Synthesis and Chemical Reactivity of α-Oxo Aldehyde-Supported Silicas

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The synthesis and characterisation of α-oxo aldehyde-supported silicas by the sol-gel procedure is described. The glyoxylyl group was generated after gelation, either by periodic oxidation of gluconamide chains or by deprotection of a diisopropylthioacetal-protected derivative. The accessibility and reactivity of the supported α-oxo aldehyde function was investigated in model reactions with hydroxylamine and hydrazine derivatives.

Introduction

Sol-gel chemistry[1] is an important and general route for the synthesis of modified silicas incorporating organic moieties. Hybrid organic-inorganic[2] silica-based materials are prepared by sol-gel hydrolysis and condensation of alkoxysilylated organic molecules, combining the characteristics of the inorganic network and of the organic component, both organic and inorganic units being linked through stable Si−C bonds. Many applications have so far been described, in fields such as catalysis,[3a] nonlinear optics[3b−3c] or biomaterials,[3d−3g] as the mild conditions of the sol-gel procedure preserve the characteristics of sensitive molecules. In the course of our work on hybrid organic-inorganic materials, we were interested in the preparation of α-oxo aldehyde (COCHO) functionalised silicas. Indeed, such materials have scarcely been studied[4] despite the unique reactivity of the glyoxylyl group in solution,[5] and the procedures described need several steps. In solution, the COCHO group reacts efficiently with hydroxylamines, hydrazine derivatives or β-aminothiols to give oxime, hydrazone or thiazolidine adducts under very mild experimental conditions. These reactions have been extensively exploited for site-specific biomolecule modification and for the convergent synthesis of macromolecules.[6] These classical liquid-state reactions are not necessarily efficient when one of the reactants is confined to a surface[7] and depend on the accessibility at the surface, the polarity and porosity of the material, and the steric hindrance of the reactants. We thus set out to examine the reactivity of the glyoxylyl group inside the silica matrix and to examine the potential of the COCHO function chemistry for the preparation of diverse hybrid organic-inorganic materials.

In this paper we describe trialkoxysilanes precursors bearing a masked COCHO function and their use for the preparation of glyoxylyl silicas. The reactivity of the new materials was examined in model reactions with hydroxylamine or 3-methyl-2-benzothiazolinone hydrazone hydrochloride (MBTH).

Results and Discussion

To overcome time-consuming multi-step syntheses of trialkoxysilane precursors, we first examined the viability of commercially available and cheap(triethoxysilyl)propylgluconamide (GAPS) as a masked glyoxylyl group for the preparation of the materials.

The NH_4F-catalysed nucleophilic co-gelation of GAPS (solution in ethanol) with tetraethoxysilane was performed as shown in Scheme 1. The gelation was efficient only for low values of x (1,2). At high values of x, phase separation and precipitation occurred.

The gels **X1** were analysed by IR and solid-state NMR spectroscopy. CP MAS ^{29}Si NMR (ppm) shows resonances at $\delta = -111$ (Q^4) and -101 ppm (Q^3), corresponding to SiO_4 units possessing four and three siloxane bridges, respectively. Resonances at $\delta = -66$ (T^3) and -56 ppm (T^2) (minor) correspond to SiO_3 units with three and two siloxane bridges, respectively. Xerogels **X1** are well condensed, as no units with one siloxane bridge are observed. IR (cm^{-1}) shows resonances at 3500−3200 (ν OH), 2944 (ν CH), 2893 (ν CH), 1654 (ν C=O), 1554 (δ NH), 1200−1050 and 950 (ν Si−O). CP MAS ^{13}C NMR shows resonances at $\delta = 10$ (CH_2−Si), 23 (CH_2), 43 (CH_2−N), 72 (CH−OH,

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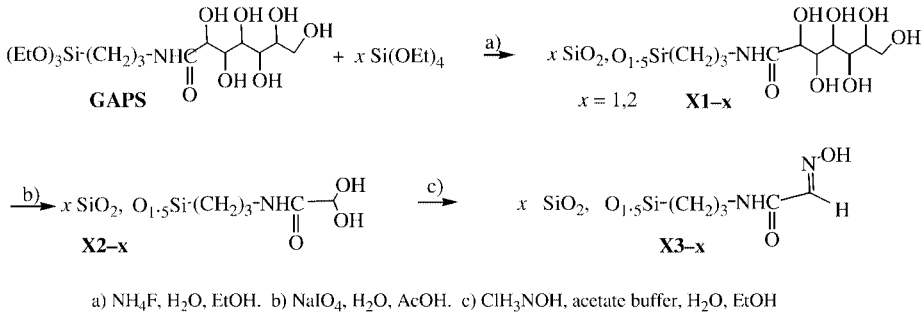


Scheme 1. Syntheses and reactivities of COCHO xerogels from GAPS precursor

major large signal) and 172 ppm (C=O). The carbon chain was not damaged by the sol-gel procedure.

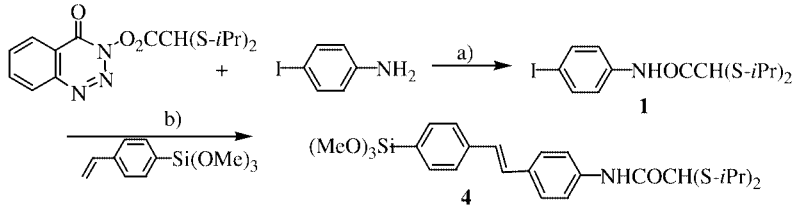
With the GAPS material to hand, we next examined the conversion of the gluconamide chain into the glyoxylyl group. We anticipated that oxidative cleavage of the polyol moiety by periodate should provide a COCHO group, since diols, α-hydroxy ketones and α-diketones, but not α-keto amides,[9] are readily cleaved under those conditions. Xerogel **X1** was therefore treated with aqueous sodium periodate[8] and the new material was characterised as above. IR spectroscopy shows resonances at 3500−3200 (ν OH), 2942 (ν CH), 1663 (ν C=O), 1558 (δ NH), 1085 and 943 (ν Si−O). The (ν C=O) band is shifted to higher wavelength after oxidation. CP MAS ^{13}C NMR shows resonances at δ = 10.9 (CH_2−Si), 22.9 (CH_2), 42.3 (CH_2−N), 87.5 [$CH(OH)_2$] and 171.2 ppm (C=O). The disappearance of the signals at δ = 72 ppm demonstrates the cleavage of the polyol chain and, importantly, the appearance of a new signal at δ = 87.5 ppm confirms the presence of the α-oxo aldehyde function in the hydrated form. Indeed, glyoxylic acid is known to exist essentially in its hydrated form in water.[5] Signals around δ = 185 ppm, which could have arisen from partial oxidation of the gluconamide chain, are not observed.

The accessibility and reactivity of the supported COCHO function was next examined with hydroxylamine[10] as a model compound for oxime formation (xerogel **X3-1**, Scheme 1). IR spectroscopy shows resonances at 3500−3200 (ν OH), 2942 (ν CH), 1669 (ν C=O), 1617 (ν C=N), 1552 (δ NH), 1200−1050 and 970 (ν Si−O). CP MAS ^{13}C NMR shows resonances at δ = 10.7 (CH_2−Si), 23 (CH_2), 42 (CH_2−N), 144.5 (C=N) and 164.2 ppm (C=O). The data, in particular the disappearance of the hydrate at δ = 87.7 ppm and the appearance of a new signal at δ = 144 ppm, confirm the formation of the oxime bond. Microanalysis on our functionalised solids is rather inexact[11] (±10%) but it was used to estimate the yield. From the nitrogen content, we deduced 75% functionalisation, although NMR spectra analyses suggest this is probably higher. GAPS is thus an efficient precursor for the preparation of COCHO supported silicas, and the chemical reactivity of the COCHO function with a small molecule had been demonstrated. However, the low solubility of $Si(OEt)_4$ in ethanolic GAPS proscribed its use for xerogels with low proportions of organic component in the solid, due to phase separation.

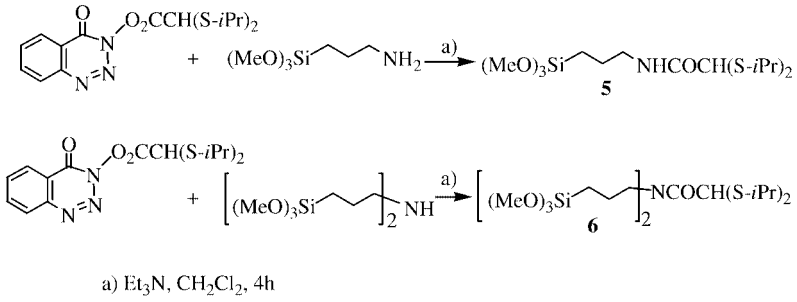
We turned to thioacetal as a protective group for the COCHO function to enhance the solubility of the precursor and thus have access to materials of low COCHO content. This protective group has successfully been used in the solid-phase synthesis of COCHO functionalised peptides,[12] aromatic (Scheme 2) and aliphatic precursors (Scheme 3) having been prepared. Precursor **4** was synthesised by means of a Heck[13] reaction between 4-styryl-(trimethoxy)silane[14] and intermediate **1**. Intermediate **1** was in turn prepared by coupling of 3,4-dihydro-4-oxo-1,2,3-benzotriazin-3-yl diisopropylthioacetate[12] with 4-iodoaniline in the presence of triethylamine.

The precursors **5** and **6** were obtained by coupling of 3,4-dihydro-4-oxo-1,2,3-benzotriazin-3-yl diisopropylthioacetate[12] with (3-aminopropyl)trimethoxysilane and bis[3-(trimethoxysilyl)propyl]amine, respectively, in the presence of triethylamine. Note that the methoxysilyl groups of 6 were not equivalent (two signals by ^{29}Si NMR) because of the presence of the tertiary amide.

Precursors **4**, **5** or **6** were then dissolved in a MeOH/THF mixture (1:1) in the presence of various amounts of TMOS (y = 1 to 100). No phase separation occurred. After the

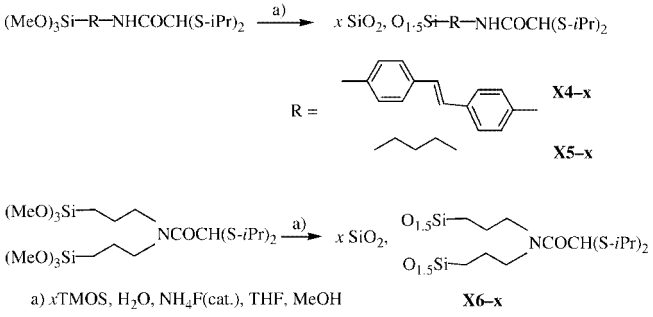


Scheme 2. Synthesis of precursor **4**



Scheme 3. Synthesis of precursors **5** and **6**

nucleophilic gelation procedure (Scheme 4), the protected *N*-glyoxylyl silica gels were characterised by EDX, solid-state NMR, IR and microanalysis.



Scheme 4. Synthesis of xerogels **X4-X6**

Electron dispersive X-ray analysis (EDX) was used as a qualitative method to detect Si and S atoms. The technique shows that the samples are homogeneous on a micrometric scale, as no variation in the Si/S ratio is observed from one analysis to another, either on the same particle or on different particles. IR spectroscopy shows intense bands characteristic of gel formation at 3500−3200 (ν Si−OH), 1150−1050 and 960 (ν Si−O). For xerogels **X4**, the organic component is observed at 2960−2866 (ν CH), 1665 (ν CO), 1590 (ν C=C) and 1520 (ν NH). For xerogels **X5**, the organic component is observed at 2965−2855 (ν CH), 1650 (ν C=O) and 1540 (ν NH), the aliphatic CO group thus being observed at lower frequency. For xerogel **X6**, the organic component is observed at 2965−2860 (ν CH), 1635 (ν C=O) and 1450 (δ CH). The ^{13}C solid-state NMR spectra of xerogels **X4** show resonances at 170 (CO), 134−128 (C=C), 52 (S−CH−S), 38 and 24 ppm (CH, CH_3). Xerogels **X5** show resonances at 170 (CO), 50 (S−CH−S), 42 (CH_2-NH) 35, 23 and 10 ppm (CH, CH_2, CH_3); xerogels **X6** show the same type of resonances, with CH_2−N being shifted downfield and superimposed on the (S−CH−S) signal at δ = 50 ppm. The carbon skeleton was not damaged by the sol-gel procedure, and the signals characteristic of the dithioacetal group are present at 50−52 ppm. The ^{29}Si solid-state NMR spectra show two major resonances, Q^4 and Q^3, at −109 and −102 ppm and a minor one, Q^2, at δ = −92 ppm. The T^3 and T^2 resonances are observed at −77 and −70 ppm for xerogels **X4** and at −62 and −55 ppm for xerogels **X5** and **X6**. These analyses are in agreement with well condensed xerogels. Note that in the microanalysis for ($x \geq 20$), the Si and C values are lower (up to 7%) and H values higher than those obtained from the theoretical values calculated from total condensation. This is consistent with the presence of SiOH groups (Q^3, Q^2, T^2) and water at the surfaces of the materials.

Porosity measurements on **X4**, **X5** and **X6** gels were performed by nitrogen sorption,[15] and the specific surface areas were determined by use of the BET equation (35 points). Evaluation of the porous volume was achieved by the BJH method and the microporous volume was determined by analysis of the *t*-plot diagram. The results are summarised in Table 1.

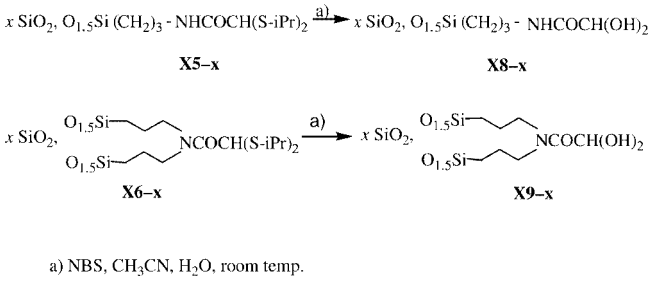
Table 1. Porosity measurements of xerogels **X4**−**X6**

Xerogel	Porous diameter (Å)	Microporous contribution (% volume)	Specific surface area (m^2/g)
X4-50	38	33	545
X5-10	36	−	284
X5-20	36−80	3	334
X5-50	38	15	587
X5-100	40	13	805
X6-10	37	22	279
X6-20	38	18	495
X6-50	39	24	656
X6-100	39	22	754

We observed that **X4-*x*** presented specific surface area for $x > 20$ when the surface area for **X5** and **X6** at $x = 10$ was already high. The specific surface area increased with increasing *x*. Xerogel **X4-50** presented a type I and IV isotherm, with an important microporous contribution and a narrow mesoporous distribution. Xerogels **X5-*x*** showed different behaviour: xerogels **X5-50** and **X5-100** presented type I and type IV isotherms with narrow mesopores and a 15% microporous contribution, while **X5-10** presented a type IV isotherm with the hysteresis not closing, which suggests that some pores have an "ink bottle" shape with small pore openings that do not facilitate N_2 desorption. Xerogel **X5-20** presented a type IV isotherm with a large distribution of mesopores from 36 to 80 Å. With **X6**, we did not observe important textural variations, all compounds presenting type I and type IV isotherms with a narrow distribution of mesopores and 20% microporous character.

The characteristic of the organic precursor therefore contributes to the texture of the solid.

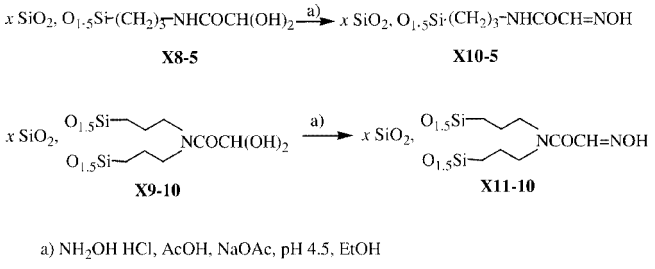
Removal of the dithiane function was next examined. Xerogels **X5-(5,10)** and **X6-(5,10)** were treated with *N*-bromosuccinimide[12] in aqueous CH_3CN (Scheme 5). Microanalysis showed very low amounts of residual S (< 0.5%), indicating that the cleavage was efficient in 90−95% yield.



Scheme 5. Deprotection of the dithiane-protected COCHO groups

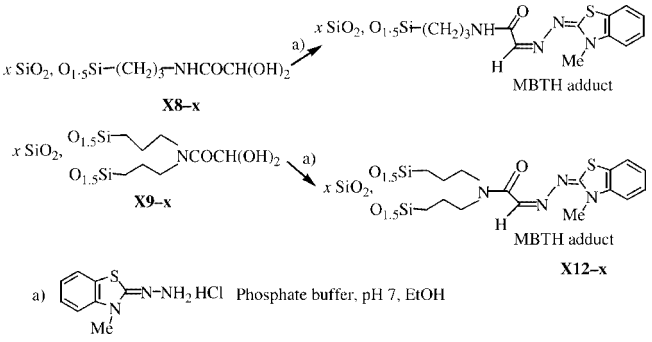
The IR spectra show a shift of the NCO band to higher wavelength: from 1650 to 1665 for **X8** and from 1632 to 1640 for **X9**. In the ^{13}C NMR, disappearance of the signals at δ = 24, 38 and 50 ppm, corresponding to the dithiane group, is observed, and signals at δ = 189 and 88 ppm appear, these being attributed to the nonhydrated and hydrated forms of aldehyde groups. Aliphatic chains were not damaged, so the procedure allowed the quasi-total deprotection of **X5-(5,10)** and **X6-(5,10)**. The same glyoxylic xerogels **X2** and **X8** were obtained by two different pathways (Scheme 1 and Scheme 5). Note that **X8-5** was dried at 120 °C for 2 h under vacuum and **X2-1** was dried at room temp., so **X8-5** presented both the aldehyde and hydrated forms of the COCHO function (^{13}C NMR: δ = 188 and 88 ppm) while the COCHO function of **X2-1** was only in its hydrated state (δ = 88 ppm).

The reactivity of the supported COCHO function was then studied by treatment with hydroxylamine. Xerogels **X8-5** and **X9-10** were treated under the same experimental conditions as used for **X2-1** (Scheme 6). The reaction worked in every case, and the spectra of **X10-5** are similar to those of **X3-1**. From the increases in the N content (1.97 for **X8-5** to 3.25 for **X10-5**, and 1.1 for **X9-10** to 1.82 for **X11-10**), the estimated yield was 80%.



Scheme 6. Reactivities of **X8** and **X9** with hydroxylamine

The coupling reaction with more bulky molecules was then examined. MBTH is known to be a sensitive reagent for the detection of aldehydes,[16] so we carried out reactions between MBTH and xerogels **X8-X9** (Scheme 7). The reaction was usually incomplete as determined by ^{13}C NMR analyses (50% conversion or less), the best result being obtained with **X9-5**. In this case the α-oxo aldehyde function of **X12-5** is no longer detected, and the ^{13}C NMR shows major changes, with the appearance of aromatic carbons (δ = 122, 111 ppm), C=N (δ = 145 ppm) and N−Me (δ = 32 ppm). The IR shows a shift in the CO band to 1632, the appearance of C=N bands (1600), and aromatics (1539, 1474, 744). From the increases in the N (1.52 for **X9-5** to 4.89 for **X12-5**) and C contents (12.47 for **X9-5** to 19.82 for **X12-5**), the estimated yield was 85%.



Scheme 7. Reactivities of **X8**, **X9** with MBTH

The fluorescence emission spectrum of **X12-5** confirms the presence of the conjugated chromophore with $\lambda_{M,em}$ = 520 nm (Figure 1).

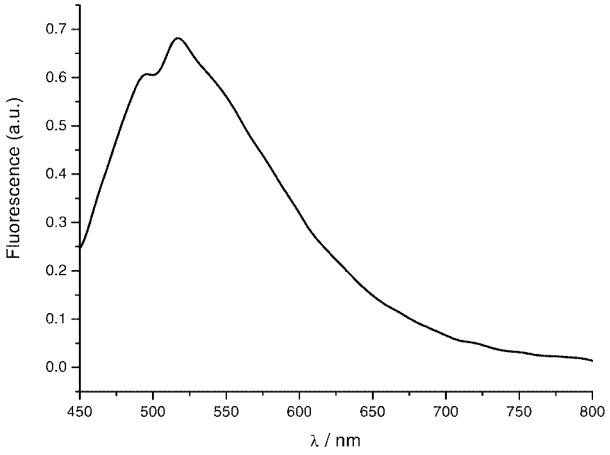


Figure 1. Fluorescence emission spectrum of **X9-5** after coupling with MBTH

The reactivity of the COCHO depends on the accessibility of the function. The texture of the material is essential in this case, and MBTH seems to be less reactive than NH_2OH, which is smaller and could thus diffuse more easily at the surface and inside the pores of the solid matrix.

In conclusion, we have described the syntheses of COCHO-functionalised silicas by the sol-gel procedure. The glyoxylyl group was formed either by periodate oxidation of a gluconamide chain or by removal of a diisopro-

pylthioacetal group. We have shown by solid-state MAS ^{13}C NMR that the COCHO function might exist in its hydrated form on the solids. The supported COCHO functions reacted with small molecules such as NH_2OH. Work to exploit this approach for the preparation of sophisticated silica-based materials is in progress.

Experimental Section

Manipulations of air-sensitive compounds were carried out under N_2. Solid-state NMR spectra were recorded with Bruker 250 and 400 MHz spectrometers with a MAS 4 (spinning rate 9 kHz) or MAS 7 (spinning rate 3.5 kHz) probe. Contact time was 5 ms for CP MAS experiments and decoupling power was 200 W for hpdec MAS experiments. IR-FT (KBr pellets) were recorded with a Nicolet instrument. Microanalyses were performed at the central service of microanalyses (CNRS at Vernaison). High resolution mass spectra (FAB^+) were performed with a JEOL DL-100 spectrometer, with a nitrobenzyl alcohol (NBA) or a glycerolthioglycerol (GT) matrix. Surface area measurements (BET) were recorded by use of a Micromeritics Gemini III 2375 under nitrogen. Fluorescence was registered with a SLM Aminco 8100 spectrometer, by reflection on a KBr pellet. A front face sample holder was used and oriented at 60° in order to minimise specular reflection. Appropriate filters were used to eliminate Rayleigh and Raman scatters from the emission.

Precursor 1: A mixture of 4-iodoaniline (1.5 g, 6.8 mmol), 3,4-dihydro-4-oxo-1,2,3-benzotriazin-3-yl diisopropylthioacetate (2.42 g, 6.8 mmol) and triethylamine (1.42 mL, 10.2 mmol) in dichloromethane (50 mL) was stirred at room temperature for 2 h. The reaction mixture was thoroughly washed with water (3× 50 ml), dried with $MgSO_4$ and evaporated to gave the corresponding iodo compound, which was crystallised from cyclohexane (2.6 g, 94%). ^1H NMR (200 MHz, $CDCl_3$): δ = 1.36 (2d, J = 6.8 Hz, 12 H, CH_3), 3.19 (m, 2 H, *i*Pr), 4.46 (s, 1 H, SCHS), 7.37(d, J = 8.8 Hz, 2 H, Ar), 7.68 (d, J = 8.8 Hz, 2 H, Ar), 8.5 (s, 1 H, NH) ppm. ^{13}C NMR (50 MHz, $CDCl_3$): δ = 23.5, 37.8, 50.8, 88.2, 121.8, 137.7, 138.4, 168.3 ppm. IR (KBr): $\tilde{\nu}$ = 3288.5, 3250.6, 3183.0, 3114.1, 3059.5, 2949.0, 2929.7, 2861.1, 1660.3, 1607.4, 1585.4, 1538.0, 1487.6, 1458.2, 1393.9, 1335.8, 1236.0, 1172.0, 1155.4, 1053.9, 1003.3, 968.1, 934.9, 823.2 cm^{-1}. HRMS (FAB^+, GT) of $C_{14}H_{20}NOS_2I^+$ [M^+] calcd. 410.3613; found 410.3625.

Precursor 4: A mixture of trimethoxy(4-vinylphenyl)silane (493 mg, 2.2 mmol), the iodo compound (900 mg, 2.2 mmol), palladium acetate (50 mg, 0.22 mmol) and trimethylamine (0.03 mL, 22 mmol) in acetonitrile (15 mL) was heated in a sealed tube at 115 °C. After stirring for 44 h at 115 °C, the solution was cooled to room temperature and the solvent was evaporated under vacuum. The resulting mass was dissolved in dry toluene (50 mL). The resulting solution was purified by passage through a short column of silanised silica gel 60 under argon, and the compound was obtained as a liquid (1.07 g, 92%) after evaporation of the solvent. ^1H NMR (200 MHz, $CDCl_3$): δ = 1.29−1.38 (m, 12 H, CH_3), 3.22 (m, 2 H, *i*Pr), 3.66 (s, 9 H, OMe), 4.49 (s, 1 H, SCHS) 7.11−7.70 (m,10 H, aromatic), 8.53 (br. s, 1 H, NH) ppm. ^{13}C NMR (50 MHz, $CDCl_3$): δ = 23.5, 37.8, 50.9, 51.3, 117.4, 120.1, 126.4127.7, 128.2, 128.8, 129.5, 134.0, 135.6, 139.9, 168.1 ppm. ^{29}Si (40 MHz, $CDCl_3$): δ = − 54. IR (neat): $\tilde{\nu}$ = 3301.1, 2960.3, 2840.8, 1660.1, 1594.8, 1412.1, 1325.9, 1244.8, 1188.5, 1085.5, 967.0, 820.0, 737.9 cm^{-1}. HRMS (EI) for $C_{25}H_{35}O_4NS_2^+$ [M^+] calcd. 505.7749; found 505.7733.

Precursor 5: A mixture of (3-aminopropyl)trimethoxysilane (1.07 g, 6 mmol), 3,4-dihydro-4-oxo-1,2,3-benzotriazin-3-yl diisopropylthioacetate (2.1 g, 6 mmol) and triethylamine (1.25 mL, 9 mmol) in dichloromethane (40 mL) was stirred at room temperature for 4 h and the solvent was evaporated under vacuum. The resulting mass was dissolved in dry diethyl ether/pentane (1:3) mixture, the solution was purified by passage through a short column of silanised silica gel 60 under argon, and the compound (2.125 g, 96%) was obtained as a liquid after evaporation of the solvent. ^1H NMR (200 MHz, $CDCl_3$): δ = 0.69 (t, 2 H, $SiCH_2$), 1.30−1.36 (m, 12 H, CH_3), 1.68 (t, 2 H), 3.15 (m, 2 H), 3.32 (m, 2 H), 3.6 (s, 9 H, OMe), 4.36 (s, 1 H, SCHS) ppm. ^{13}C NMR (50 MHz, $CDCl_3$): δ = 6.8, 23.1, 23.5, 37.4, 42.6, 50.3, 50.9, 170.0 ppm. ^{29}Si (40 MHz, $CDCl_3$): δ = − 42.2 ppm. IR (neat): $\tilde{\nu}$ = 3276.2, 3074.8, 2958.4, 2865.8, 2840.0, 1643.7, 1551.8, 1453.7, 1195.0, 1087.9, 820.0 cm^{-1}. HRMS (FAB^+, GT) of $C_{14}H_{31}NOS_2^+$ [MH^+] calcd. 370.6299; found 370.6280.

Precursor 6: A mixture of bis[3-(trimethoxysilyl)propyl]amine (2.05 g, 6 mmol), 3,4-dihydro-4-oxo-1,2,3-benzotriazin-3-yl diisopropylthioacetate (2.1 g, 6 mmol) and triethylamine (1.25 mL, 9 mmol) in dichloromethane (40 mL) was stirred at room temperature for 4 h. and solvent was evaporated under vacuum. The resulting mass was dissolved in dry diethyl ether/pentane (1:3) mixture, The resulting solution was purified by passage through a short column of silanised silica gel 60 under argon, and the compound (3.03 g, 95%) was obtained as a liquid after evaporation of the solvent. ^1H NMR (200 MHz, $CDCl_3$): δ = 0.64 (t, 4 H, $SiCH_2$), 1.28−1.36 (m, 12 H), 1.68−1.72 (m, 4 H), 3.25−3.36 (m, 6 H), 3.59 (s, 9 H, OMe), 3.60 (s, 9 H, OMe), 4.72 (s, 1 H, SCHS) ppm. ^{13}C NMR (50 MHz, $CDCl_3$): δ = 6.6, 6.8, 20.9, 22.8, 24.0, 24.5, 35.4, 49.3, 50.2, 50.9, 51.0, 168.8 ppm. ^{29}Si NMR (40 MHz, $CDCl_3$): δ = −42.0, − 42.6 ppm. IR (neat): $\tilde{\nu}$ = 2964.7, 2844.9, 1643.3, 1458.0, 1425.3, 1365.4, 1191.0, 1087.5, 1011.2, 798.7 cm^{-1}. HRMS (FAB^+, GT) of $C_{20}H_{46}NOS_2^+$ [MH^+] calcd. 532.8911; found 532.8893.

Cogel X1-1: $Si(OEt)_4$ (3.34 mL, 15 mmol) was added with stirring to a 12 g solution of GAPS (50% in EtOH, 15 mmol). H_2O (0.4 mL) and NH_4F (0.25 M in H_2O, 0.6 mL) were then added. Gelation occurred after 1 h. After curing for one week, the gel was washed with EtOH, acetone and Et_2O and dried under vacuum. CP MAS ^{29}Si NMR: δ = −66.1 (T^3), −101.7 (Q^3), −111.2 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 10.5, 23.8, 43.6, 72.4, 172.04 ppm. IR (KBr): $\tilde{\nu}$ = 3423, 2944, 2893, 1654, 1554, 1453, 1412, 1200−1050, 950 cm^{-1}.

Cogel X1-2: The same procedure was repeated with a 1 g solution of GAPS (50% in EtOH, 1.3 mmol), $Si(OEt)_4$ (0.55 mL, 2.6 mmol), NH_4F (0.25 M, 50 μL) and H_2O (64 μL).

Cogel X2-1: Xerogel **X1-1** (510 mg) and $NaIO_4$ (2.5 g, 11.7 mmol) were stirred in H_2O (11 mL) and AcOH, (1 mL). After 2 h, the gel was filtered and the solid was washed thoroughly with H_2O, THF and Et_2O. The gel was dried in air. CP MAS ^{13}C NMR: δ = 10.9, 22.9, 30.9 (minor), 42.3, 87.5, 171.2 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2942, 1664, 1558, 1445, 1200−1050, 944 cm^{-1}.

Cogel X3-1: Xerogel **X2-1** (500 mg) was added to a solution of $ClNH_3OH$ (1 g, 14.5 mmol), AcOH, (10 mL), AcONa, (1.26 g), H_2O (15 mL) and EtOH (10 mL). The reaction mixture was stirred for 2 h and filtered, and the solid was washed thoroughly with H_2O, EtOH and Et_2O. The solid was washed at 80 °C under vacuum. CP MAS ^{13}C NMR: δ = 10.7, 23.3, 42.6, 144.5, 164.2 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2942, 1669, 1617, 1553, 1453, 1389, 1200−1050, 945 cm^{-1}.

Table 2. Synthesis of Co-Gels **X4**

Solid	**4** (mg)	*y* mmol	NH_4F (%)	*x*	TMOS (mg)	mmol	H_2O (mL)	Solvent (mL)
X4-1	500	0.99	1	1	150	0.99	0.06	3.9
X4-2	200	0.396	1	2	120	0.789	0.023	2.3
X4-5	200	0.396	1	5	300	1.97	0.066	4.6
X4-10	300	0.594	1	10	900	5.92	0.198	12.8
X4-20	300	0.594	2	20	1805	11.87	0.421	24.5
X4-50	200	0.396	4	50	3010	19.8	0.691	39.7

Table 3. Synthesis of Co-Gels **X5**

Solid	**5** (g)	*y* mmol	NH_4F (%)	*x*	TMOS (g)	mmol	H_2O (mL)	Solvent (mL)
X5-5	0.5	1.35	1	5	1.029	6.775	0.226	16
X5-10	0.5	1.35	1	10	2.059	13.55	0.470	29.3
X5-20	0.5	1.35	2	20	4.119	27.1	0.958	55.9
X5-50	0.05	0.135	4	50	1.0298	6.775	0.236	13.6
X5-100	0.05	0.135	4	100	2.0596	13.55	0.469	26.9

Table 4. Synthesis of Co-Gels **X6**

Solid	**6** (mg)	*y* mmol	NH_4F (%)	*x*	TMOS (mg)	mmol	H_2O (mL)	Solvent (mL)
X6-1	531	1	1	1	152	1	0.0505	3.95
X6-5	531	1	1	5	760	5	0.1945	11.8
X6-10	531	1	1	10	1520	10	0.3745	21.6
X6-20	531	1	2	20	3040	20	0.7419	41.3
X6-50	53	1	4	50	760	5	0.17	10
X6-100	53	1	4	100	1520	10	0.35	19.8

Co-Gels X4, X5 and X6: (Tables 2, 3 and 4) Precursor **4**, **5** or **6** (*y* mmol) and $Si(OMe)_4$ (*y*·*x* mmol) were dissolved in a MeOH/THF mixture (50:50, concentration of Si species: 0.5 M). After addition of water [(1.5 +2*x*)*y* mmol] and a catalytic amount of NH_4F (0.25 M) in water, transparent gels were formed within few h. After ageing for 1 week the materials were then powdered and washed with acetone and diethyl ether to give xerogels and dried at 100 °C overnight under vacuum.

X4-1: CP MAS ^{29}Si NMR:δ = −68 (T^2), −77.1 (T^3), −100 (Q^3), −109.7 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 23.9, 37.9, 51.7, 128.0, 134.9, 169.7 ppm. IR (KBr): ṽ = 3500−3200, 2960, 2924, 2866, 1661, 1593, 1519, 1402, 1312, 1200−1050, 956, 824 cm^{-1}. S_{BET} = 1.4 m^2/g.

X4-2: IR (KBr): ṽ = 3500−3200, 2960, 2922, 2862, 1663, 1587, 1519, 1413, 1314, 1200−1050, 963, 829 cm^{-1}. S_{BET} = 2 m^2/g.

X4-5: IR (KBr): ṽ = 3500−3200, 2959, 2930, 2866, 1668, 1596, 1524, 1409, 1316.5, 1200−1050, 957 cm^{-1}. S_{BET} = 13 m^2/g.

X4-10: CP MAS ^{29}Si NMR: δ = −68.6 (T^2), −77.1 (T^3), −91.7 −100 (Q^3), −109.7 (Q^4) ppm. IR (KBr): ṽ = 3500−3200, 2967, 2926, 2865, 1663, 1601, 1526, 1458, 1417, 1200−1050, 960 cm^{-1}. $C_{22}H_{26}NO_{22.5}S_2Si_{11}$: calcd. C 25.46, H 2.52, N 1.35, Si 29.77, S 6.18; found C 26.52, H 3.24, N 1.57, Si 28.52, S 6.16. S_{BET} = 13 m^2/g.

X4-20: IR (KBr): ṽ = 3500−3200, 2967, 2932, 2871, 1663, 1601, 1526, 1465, 1417, 1200−1050, 947 cm^{-1}. $C_{22}H_{26}NO_{42.5}S_2Si_{21}$: calcd. C 16.12, H 1.59, N 0.85, Si 35.99, S 3.91; found C 13.63, H 2.34, N 0.56, Si 29.80, S 3.46. S_{BET} = 13 m^2/g.

X4-50: $C_{22}H_{26}NO_{102.5}S_2Si_{51}$: calcd. C 8.41, H 0.83, N 0.44, S 2.04, Si 45.61; found C 5.17, H 2.08, N 0.13, S 1.28, Si 34.52. S_{BET} = 545 m^2/g.

X5-5: CP MAS ^{29}Si NMR: δ = −62 (T^3), −102.8 (Q^3), −108.9 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 10.1, 24.0, 37.8, 42.2, 50.3, 172.6 ppm. IR (KBr): ṽ = 3500−3200, 2964.3, 2932.1, 2867.8, 1651.5, 1539.0, 1458.6, 1200−1050, 954.9, 804.8 cm^{-1}. S_{BET} = 2 m^2/g.

X5-10: IR (KBr): ṽ = 3500−3200, 2964, 2921, 2866, 1648, 1539, 1458, 1200−1050, 956 cm^{-1}. $C_{11}H_{22}NO_{22.5}S_2Si_{11}$: calcd. C 14.09, H 2.36, N 1.31, Si 32.95, S 6.84; found C 13.14, H 2.82, N 2.12, Si 32.00, S, 4.83. S_{BET} = 284 m^2/g.

X5-20: CP MAS ^{29}Si NMR: δ = −56.7 (T^2), −63.6 (T^3), −101.3 (Q^3), −109.2 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 8.8, 23.0, 37.2, 41.8, 50.0, 175.7 ppm. IR (KBr): ṽ = 3500−3200, 2964, 2855, 1643, 1539, 1453, 1200−1050, 804.2 cm^{-1}. $C_{11}H_{22}NO_{42.5}S_2Si_{21}$: calcd. C 8.53, H1.43, N 0.90, Si 38.57, S 4.14; found C 9.89, H 2.44, N 1.20, Si 35.20, S 2.88. S_{BET} = 334 m^2/g.

X5-50: S_{BET} = 587 m^2/g.

X5-100: S_{BET} = 806 m^2/g.

X6-1: CP MAS ^{29}Si NMR: δ = −56.9 (T^2), −65.7 (T^3), −101.2 (Q^3), 109.4 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 7.6, 21.1, 32.5, 48.0, 167.5 ppm. IR (KBr): ṽ = 3500−3200, 2958, 2916, 1630, 1459, 1368, 1200−1050, 914, 791 cm^{-1}. S_{BET} = 2 m^2/g.

X6-5: CP MAS ^{29}Si NMR: −58.2 (T^2), −65.6 (T^3), −100.8 (Q^3), −109.3 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 10.3, 23.7, 35.5, 50.5,

169.6 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2964, 2921, 2858, 1632, 1458, 1370, 1200−1050, 962 cm^{-1}. S_{BET} = 2 m^2/g.

X6-10: CP MAS ^{29}Si NMR: δ = −58.8 (T^2), −65.2 (T^3), −91.1 (Q^2), −101.1 (Q^3), −108.6 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 10.4, 23.4, 35.9, 50.1, 168.1 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2964, 2921, 1632, 1458, 1200−1050, 956, 798 cm^{-1}. $C_{14}H_{27}NO_{24}S_2Si_{12}$: calcd. C 16.89, H 2.73, N 1.40, Si 33.89, S 6.44; found C 15.35, H 3.57, N 1.02, Si 32.83, S 4.90. S_{BET} = 279 m^2/g.

X6-20: IR (KBr): $\tilde{\nu}$ = 3500−3200, 2969, 2916, 1635, 1459, 951, 796 cm^{-1}. $C_{14}H_{27}NO_{44}S_2Si_{22}$: calcd. C 10.28, H 1.70, N 0.87, Si 38.73, S 4.01; found C 9.45, H 2.86, N 0.60, Si 32.83, S 2.89. S_{BET} = 495 m^2/g.

X6-50: S_{BET} = 656 m^2/g.

X6-100: S_{BET} = 754 m^2/g.

Glyoxylyl-Silica Gel (General Procedure for the Preparation of Silica Gel): A suspension of **X5-*x*** or **X6-*x*** in acetonitrile/water (8:2) was treated at room temperature with solid *N*-bromosuccinimide (NBS) in one portion (Table 5 and 6). After 4 h, the functionalised silica gel was filtered off and washed with water and acetonitrile. The functionalised silica gel was dried under vacuum at 100 °C for 8 h.

Table 5. Synthesis of Glyoxylyl-Silica Gels X8

Solid	**X5** (mg)	NBS (mg/mmol)	CH_3CN/H_2O (mL)
X8-5	600	890/5	16/4
X8-10	840	800/4.5	32/8

Table 6. Synthesis of Glyoxylyl-Silica Gels **X9**

Solid	**X6** (mg)	NBS (mg/mmol)	CH_3CN/H_2O (mL)
X9-5	420	600/3.37	16/4
X9-10	510	700/3.93	32/8

X8-5: CP MAS ^{29}Si NMR: δ = −59.9 (T^2), −65.4 (T^3), −102.2 (Q^3), −108.9 (Q^4) ppm. CP MAS ^{13}C NMR: δ = 9.6, 21.9, 42.5, 88.3, 171.5, 188.6 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2943, 1665, 1561.5, 1447, 1200−1050, 951, 793 cm^{-1}. $C_5H_{10}NO_{14.5}Si_6$: calcd. C 12.4, N 2.89, Si 34.71; found C 8.96, N 1.97, Si 30.9, S < 0.3.

X8-10: IR (KBr): $\tilde{\nu}$ = 3500−3200, 2964, 1670, 1556, 1452, 1200−1050, 951, 842.9 cm^{-1}. $C_5H_{10}NO_{24.5}Si_{11}$: calcd. C 7.65, N 1.8, Si 39.20; found C 6.37, N 1.26, Si 35.7, S < 0.5.

X9-5: CP MAS ^{13}C NMR: δ = 7.2, 18.5, 48.2, 167.2, 189.4 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2953.8, 1637.8, 1409, 1200−1050, 951.3, 798.7 cm^{-1}. $C_8H_{15}NO_{16}Si_7$: calcd. C 16.6, N 2.40, Si 33.90; found C 12.47, N 1.52, Si 28.25, S <0.45.

X9-10: IR (KBr): $\tilde{\nu}$ = 3500−3200, 2953, 1643, 1200−1050, 962 cm^{-1}. $C_8H_{15}NO_{26}Si_{12}$: calcd. C 10.9, N 1.6, Si 38.3; found, C 9.25, N 1.1, Si 30.87, S < 0.3.

Hydroxylamine Adduct of Glyoxylyl-Silica Gel

X10-5: A suspension of **X8-5** (242 mg, 0.5 mmol), hydroxylamine hydrochloride (173 mg, 2.5 mmol) and sodium acetate buffer (12 mL, pH 4.5) in ethanol (8 mL) was stirred at room temperature for 6 h. The functionalised silica gel was then filtered off and washed with water, ethanol, acetone and diethyl ether. The functionalised silica gel was dried under vacuum at 120 °C for 2 h. CP-MAS ^{13}C NMR (75 MHz): δ = 9.8, 22.6, 42.2, 143.8, 164.5 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2942, 1665, 1610, 1561, 1447, 1200−1050, 956 cm^{-1}. $C_5H_8N_2O_{13.5}Si_6$: calcd. C 12.50, N 5.82, Si 34.93; found C 9.41, N 3.25, Si 32.20.

Xerogel X11-10: The same procedure was applied with **X9-10** (130 mg), NH_2OH,HCl (230 mg, 3.32 mmol), sodium acetate buffer (11 mL, pH 4.5) and EtOH (8 mL). CP MAS ^{13}C NMR (75 MHz): δ = 10.1, 22.5, 51.2, 144.0, 165.2 ppm. CP MAS ^{29}Si NMR (60 MHz): δ = −55.9 (T_2), −64.8 (T_3), −91.2 (Q_2), −101.2 (Q_3), −110.4 (Q_4) ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2953, 1643, 1496, 1441, 1200−1050, 951 cm^{-1}. $C_8H_{14}N_2O_{25}Si_{12}$: calcd. C 10.98, N 3.20, Si 38.44; found C 8.68, N 1.82, Si 28.31.

MBTH Adduct of Glyoxylyl-Silica Gel: A suspension of xerogel **X9-5** (100 mg), 3-methyl-2-benzothiazolinone hydrazone hydrochloride hydrate (MBTH, 220 mg, 1.02 mmol) and phosphate buffer (4 mL, pH 7) in ethanol (6 mL) was stirred at room temperature for 6 h. The functionalised silica gel was filtered off and washed with water, ethanol, acetone and diethyl ether. The functionalised silica gel was dried under vacuum at 120 °C for 2 h. CP MAS ^{13}C NMR (75 MHz): δ = 10.7, 22.5, 31.7, 51.0, 111.8, 123.0, 145, 165.4 ppm. IR (KBr): $\tilde{\nu}$ = 3500−3200, 2953, 1632, 1599, 1539, 1474, 1414, 1359, 1200−1050, 962 cm^{-1}. $C_{16}H_{20}N_4O_{14}SSi_{12}$: calcd. C 25.00, N 7.79, S 4.40, Si 27.26; found C 19.81, N 1.97, S 2.81, Si 26.65.

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