-1.37 (br., 2H, - CH_2 -), 1.22 (br., 30H, -(CH_2 -)), 0.84-0.81 (t, 3H, J = 6, - CH_3).

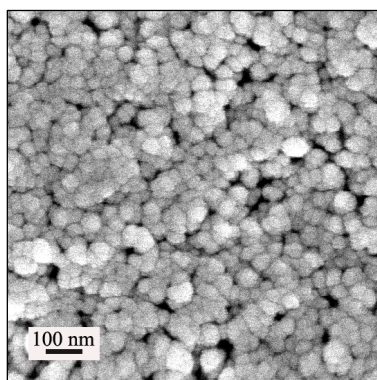


Figure S11: FESEM image of the silica gel formed after 2nd cycle using recovered C₁₇H₃₅-Tyr-OH after 1st cycle in water/DMSO at 0.5%.

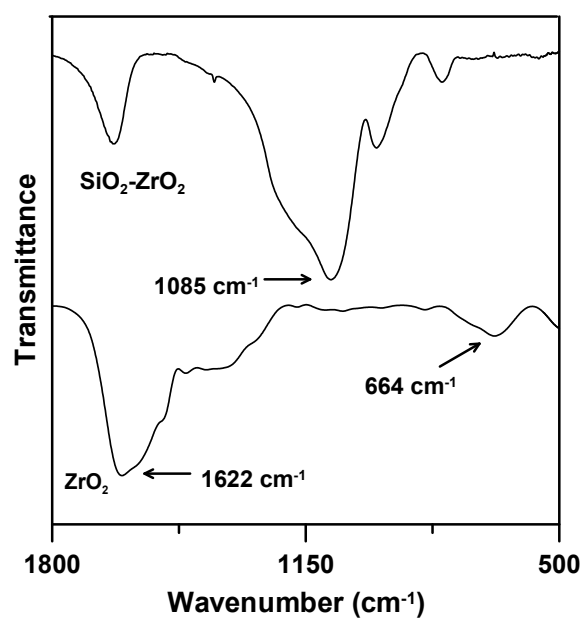


Figure S12: FTIR spectra of SiO₂-ZrO₂ and pure ZrO₂ nanostructures

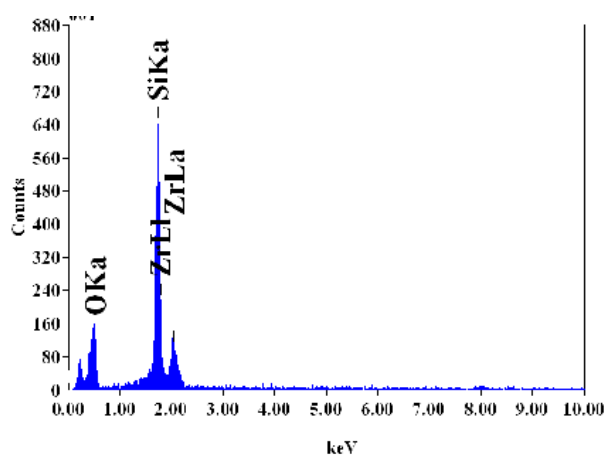


Figure S13: FESEM-EDX analysis of $\text{SiO}_2\text{-ZrO}_2$ nanostructures.

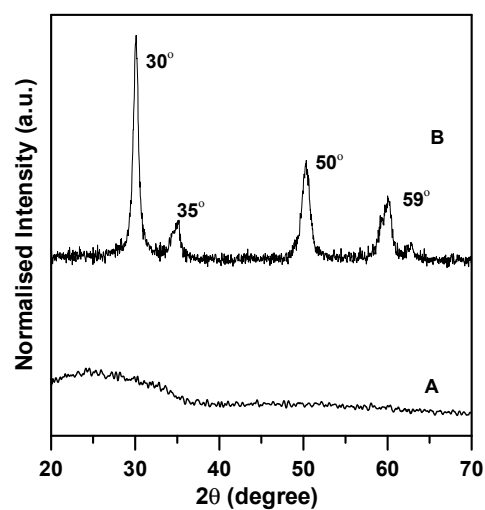


Figure S14: XRD pattern of (A) $\text{SiO}_2\text{-ZrO}_2$ and (B) neat ZrO_2 maintaining at their normalized intensity.

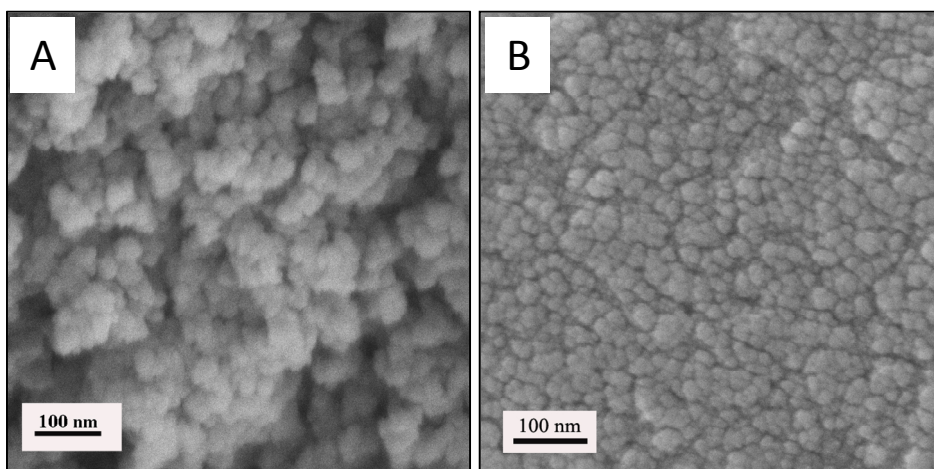


Figure S15: FESEM image of (A) SiO₂-ZrO₂ and (B) ZrO₂ obtained using C₁₇H₃₅-Tyr-OH gel (0.5%) in (4:1) water/DMSO mixture.

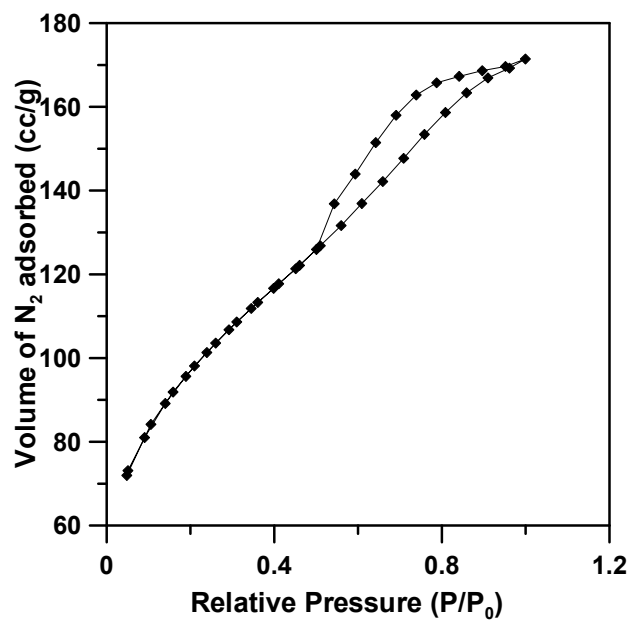


Figure S16: N₂ adsorption/desorption isotherm of SiO₂-ZrO₂ nanostructures

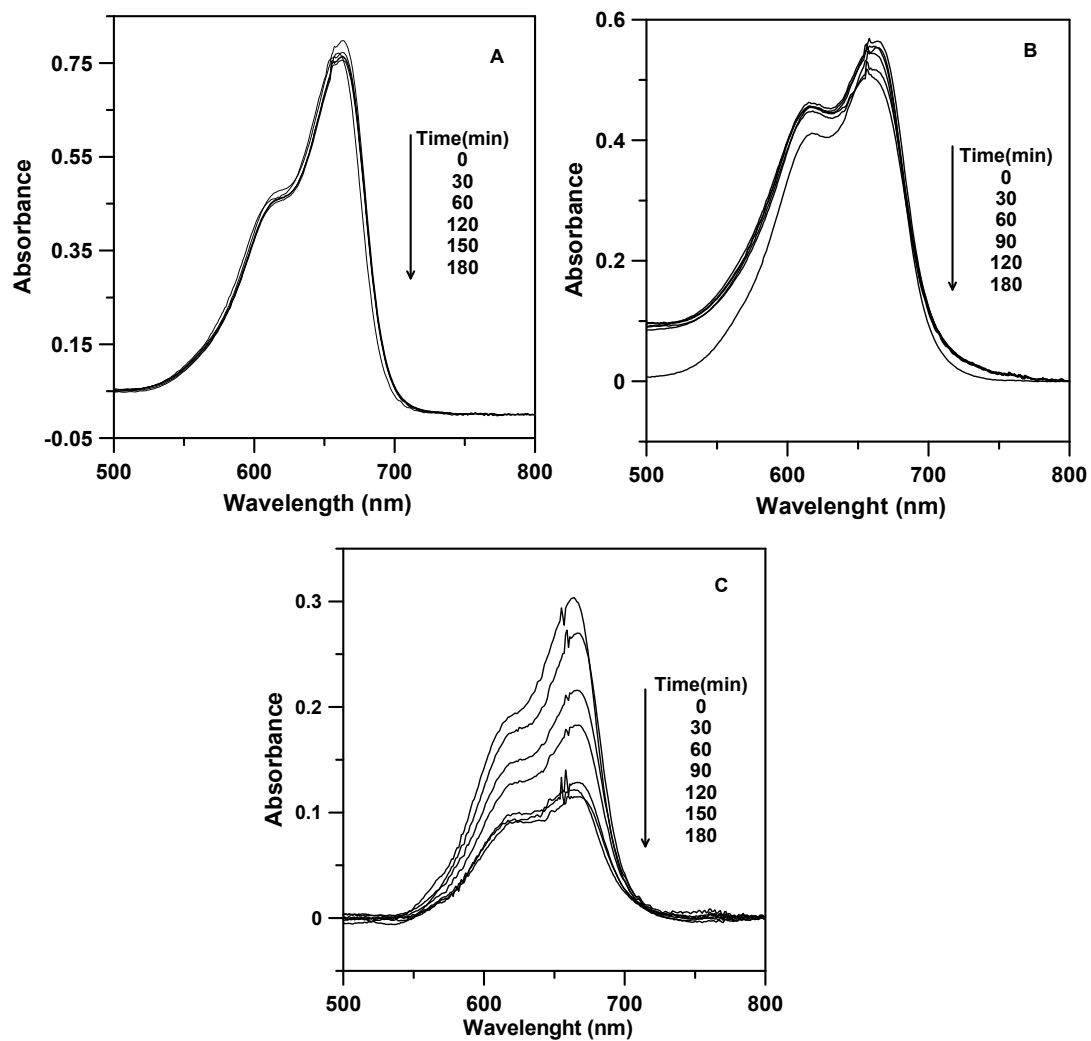


Figure S17: (A) Successive UV-vis absorption spectra of the blank photodegradation of methylene blue and using (B) neat ZrO_2 photocatalyst and (C) SiO_2-ZrO_2 mixed oxide.