

A new class of silica-supported chromo-fluorogenic chemosensors for anion recognition based on a selenourea scaffold

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General Information

All reactions were performed in oven-dried glassware under a slight positive pressure of nitrogen. ^1H -NMR (400 MHz, 500MHz) and ^{13}C NMR (100 MHz, 125MHz) spectra were determined on a Varian INOVA-400 spectrometer, and Varian INOVA-500 spectrometer. ^{77}Se NMR (76 MHz) were determined in a Bruker DRX-Advance-400 spectrometer. Chemical shifts for ^1H -NMR are reported in parts per million (ppm), calibrated to the residual solvent peak set, with coupling constants reported in Hertz (Hz). The following abbreviations are used for spin multiplicity: s = singlet, d = doublet, t = triplet, m = multiplet. Chemical shifts for ^{13}C NMR are reported in ppm, relative to the central line of a septet at $\delta = 39.52$ ppm for deuterio-dimethylsulfoxide. Chemical shifts for ^{77}Se NMR are reported in ppm, relative to the chemical shift of diphenyl diselenide (measured in $\text{DMSO}-d_6$ at $\delta = 446$ ppm). Infrared (IR) spectra were recorded on a NICOLET 5700 FT-IR spectrophotometer and reported in wavenumbers (cm^{-1}). Microanalytical data were obtained using a Fisons EA CHNS-O instrument ($T = 1000$ °C). Fluorescence spectra were recorded on a Cary Eclipse spectrofluorimeter. UV-visible spectra were acquired using a JASCO V-650 Spectrophotometer. LR-Mass spectra were recorded on a TripleTOF 5600 System, a triple quadrupole time-of-flight mass spectrometer, from AB Sciex. PXRD measurements were performed in a Seifert 3000TT diffractometer using CuK_α radiation. TEM images were acquired using a JEOL TEM-1010 Electron microscope working at 100 kV. N_2 adsorption-desorption isotherms were carried out on a Micromeritics TriStar II Plus automated analyzer. Thermogravimetric analysis were carried out on a TGA/SDTA 851e Mettler Toledo equipment, using an oxidant atmosphere (Air, 80 mL/min) with a heating program consisting on a heating ramp of 10 °C per minute from 393 K to 1273 K and an isothermal heating step at this temperature for 30 minutes. Elemental analysis were recorded on a CE Instrument EA-1110 CHN Elemental Analyzer. All solvents and starting materials were purchased from commercial sources where available. Proton NMR titrations were performed by adding aliquots of the putative anionic guest (as the TBA salt, 0.075 M) in a solution of the receptor (0.005M) in $\text{DMSO}-d_6/0.5\%$ water to a solution of the receptor (0.005M). Phenylisoselenocyanate was synthesised following a literature procedure.¹

¹J. G. Fernández-Bolaños, Ó. López, V. Ulgar, I. Maya and J. Fuentes, *Tetrahedron Letters*, 2004, **45**, 4081-4084.

Synthesis of L

A solution of phenylisoselenocyanate (0.25 g, 1.37 mmol) in dry DCM (3 ml) was added dropwise to a solution of 7-aminomethylcoumarin (0.241 g, 1.37 mmol) in ethanol absolute (2ml) in the darkness under N_2 atmosphere. The mixture was stirred for 3h at 40°C and then it was filtered to give the desired compound as a yellow solid. Yield 37 % (0.181 g, 0.51 mmol). Mp: 168°C with decomposition. ^1H -NMR (400 MHz, $\text{DMSO}-d_6$, 298K): δ H: 10.50 (s, 1H); 10.45 (s, 1H); 7.71 (d, $J = 8.6$ Hz, 1H); 7.59 (s, 1H); 7.46 (d, $J = 8.6$ Hz, 1H); 7.42 (d, $J = 7.9$ Hz, 2H); 7.36 (t, $J = 7.6$ Hz, 2H); 7.20 (t, $J = 7.3$ Hz, 1H); 6.32 (s, 1H); 7.36 (s, 3H). ^{13}C -NMR

(100 MHz, DMSO- d_6 , 298 K), δ_C : 178.94, 159.84, 153.10, 153.04, 143.17, 139.47, 128.65, 125.45, 125.31, 124.53, 119.69, 116.04, 112.80, 110.34, 18.08. +HR-ESI-TOF MS: m/z 359.0316 $[M-H]^+$.

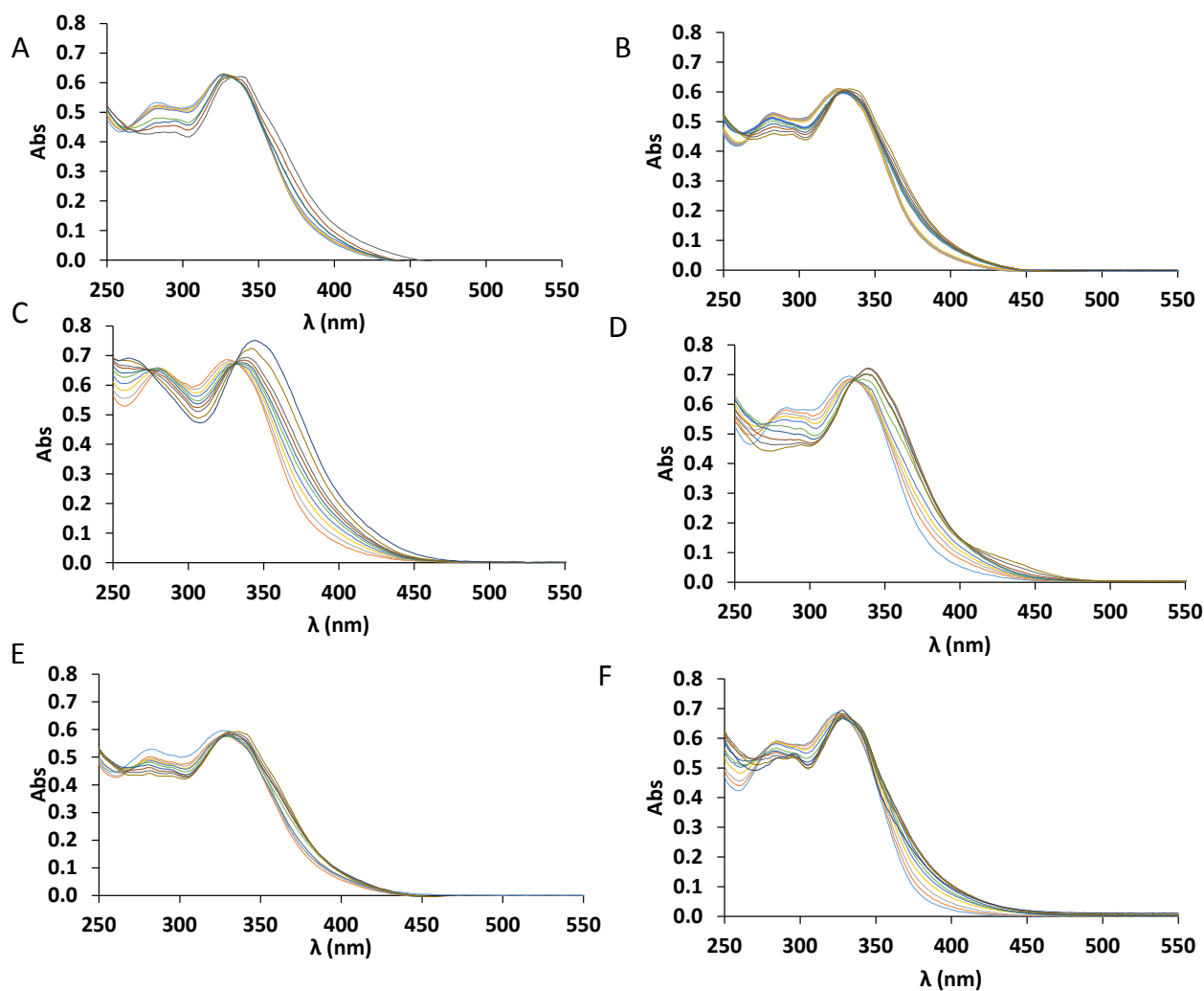


Figure S1 Changes in the absorption spectra of **L** ($3.0 \cdot 10^{-5} M$) in MeCN upon addition of increasing amounts (up to 1 equivalent) of anion ($2.5 \cdot 10^{-3} M$): A) HCO_3^- , B) F^- , C) CN^- , D) AcO^- , E) BzO^- , F) S^{2-} . Anions were added as TBA salts (AcO^- , F^- , CN^-), TEA (HCO_3^-), Na (S^{2-}).

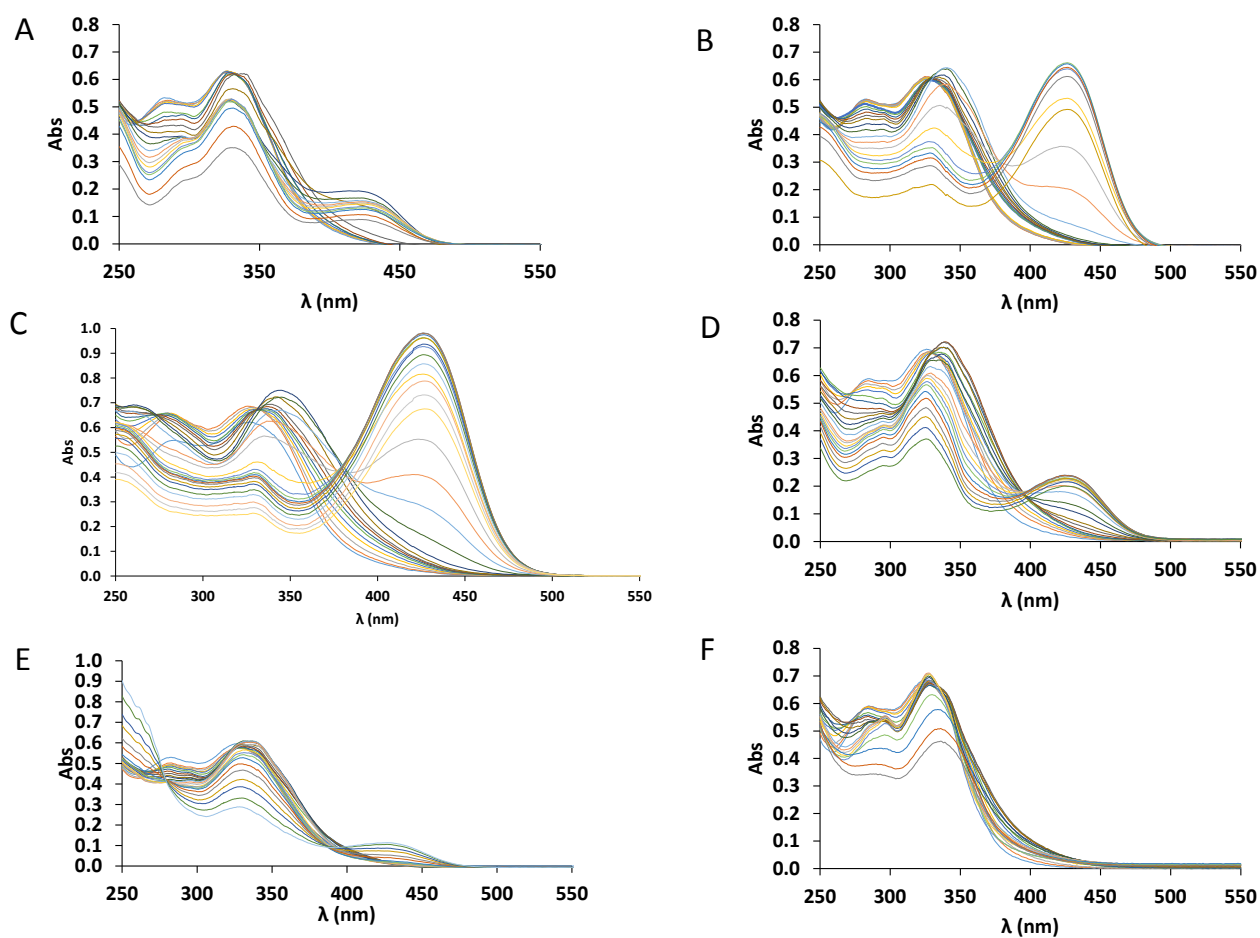


Figure S2 Changes in the absorption spectra of **L** ($3.0 \cdot 10^{-5} \text{ M}$) in MeCN upon addition of increasing amounts (up to 50 equivalents) of anion ($2.5 \cdot 10^{-3} \text{ M}$): A) HCO_3^- , B) F^- , C) CN^- , D) AcO^- , E) BzO^- , F) S^{2-} . Anions were added as TBA salts (AcO^- , F^- , CN^-), TEA (HCO_3^-), Na (S^{2-}).

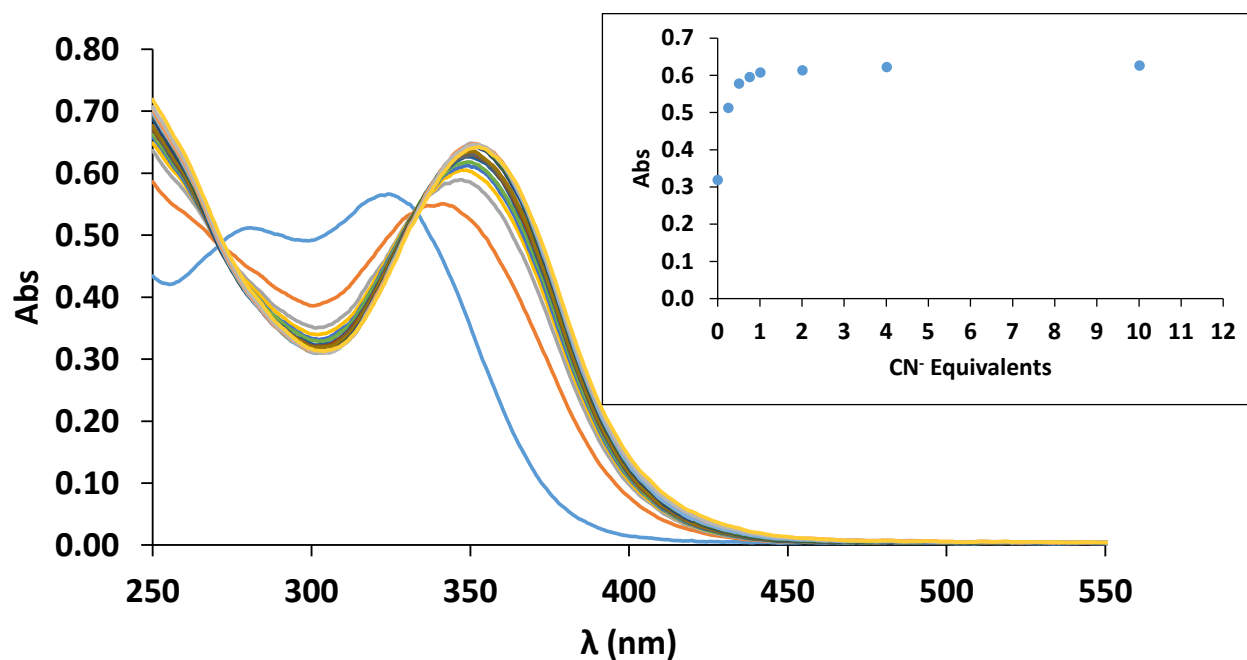


Figure S3. Changes in the absorption spectrum of **L** ($3.0 \cdot 10^{-5} \text{M}$) in $\text{H}_2\text{O}/ \text{MeCN}$ (75:25 v/v) upon addition of increasing amounts (up to 10 equivalents) of TBACN (0.1 M). Inset: Plot of absorbance (353 nm) vs. equivalents of CN^- .

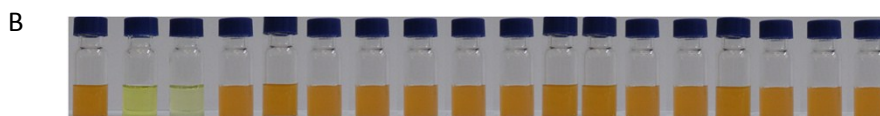
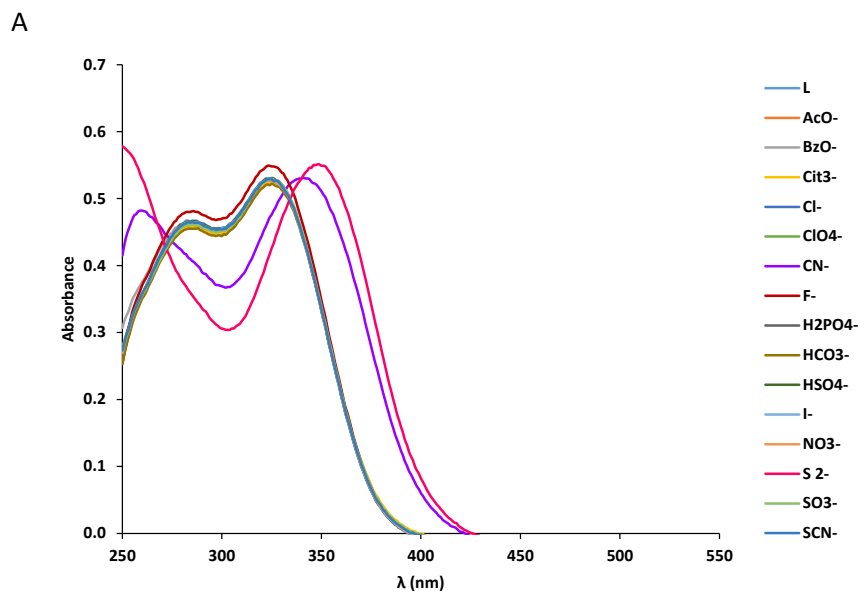


Figure S4 A) Changes in the absorption spectrum of **L** ($3.0 \cdot 10^{-5} \text{M}$) in $\text{H}_2\text{O}/ \text{MeCN}$ (75:25 v/v) upon addition one equivalent of anions. B) Naked-eye colour change. From left to right : **L**, CN^- , S^{2-} , BzO^- , Cl^- , H_2PO_4^- , I^- , Br^- , NO_3^- , AcO^- , HSO_4^- , ClO_4^- , SO_3^{2-} , F^- , HCO_3^- , SCN^- , Cit^{3-} .

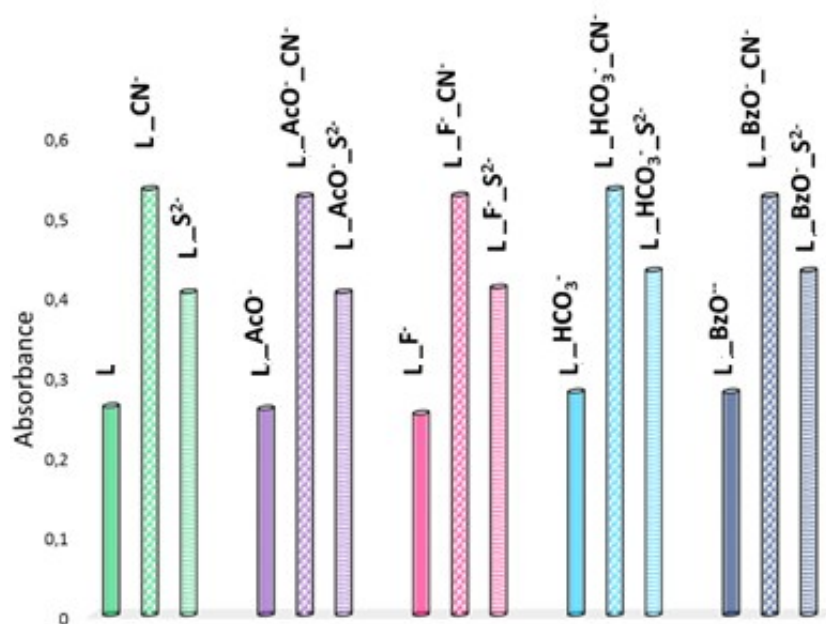


Figure S5. Anion competition study for L [$3.0 \cdot 10^{-5}$ M] in the presence of 1 equivalent of CN⁻ and S²⁻ and 1 equivalent of the other anions (0,1 M) in H₂O/ MeCN (75:25 v/v) (λ_{ABS} : 353 nm).

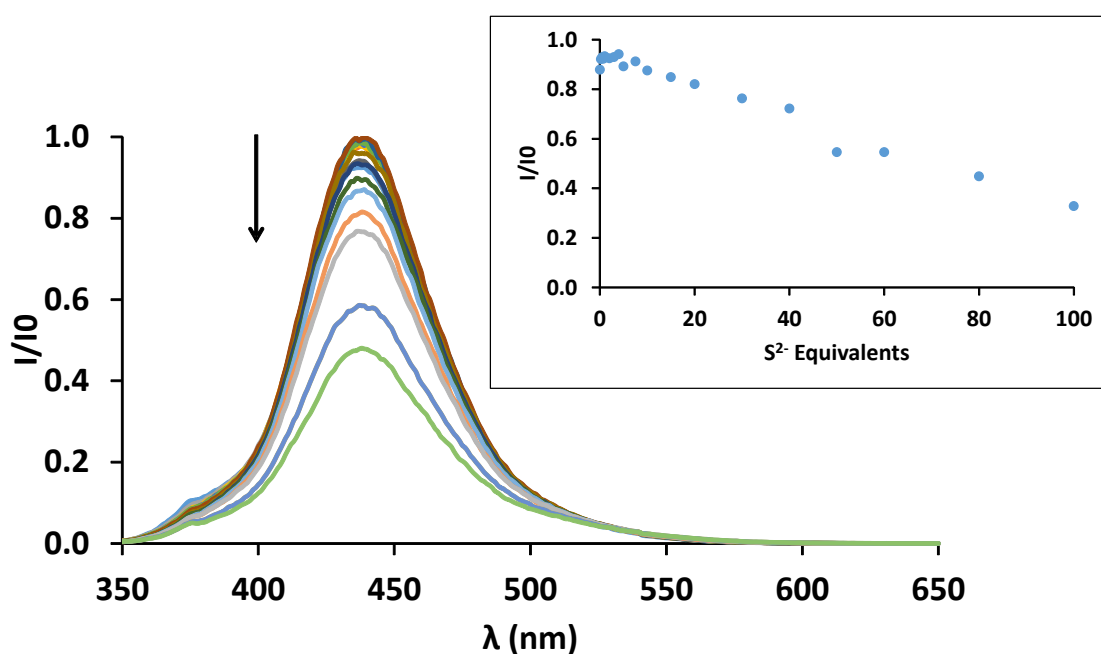


Figure S6. Changes in the emission spectrum of L ($3.0 \cdot 10^{-5}$ M) in H₂O/ MeCN (75:25 v/v) upon addition of increasing amounts (up to 100 equivalents) of Na₂S (0.1 M). Inset: Plot of emission at 438 nm vs. equivalents of S²⁻ added.

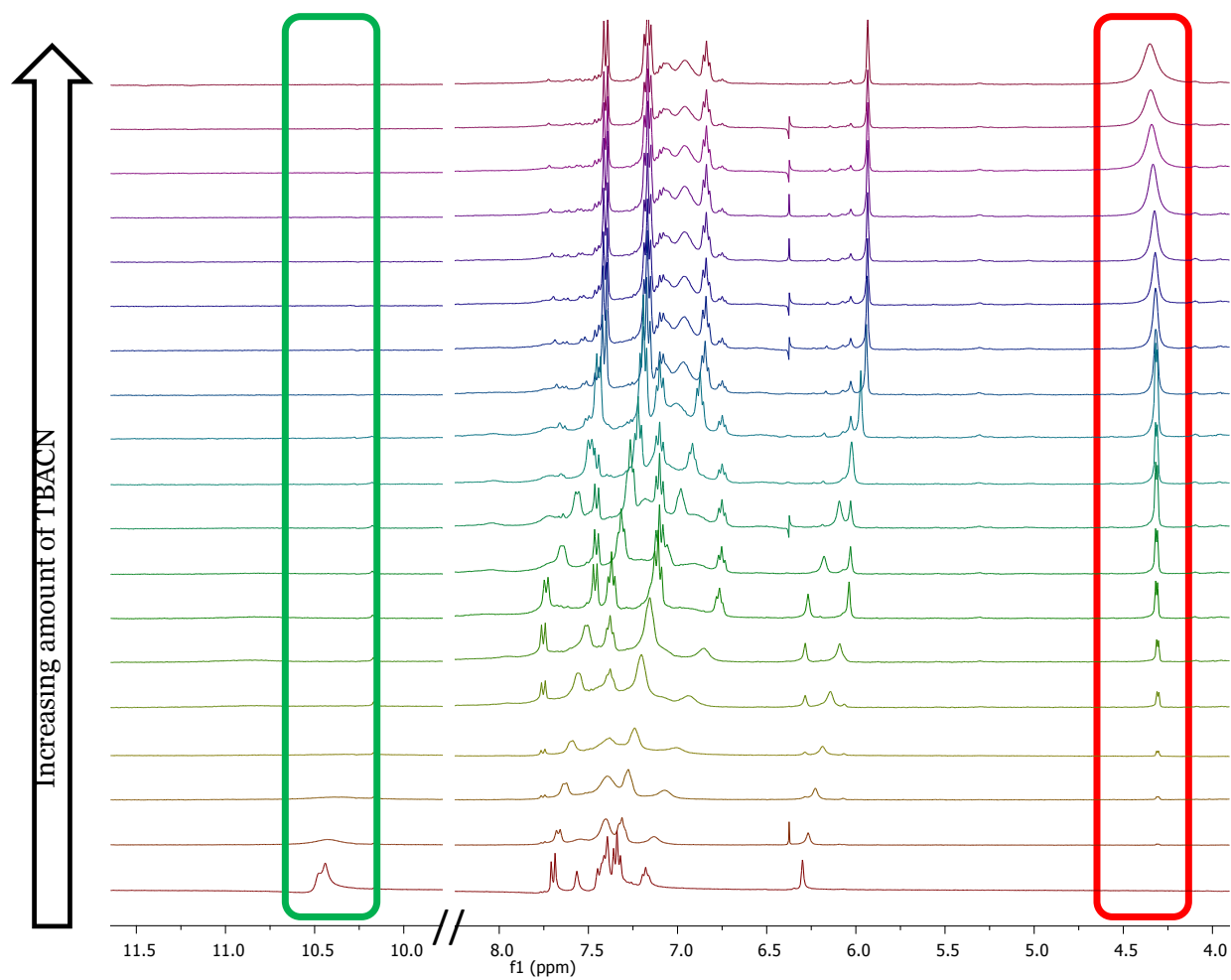


Figure S7. Stack plot of the ¹H-NMR titration of **L** in the presence of TBACN in DMSO-*d*₆/0.5% H₂O.

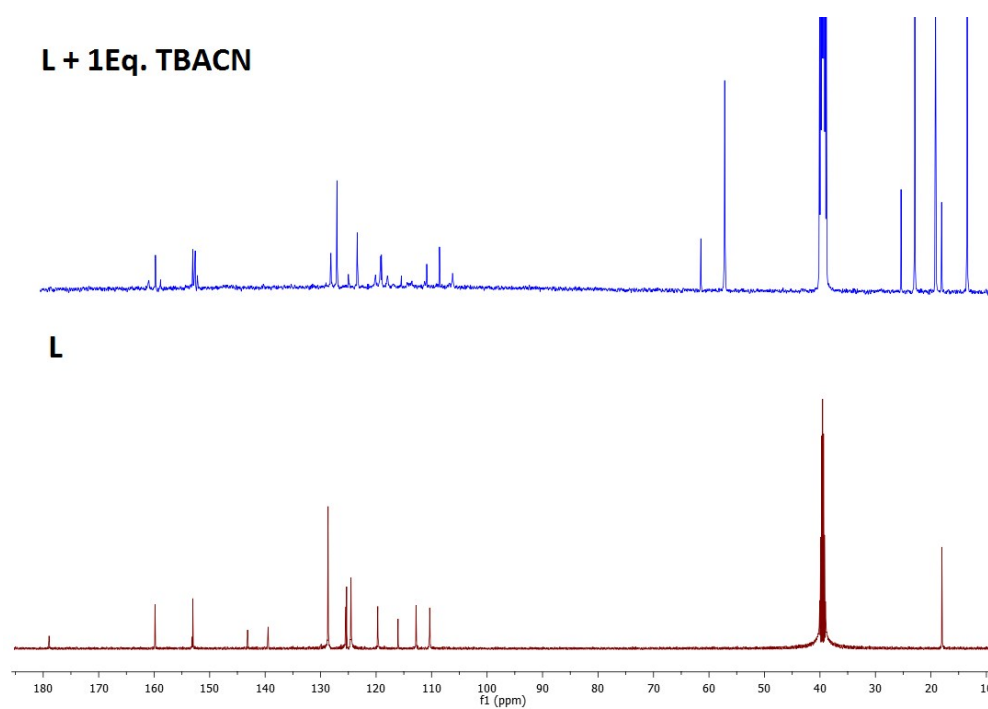


Figure S8 ^{13}C -NMR spectrum of free **L** and in the presence of 1 and 2 equivalents of TBACN in $\text{DMSO-}d_6/0.5\% \text{H}_2\text{O}$.

Table S1. ^{13}C -NMR peaks of free **L** and upon addition of 1 equivalent of TBACN in $\text{DMSO-}d_6/0.5\% \text{H}_2\text{O}$.

^{13}C free L	^{13}C free L + 1 Eq. CN^-
179.01 (C=Se)	
159.88	160.17
153.10	159.91
153.04	153.49
143.16	153.39
139.46	153.23
128.65	128.37
125.45	126.02
125.31	124.95
124.53	123.07
119.69	119.27
116.69	116.24
112.80	112.55
	111.66 (CN^-)
110.33	109.21
	61.92 (C-Se-Se-C)
18	18

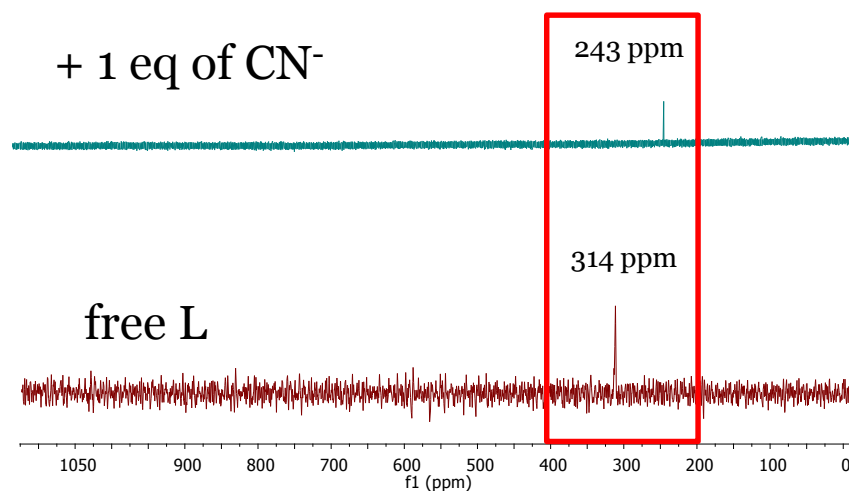


Figure S9 ^{77}Se -NMR spectrum of free **L** and in the presence of 1 equivalent of TBACN in $\text{DMSO-}d_6/0.5\% \text{ H}_2\text{O}$.

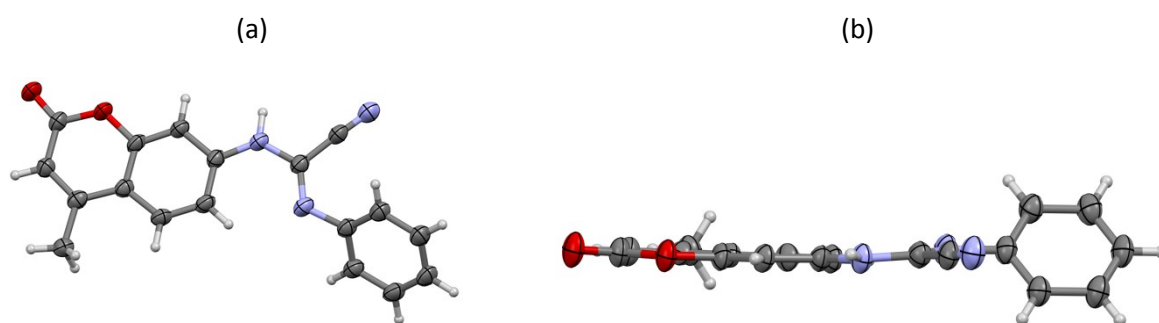


Figure S10 Crystal structure of the carbonocyanamidic amide **3**. View from the front (a) and from the side (b).

Table S2. Crystallographic data

Empirical formula	$\text{C}_{18}\text{H}_{13}\text{N}_3\text{O}_2$
Formula weight	303.31
Crystal system	monoclinic
Space group	$P 2_1/n$
a / Å	18.832(3)
b / Å	3.8846(6)
c / Å	20.977(3)
α / °	90
β / °	115.297(17)
γ / °	90
v / Å³	1387.4(4)

T / K	130(1)
Crystal shape	PRISM
Crystal size / m³	0.12 × 0.05 × 0.05 mm ³
Colour	yellow
Z	4
θ range for data collection	2.65–67.50°
Index ranges	$-22 \leq h \leq 20$, $-4 \leq k \leq 4$, $-16 \leq l \leq 25$
Reflections collected	5060
Independent reflections	2502 [$R_{int} = 0.0658$]
Completeness	99.4 % ($\theta = 67.5^\circ$)
Absorption correction	multi-scan
Max. and min. transmission	0.74927 and 0.76233
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2502 / 0 / 213
Goodness-of-fit on F^2	1.076
Final R indices [$F^2 > 2\sigma(F^2)$]	$R1 = 0.0742$, $wR2 = 0.1816$
R indices (all data)	$R1 = 0.0935$, $wR2 = 0.1972$
Largest diff. peak and hole	0.306 and $-0.425 \text{ \AA}^{-3}$

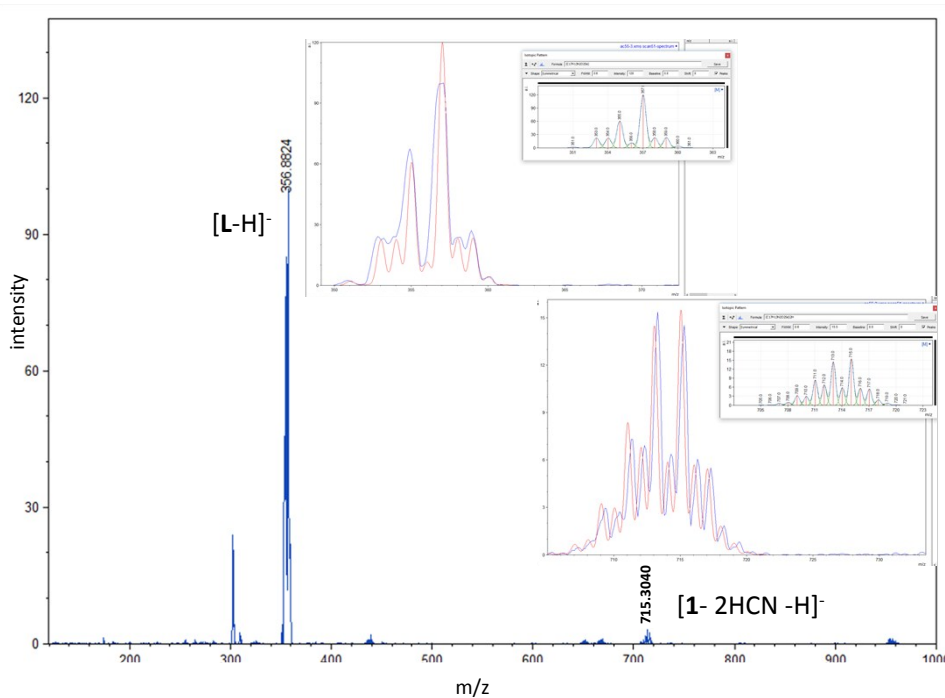


Figure S11 LR-ESI-MS spectrum of **L** in the presence of two equivalent of TBACN and the simulated isotopic pattern. The shift of m/z 0.23 between the experimental and the calculated peaks is due to the instrument.

+ 1 eq of S^{2-}



free **L**

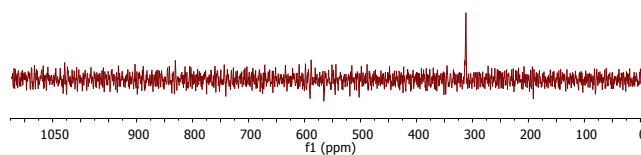


Figure S12. ^{77}Se -NMR spectrum of free **L** and in the presence of 1 equivalent of Na_2S in $\text{DMSO}-d_6/0.5\% \text{H}_2\text{O}$.

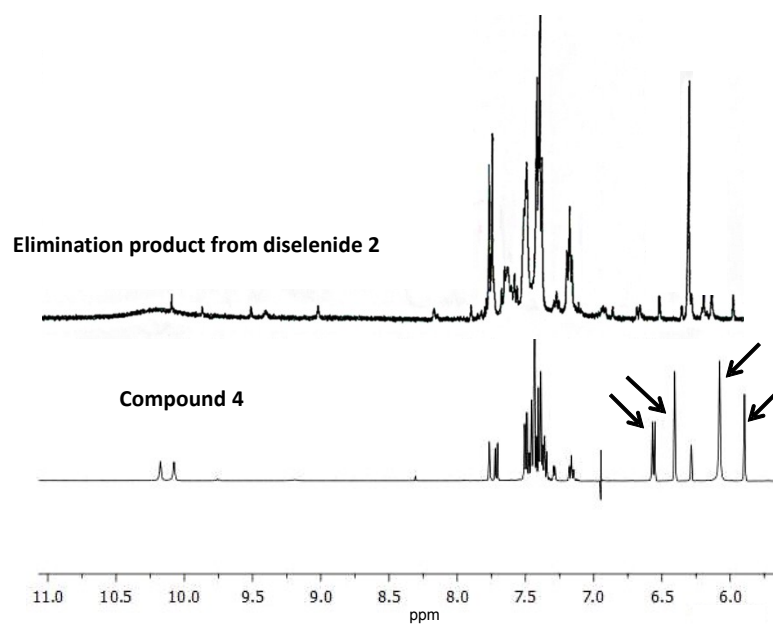


Figure S13. ^1H -NMR spectra of the product obtained by reaction of **L** with one equivalent of Na_2S and the thiourea **4** in $\text{DMSO}-d_6/0.5\% \text{H}_2\text{O}$. The arrows indicate the peaks of 7-amino-4-methylcoumarin used as starting material.

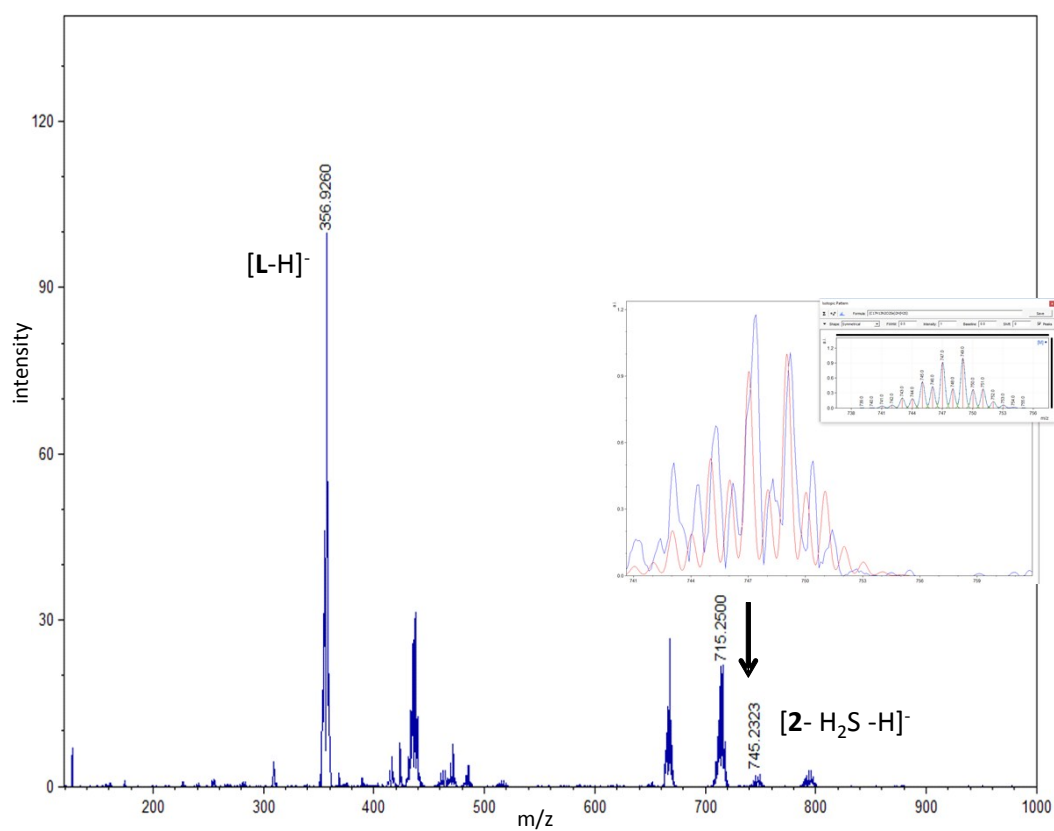
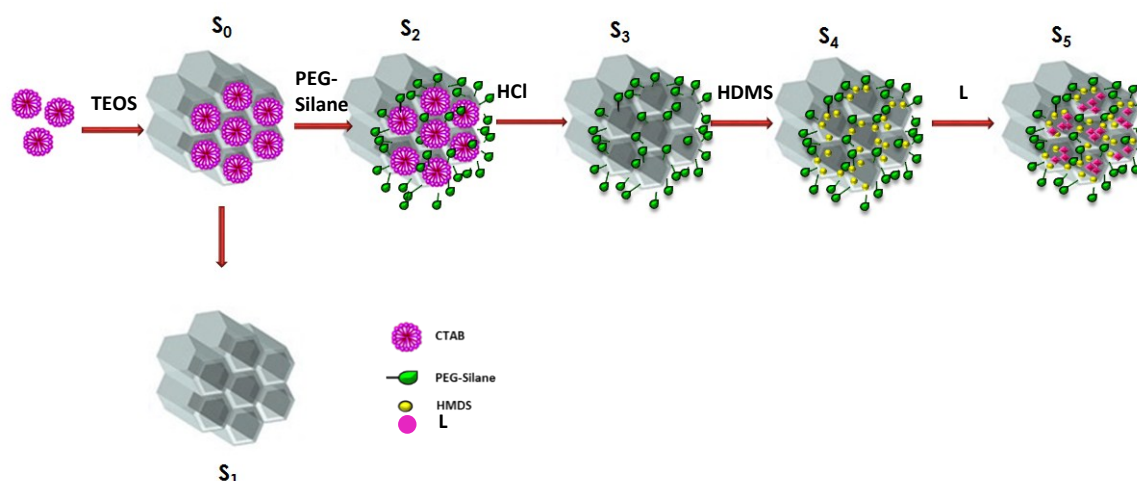


Figure S14 LR-ESI-MS spectrum of **L** in the presence of two equivalent of Na_2S and the simulated isotopic pattern. The shift of m/z 0.18 between the experimental and the calculated peaks is due to the instrument.

Synthesis of the Hybrid MCM-41 nanoparticles



Scheme S1 Synthesis procedure of hybrid MCM-41 nanoparticles.

Synthesis of MCM-41 mesoporous silica nanoparticles

N-cetyltrimethylammonium bromide (CTAB, 1.00 g, 2.74 mmol) was first dissolved in deionized water (480 mL). Then, NaOH (3.5 mL, 2.00 M) in deionized water was added to the CTAB solution, followed by adjusting the temperature to 80 °C. TEOS (5 mL, 25.7 mmol) was then added dropwise. The mixture was stirred for 2 h to give a white precipitate. Finally, the solid product was centrifuged, washed with deionized water and ethanol, and dried at 60 °C (as-made MCM-41).

A portion of the synthesized mesoporous silica nanoparticles was calcined at 550 °C using an oxidant atmosphere for 5 h in order to remove the template phase (calcined MCM-41).

Synthesis of MCM-41 with hydrophobic pockets (S1)

In order to prepare MCM-41 nanoparticles with hydrophobic pockets, first 0.5 g of as-made **MCM-41** was suspended in acetonitrile (40 mL) and 2.5 mmol (1.67 mL) of 3-[Methoxy(polyethylenoxy)propyl] trimethoxy silane (PEG-Silane [9-12]) was added. The suspension was stirred for 5.5 h at room temperature with the aim of achieving the functionalization of the external surface of the nanoparticles. Then, the solid was isolated by centrifugation, washed with acetonitrile and abundant water, and dried at 37 °C for 12 h.

Then, the CTAB template was removed by extraction with HCl solution. At this respect, 0.5 g of this solid was suspended in 50 mL of hydrochloride acid solution in EtOH (1 M) and refluxed for 12 h. This procedure was repeated 3 times, washing the solid between each cycle with deionized water. To functionalize the internal surface, 0.341 g of the template-free solid was suspended in acetonitrile (50 mL) and hexamethyldisilazane (HMDS, 0.590 mL, 2.83 mmol) was added. The mixture was stirred 18 h at room temperature in order to achieve the maximum functionalization of the pores. Finally, the obtained solid (**S1**) was isolated by centrifugation, washed with abundant water and dried at 37 °C for 12 h.

Preparation of L-loaded nanoparticles (S2)

For the preparation of loaded sensing solid **S2**, 0.06 g of nanoparticles **S1** were suspended in 5 mL of a solution of probe **L** (2.33 mg, 0.17 mmol) in acetonitrile. Then, the mixture was stirred for 12 hours at room temperature with the aim of achieving maximum loading of the pores of the MCM-41 scaffolding. Finally, the final sensing solid (**S2**) was isolated by centrifugation, washed with water and acetonitrile and dried under vacuum.

Characterization of the Hybrid MCM-41 nanoparticles

The power X-ray diffraction (PXRD) of the as-made MCM-41 (see Figure S13, curve A) shows the typical low-angle reflections that index as (100), (110), (200) and (210) Bragg peaks. From the PXRD data of the as-made MCM-41, a d100 spacing of 39.99 Å was calculated. A displacement of the peaks in the PXRD of the calcined MCM-41 was found it is related to further condensation of silanol groups during the calcination step (Figure S12, curve B). The presence of the main peak at 2.2° in the functionalized material (**S1**) indicates that the 3D mesoporous structure is maintained after the different chemical treatments (Figure S12, curve C).

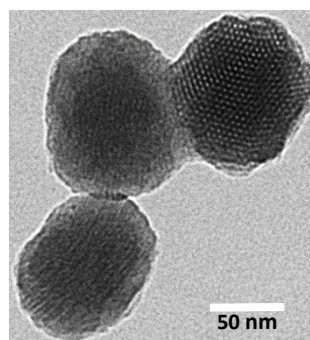
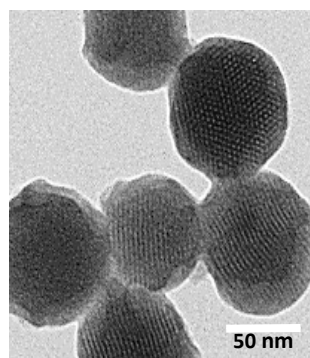
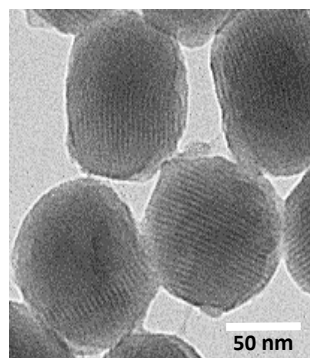
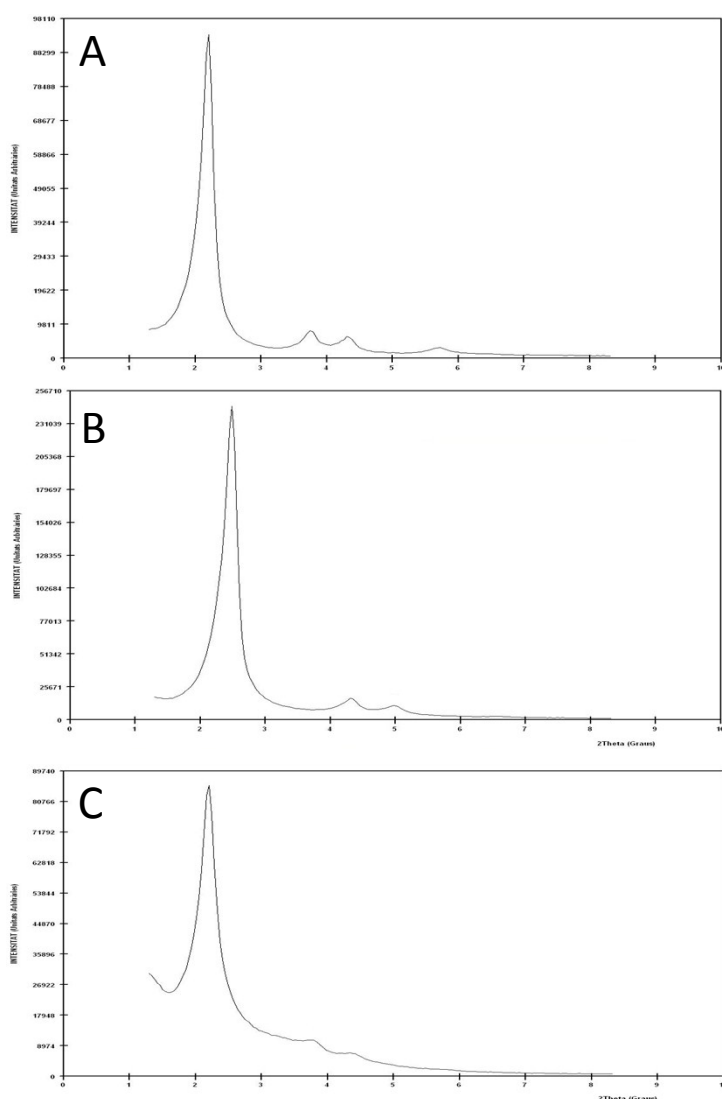


Figure S15 Powder X-ray patterns of the solids MCM-41 as synthesized S_0 (A), calcined MCM-41 S_1 (B) and functionalized MCM-41 S_4 (C). Right: TEM images of MCM-41 as synthesized S_0 (A'), calcined MCM-41 S_1 (B') and functionalized MCM-41 S_4 (C'), showing the typical hexagonal porosity of the MCM-41 mesoporous matrix.

The N_2 adsorption-desorption isotherms of the calcined MCM-41 S_1 and functionalized nanoparticles S_4 show the typical curve for mesoporous solid; i.e. an adsorption step at intermediate P/P_0 value 0.3 (figure S13, curves A and B). This step is related to the nitrogen condensation inside the mesopores by capillarity. The absence of a hysteresis loop in this interval and the narrow BJH pore distribution suggest the existence of uniform cylindrical mesopores. The application of the BET model results in a value for the total specific surface of $1004.5 \text{ m}^2 \cdot \text{g}^{-1}$ for calcined MCM-41 S_1 and $627.0 \text{ m}^2 \cdot \text{g}^{-1}$ for S_4 .

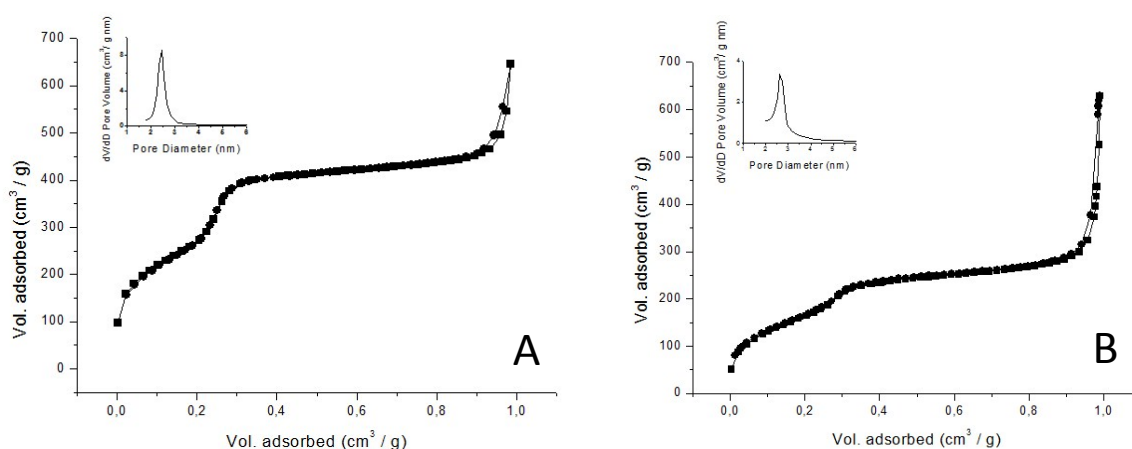


Figure S16. The N_2 adsorption-desorption isotherms for (A) the calcined MCM-41 mesoporous nanoparticles S_1 and (B) functionalized nanoparticles S_4 . Inset: Pore size distribution.

N_2 adsorption-desorption isotherms for the solids S_1 and S_4 show a significant decrease in N_2 volume adsorbed as a consequence of functionalization. The pore size was estimated by using the BJH model applied on the adsorption band of the isotherm for $P/P_0 < 0.6$. Total pore volume was also calculated according to BJH model. BET specific values, pore volumes and pore sizes calculated from N_2 adsorption-desorption isotherms for selected materials are reported in Table S3.

Table S3. BET specific surface values, pore volumes and pore sizes calculated from N_2 adsorption-desorption isotherms for selected materials.

	S_{BET}	Pore volume ^a	Pore size ^a
	$(\text{m}^2 \cdot \text{g}^{-1})$	$(\text{cm}^3 \cdot \text{g}^{-1})$	(nm)
Calcined	1004.5	0.764	2.53

Functionalized	627.0	0.46	2.65
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[a] Pore volume and Pore size estimated by using the BJH model applied to the adsorption branch of the isotherm, for $P/P_0 < 0.6$, which can be associated with the surfactant-generated mesopores.

The thermal analysis of S_4 and S_5 shows a typical behaviour of functionalized mesoporous materials, that is, an initial weight loss between 50 and 150 °C related to solvent evaporation, a second loss between 150 and 800 °C due to the combustion of organic material, and a final loss in the 800-1000 °C range related to the condensation of the silanol groups. The loading of the final solid S_5 was determined by elemental analysis and thermogravimetric studies. A ratio of 0,442 mmol L/g SiO_2 was calculated.