

1 **Supported Choline Hydroxide (Ionic Liquid) on Mesoporous Silica as Heterogeneous**  
2 **Catalyst for Knoevenagel Condensation Reactions.**

3 **Isabel del Hierro<sup>a\*</sup>, Yolanda Pérez<sup>a\*</sup>, Mariano Fajardo<sup>a</sup>.**

4 Departamento de Biología y Geología, Física y Química Inorgánica. Escuela Superior de  
5 Ciencias Experimentales y Tecnología. Universidad Rey Juan Carlos. 28933 Móstoles  
6 (Madrid), Spain. Tel.: (+34) 916647022 Fax: (+34) 914888143

7 E-mail: [isabel.hierro@urjc.es](mailto:isabel.hierro@urjc.es)

8 **Abstract**

9 In this work hybrid mesoporous SBA-15 and mesoporous silica microspheres  
10 functionalized with choline hydroxide ionic liquid have been prepared. A two-step  
11 process inspired by the industrial production of choline hydroxide has been developed  
12 to synthesize the hybrid SBA-15 material with choline hydroxide ionic liquid (Chol-SBA-  
13 15) and the hybrid SBA-15 material with choline hydroxide ionic liquid and  
14 hexamethyldisilazane as capping agent (Chol-HMDS-SBA-15). For the preparation of  
15 hybrid mesoporous silica microspheres (Chol-MSMs), a co-condensation method has  
16 been employed with an ionic liquid prepared by reaction of 3-  
17 (glycidyloxypropyl)trimethoxysilane and trimethylamine in aqueous media. The  
18 synthesized materials have been fully characterized by elemental analysis, X-ray  
19 diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), N<sub>2</sub> adsorption-  
20 desorption, transmission electron microscopy (TEM) and <sup>13</sup>C CP/MAS NMR  
21 spectroscopy. These materials have been tested successfully as catalysts in Knoevenagel  
22 condensation of benzaldehyde with RCH<sub>2</sub>C≡N (R=CN (malononitrile), CO<sub>2</sub>Et (ethyl  
23 cyanoacetate)). The catalyst Chol-MSMs showed high catalytic activity, 99% of  
24 conversion and 99% of selectivity towards ethyl 2-cyano-3-phenylacrylate in 2 h of  
25 reaction and using ethanol as solvent. In addition, their reusability without loss of  
26 activity has been demonstrated.

27 **Keywords: Choline hydroxide, mesoporous silica, Knoevenagel condensation.**

1

## 2 **1. Introduction**

3 The synthesis of pharmaceutical and fine chemicals by methods inspired by green  
4 chemistry principles is still a challenge. The search of new Brønsted-type basic catalysts  
5 able to perform green chemistry condensation reactions with high activity and  
6 selectivity values is gaining prominence due to the drawbacks of their classical  
7 homogenous inorganic counterparts, KOH and NaOH [1]. In this context, the  
8 development of solid base catalysts such as heterogeneous catalysts [2,3,4] and the use  
9 of ionic liquids (ILs) able to act as basic catalysts have emerged as useful strategies. An  
10 example of the latter is the process developed by Mehnert et al. [5] for the synthesis of  
11 aldol condensation products with the use of a neutral ionic liquid medium comprising  
12 an imidazolium cation together with a basic catalyst, KOH. The synergic action of both  
13 strategies is found in the study published by Abelló et al. [6] who supported choline  
14 hydroxide onto MgO by impregnation of the ionic liquid onto the solid support and used  
15 it as heterogeneous catalyst for several aldol condensation reactions between ketones  
16 and aldehydes giving high TOF values. Sharing this perspective different materials have  
17 been chosen as supports. Komura et al. [7] synthesized the layer silicate PLS-1 which  
18 possesses tetramethylammonium hydroxide between its interlayers and used it  
19 successfully as solid base catalyst for C–C bond forming reactions and Sano et al. [8]  
20 succeeded in synthesizing layer silicates using amorphous silica and choline hydroxide.  
21 These materials were found to exhibit catalytic activity when used in a Knoevenagel  
22 condensation reaction as a base catalyst. Zhang and co-workers [9] prepared an efficient  
23 and reusable protic-ionic-liquid solvent–catalyst system under ultrasonic irradiation  
24 conditions. Corma et al. [10] reported the preparation of a strong Brønsted base catalyst  
25 obtained by preparing an inorganic–organic composite formed by an organic  
26 ammonium quaternary salt anchored on the surface of a pure silica MCM-41. The  
27 functional tetraalkylammonium groups were anchored to the Si-MCM-41 surface by  
28 reacting trimethoxysilyl-propyl-*N,N,N*-trimethylammonium chloride with hydroxyl  
29 groups located at the surface. The exchange of chloride by hydroxide anions was carried  
30 out by bringing together the functionalized MCM-41 samples with  
31 tetramethylammonium hydroxide. The authors justified the lower activity of this

1 material in comparison to its homogeneous counterpart  $\text{NMe}_4\text{OH}$  due to a possible  
2 interaction between hydroxide group and surface silanol groups and subsequent  
3 decrease of base strength. On the contrary, Shanks et al. [11] have proposed the  
4 involvement of neighbouring silanol to the ion pair mechanism in Knoevenagel reaction  
5 since silanol groups can form hydrogen bond with the water release during the reaction  
6 promoting nucleophilic addition. They have demonstrated it by testing mesoporous  
7 SBA-15 silica with and without capped silanol groups simultaneously functionalized with  
8 amine and imidazole propyl groups. Cardoso et al. [12] have also tested as catalyst non-  
9 calcined MCM-41 mesoporous silica with cetyltrimethylammonium cation into the  
10 mesoporous cavities (used as structural directing agent during its synthesis) showing its  
11 basic properties.

12 Taking these studies into account and our own experience in the field of mesoporous  
13 silica materials, we have designed, synthesized and characterized hybrid mesoporous  
14 SBA-15 and silica mesoporous microspheres with choline hydroxide ionic liquid function.  
15 The tethering to the silica surface was completed by a new and efficient method inspired  
16 by the industrial production of choline hydroxide ( $[\text{OH}-(\text{CH}_2)_2-\text{NMe}_3]^+\text{OH}^-$ ) aqueous  
17 solution by direct reaction of ethylene oxide with trimethylamine. Subsequently, we  
18 have tested these new materials as catalysts in Knoevenagel condensation of  
19 benzaldehyde with malononitrile and ethyl cyanoacetate. Influence of supporting  
20 material, the presence of capping agent and experimental reaction conditions are  
21 discussed in order to propose a reaction mechanism. Reusability tests have also been  
22 performed to demonstrate their stability.

## 1 2. Experimental

### 2 2.1. Materials

3 Tetraethylortosilicate (TEOS) 98% ( $M = 208.33 \text{ g mol}^{-1}$ ,  $d = 0.934 \text{ g mL}^{-1}$ ), Poly(ethylene  
4 glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol) (Pluronic P123,  $M_{av} =$   
5  $5800 \text{ g mol}^{-1}$ ,  $d = 1.007 \text{ g mL}^{-1}$ ), (3-glycidyoxypropyl)trimethoxysilane ( $M = 236.34 \text{ g mol}^{-1}$   
6  $d = 1.07 \text{ g mL}^{-1}$ ), trimethylamine solution 4.2 M in ethanol, hexamethyldisilazane  
7 (HMDS), ( $M = 161.39 \text{ g mol}^{-1}$ ,  $d = 1.2 \text{ g mL}^{-1}$ ), malononitrile ( $M = 66.06 \text{ g mol}^{-1}$ ,  $d = 1.019$   
8  $\text{g mL}^{-1}$ ), ethyl cyanoacetate ( $M = 111.13 \text{ g mol}^{-1}$ ,  $d = 1.063 \text{ g mL}^{-1}$ ) and benzaldehyde ( $M$   
9  $= 106.12 \text{ g mol}^{-1}$ ,  $d = 1.05 \text{ g mL}^{-1}$ ) were purchased from Sigma Aldrich and used as  
10 received. Hexadecyltrimethylammonium bromide (CTBA) ( $M = 364.45 \text{ g mol}^{-1}$ ) was  
11 purchased from Acros and used as received. Toluene and dichloromethane were  
12 purchased from SDS and distilled and dried from appropriate drying agents. Ethanol  
13 (synthesis quality) was purchased from SDS and used as received. Milli-Q water was used  
14 in the experiments. The hexagonal material SBA-15 was prepared using a poly (alkaline  
15 oxide) triblock copolymer surfactant in an acidic medium, according to the method of  
16 *Zhao et al.* [13].

### 17 2.2. Preparation of catalysts

#### 18 2.2.1. Functionalization of SBA-15 with 3-(glycidyoxypropyl)trimethoxysilane 19 (Gly-SBA-15)

20 2.0 g of SBA-15, previously dehydrated at  $150 \text{ }^{\circ}\text{C}$  in vacuum for 12 h, was suspended in  
21 30 mL of toluene and 3-(glycidyoxypropyl)trimethoxysilane (4 mmol, 0.88 mL) was  
22 added. The suspension was stirred and heated at  $85 \text{ }^{\circ}\text{C}$  for 48 h. The resulting solid,  
23 labelled as Gly-SBA-15, was obtained by filtration and washed with dichloromethane ( $2$   
24  $\times 30 \text{ mL}$ ). The solid was dried under vacuum and stored under inert atmosphere.

#### 25 2.2.2. Preparation of SBA-15 functionalized with choline hydroxide ionic liquid 26 (Chol-SBA-15).

27 2.0 g of the previously prepared Gly-SBA-15 was suspended in water and treated with a  
28 solution of trimethylamine 4.2 M in ethanol (4 mmol, 0.95 mL). The mixture was heated  
29 at  $50 \text{ }^{\circ}\text{C}$  and stirred for 48 h. The resulting white solid, labelled as Chol-SBA-15, was  
30 obtained by filtration and washed with dichloromethane ( $2 \times 30 \text{ mL}$ ). The solid was dried  
31 under vacuum and stored in air.

1           **2.2.3. Preparation of SBA-15 functionalized with choline hydroxide ionic liquid**  
2           **and capped with hexamethyldisilazane (Chol-HMDS-SBA-15).**

3   0.5 g of SBA-15, previously dehydrated at 150 °C in vacuum for 12 h, was suspended in  
4   30 mL of toluene and 3-(glycidyloxypropyl)trimethoxysilane (0.5 mL, 1.5 mmol) and  
5   hexamethyldisilazane (0.15 mL, 1 mmol) were added. The suspension was stirred and  
6   heated at 80 °C for 48 h. The resulting solid, labelled as Gly-HMDS-SBA-15 was obtained  
7   by filtration and washed with dichloromethane (2 × 30 mL). The solid was dried under  
8   vacuum, suspended in water and treated with a solution of trimethylamine 4.2 M in  
9   ethanol (1.5 mmol). The mixture was heated at 50 °C and stirred for 48 h. The resulting  
10   white solid, labelled as Chol-HMDS-SBA-15, was obtained by filtration and washed with  
11   dichloromethane (2 × 30 mL) and stored.

12           **2.2.4. Preparation of mesoporous silica microspheres functionalized with**  
13           **choline hydroxide ionic liquid by co-condensation route (Chol-MSMs).**

14   Alkyl-functionalized mesoporous organosilica particles have been prepared by one-pot  
15   synthetic method, which affords the hydrolysis and co-condensation of inorganic silane  
16   and organoalkoxysilane in the presence of the cationic surfactant CTAB as template in  
17   alkaline aqueous media. In a typical procedure, CTAB (0.2 g, 0.63 mmol) was dissolved  
18   in 96 mL of deionized water under stirring at room temperature. Then 0.7 mL of NaOH  
19   (2 M) was added to the solution. Subsequently, the temperature of the solution was  
20   raised to 80 °C and the ionic liquid,  $[\text{Si}(\text{OH})_3\text{CH}_2\text{-CH}_2\text{-CH}_2\text{-O-CH}_2\text{-CH}(\text{OH})\text{-CH}_2\text{-}$   
21    $\text{N}(\text{CH}_3)_3]^+\text{OH}^-$ , based on Choline hydroxide functionality was added (0.83 g, 3 mmol). The  
22   mixture was stirred for 0.5 h at 80 °C giving a clear solution. 1.0 mL of TEOS (0.934 g, 4.5  
23   mmol) was added dropwise. A white precipitate was observed after 5 min of stirring  
24   (400 rpm). The mixture was continuously stirred for an additional 2 h and aged 24 h at  
25   80 °C. Then, the precipitate was filtered, washed with water thoroughly and then the  
26   organic template was removed by continuous extraction with ethanol for 12 h. The  
27   resulting white solid, labelled as Chol-MSMs, was collected after drying overnight at 60  
28   °C.

### 2.3. Characterization

X-Ray diffraction (XRD) patterns of the silicas were obtained on a Phillips Diffractometer model PW3040/00 X'Pert MPD/MRD at 45 KV and 40 mA, using Cu-K $\alpha$  radiation ( $\lambda = 1.5418 \text{ \AA}$ ). N<sub>2</sub> gas adsorption-desorption isotherms were obtained using a Micromeritics TriStar 3000 analyser, and pore size distributions were calculated using the Barret-Joyner-Halenda (BJH) model on the adsorption branch. Infrared spectra were recorded on a Nicolet-550 FT-IR spectrophotometer (in the region 4000 to 400 cm<sup>-1</sup>) as KBr disks. <sup>1</sup>H NMR and <sup>13</sup>C{<sup>1</sup>H} NMR spectra were recorded on a Varian Mercury FT-400 spectrometer. Cross Polarization <sup>13</sup>C CP/MAS NMR spectra were recorded on a Varian- Infinity Plus 400 MHz Spectrometer operating at 100.52 MHz proton frequency (4  $\mu$ s 90° pulse, 4000 transients, spinning speed of 6 MHz, contact time 3 ms, pulse delay 1.5 s). Elemental analyses were carried out by the Microanalytical Service of the Universidad Complutense de Madrid. The C, H and N analysis was accomplished by combustion analysis with elemental microanalyzers LECO CHNS-932. Scanning electron micrographs and morphological analysis were carried out on a XL30 ESEM Philips.

### 2.4. Knoevenagel condensation reaction

In a typical experiment, 11 mmol of benzaldehyde, 11 mmol of ethyl cyanoacetate and 50 mg of Chol-SBA-15 (corresponding to 0.04 mmol of choline hydroxide units) in ethanol (5 mL total final volume) were mixed in a 50 mL tube and the mixture heated at 60 °C during 60 min. After reaction completion, 5 mL of dichloromethane was added to dilute the organic compounds. The solid catalyst was precipitated by centrifugation and separated from the liquid phase. To analyze the sample by gas chromatography 1 mL of sample was withdrawn and diluted in ethanol to 5 mL and a fixed amount of dodecane as internal standard. The sample was analyzed by GC-FID (Agilent 6890N, DB-Wax capillary column 30 m, 0.53 mm). In addition, the corresponding compounds obtained after C-C condensations reactions was recrystallized from ethyl acetate and checked by <sup>1</sup>H NMR (See supplementary material, Figure S6).

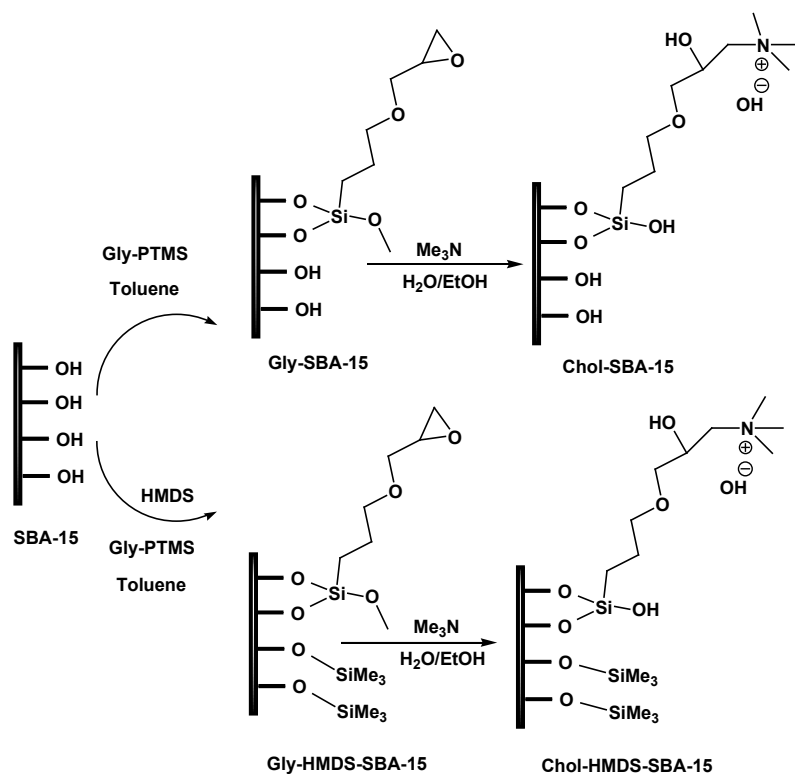
### 2.5. Reusability test

In a typical experiment and after the completion of reaction, the Chol-SBA-15 catalyst was separated by centrifugation, washed with dichloromethane, and reused several times without further treatment under the experimental conditions previously used.

### 1 3. Results and Discussion

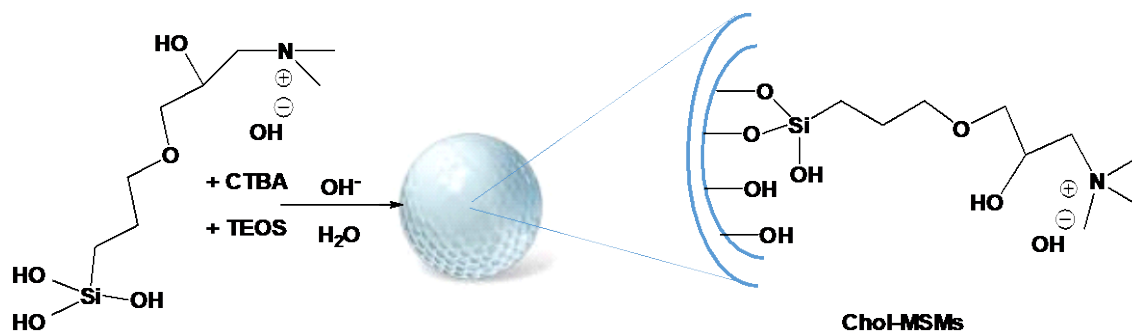
#### 2 3.1. Synthesis and Characterization

3 Choline hydroxide is a strong organic base with application in the production of other  
4 choline salts and in processes where a strong base with low levels of inorganic ions is  
5 needed or tolerated. The industrial production of choline hydroxide includes reacting at  
6 a temperature above 30 °C, ethylene oxide, trimethylamine and water in the presence  
7 of an aqueous medium in such amounts as to form a diluted choline hydroxide solution  
8 having a concentration of less than 40%. This diluted solution is concentrated by water  
9 removal to give a choline hydroxide solution at least 1.05 times more concentrated than  
10 the starting solution [14]. Similarly, in the present study, the preparation of hybrid  
11 mesoporous SBA-15 functionalized with choline hydroxide by a two-step process has  
12 successfully been achieved. Firstly, the previously dehydrated SBA-15 material was  
13 reacted with 3-(glycidyloxypropyl)trimethoxysilane (Gly-PTMS), to prepare the material  
14 labelled as Gly-SBA-15, with the epoxy group tethered to the silica surface. In a second  
15 stage, the epoxide function reacts with trimethylamine to give epoxide opening and the  
16 subsequent quaternization of the tertiary amine; since the reaction takes place in  
17 aqueous media the material thus synthesized possess the choline hydroxide (ionic  
18 liquid) molecule linked to the silica surface by a flexible medium size alkyl chain (See  
19 Scheme 1). This material has been labelled Chol-SBA-15. Alternatively, and for  
20 comparison purposes two additional materials containing the choline hydroxide  
21 function have been prepared. The material denoted as Chol-HMDS-SBA-15, in which the  
22 silanol groups remaining in the silica surface have been capped with  
23 hexamethyldisilazane (HMDS) and mesoporous functionalized silica microspheres. This  
24 latter material denoted as Chol-MSMs, was synthesized by a co-condensation route in  
25 basic medium (See Scheme 2) in the presence of the ionic liquid,  $[\text{Si}(\text{OH})_3\text{CH}_2\text{-CH}_2\text{-CH}_2\text{-}$   
26  $\text{O-CH}_2\text{-CH}(\text{OH})\text{-CH}_2\text{-N}(\text{CH}_3)_3]^+\text{OH}^-$ . The ionic liquid was prepared by reaction of 3-  
27 (glycidyloxypropyl)trimethoxysilane and trimethylamine in aqueous media [15,16].



1

2 Scheme 1. Synthesis of supported choline hydroxide (ionic liquid) onto SBA-15  
 3 mesoporous silica.



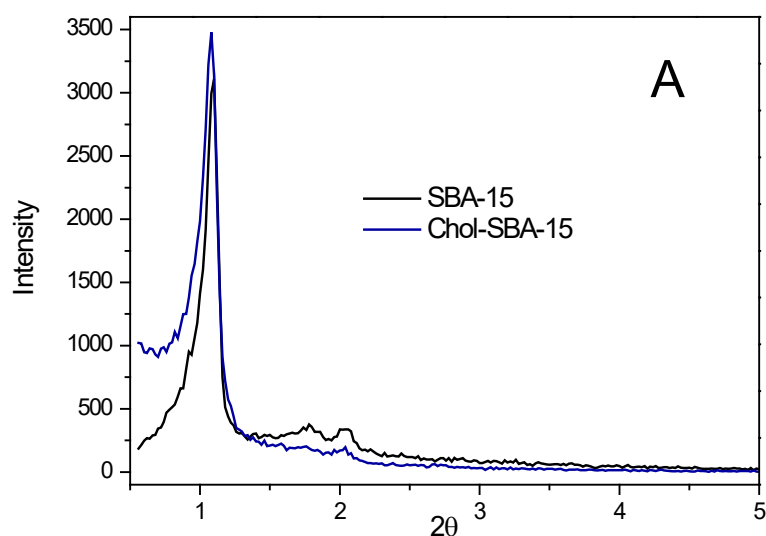
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5 Scheme 2. Synthesis of supported choline hydroxide (ionic liquid) onto mesoporous silica  
 6 microspheres synthesized by co-condensation route.

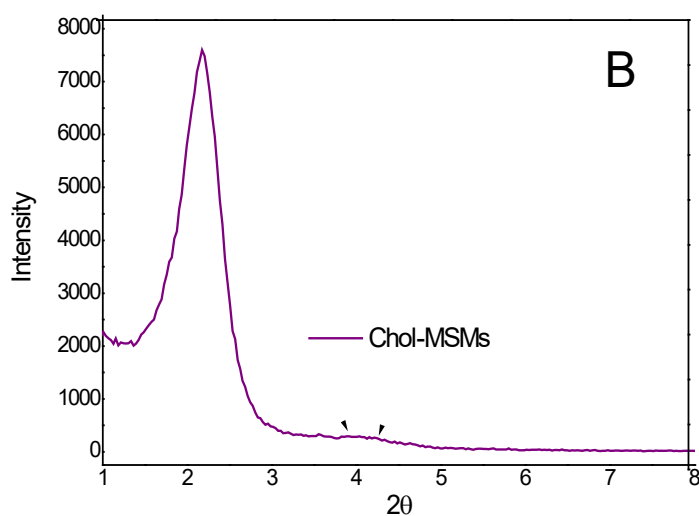
7 The mesostructured of Chol-SBA-15 material was confirmed by small-angle XRD and N<sub>2</sub>  
 8 adsorption–desorption isotherms. Unmodified SBA-15 shows a well-resolved pattern at  
 9 low 2θ values with one strong (100) diffraction peak at 0.98 and two additional high  
 10 order peaks (110) and (200) with lower intensities at 1.68 and 1.92; corresponding to a  
 11 highly ordered hexagonal mesoporous silica (Figure 1A). The SBA-15 material containing  
 12 the ionic liquid functionality showed the same pattern, indicating that the ordered



1 mesoporous structure of SBA-15 was well retained after the post synthesis  
2 functionalization process (Figure 1A). The plane (100) in the pristine SBA-15 shows  
3 higher intensity compared with Chol-SBA-15, which can be attributed to the lowering  
4 local order, due to variations in the wall thickness of the framework and the reduction  
5 of scattering contrast between the channel wall and the ligands present on the inner  
6 surface of silica materials. The mesoporous structure of Chol-MSMs is supported by its  
7 small-angle XRD; a sharp strong absorption appears at  $2\theta = 2.17$  with  $d_{100} = 4.02$  nm. The  
8 unit cell parameter  $a_o = 2d_{100} \times (\sqrt{3})^{-1}$ , was calculated to be 4.7 nm (Figure 2B). SEM  
9 micrographs of pristine SBA-15 and Chol-HMDS-SBA-15 show that both samples are  
10 uniform in shape and size with diameter and length approximately 0.5 and 1.0  $\mu\text{m}$ ,  
11 respectively (See Figure S1). The results clearly show that the framework of rod-like SBA-  
12 15 is well preserved after functionalization. This morphology renders pore channels  
13 shorter than those found in fiber like SBA-15 samples, which could facilitate mass  
14 diffusion within the pore channels.



15

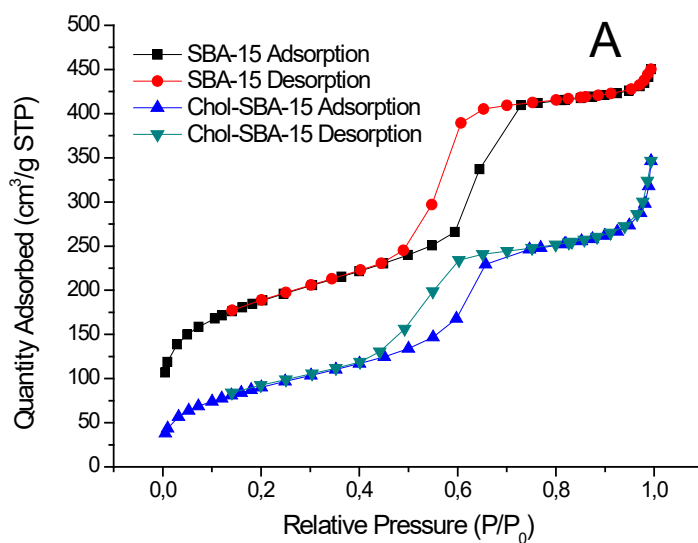


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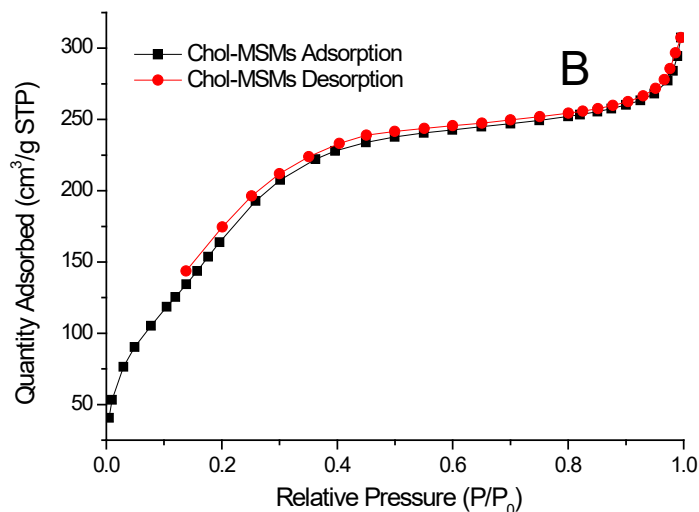
2 Figure 1. Small-angle XRD patterns of (A) SBA-15 and Chol-SBA-15 mesoporous materials  
 3 (B) mesoporous functionalized silica microspheres (Chol-MSMs) synthesized by co-  
 4 condensation route.

5 The physical parameters such as the surface area ( $S_{\text{BET}}$ ), total pore volume and BJH  
 6 average pore diameter have been measured by nitrogen adsorption experiments (Figure  
 7 2). The characteristic type IV BET isotherms for the prepared materials show the  
 8 presence of mesoscale pores. The sharp  $\text{N}_2$  condensation step at  $P/P_0 = 0.4-0.6$  for SBA-  
 9 15 type materials indicate that the supports have a highly ordered hexagonal pore  
 10 system. The parent SBA-15 material possesses  $S_{\text{BET}}$  ( $723 \text{ m}^2 \text{ g}^{-1}$ ), pore volume of  $0.81 \text{ cm}^3$   
 11  $\text{g}^{-1}$  and a BJH pore diameter of  $44 \text{ \AA}$ . The material Chol-SBA-15 presents an important  
 12 decrease in the  $S_{\text{BET}}$ , ( $333 \text{ m}^2 \text{ g}^{-1}$ ) pore volume ( $0.44 \text{ cm}^3 \text{ g}^{-1}$ ) and average BJH pore  
 13 diameter ( $32 \text{ \AA}$ ) in comparison with the parent support due to the presence of ionic  
 14 liquid anchored to the channels partially blocking the adsorption of nitrogen molecules.  
 15 Bouyer and co-workers [17] have revisited the conditions to prepare mesoporous silica  
 16 nanoparticles, they have studied the influence of the NaOH concentration on the  
 17 morphology and physicochemical properties of MSNs. They conclude that at low base  
 18 concentration the nanoparticles obtained have mesoporous worm like structure, with  
 19  $\text{N}_2$  adsorption–desorption isotherm characteristic of mesoporous materials and an  
 20 additional capillary condensation step at  $P/P_0 > 0.9$ , which confirms the formation of  
 21 interparticle porosity and increase the aggregation. Similar type IV  $\text{N}_2$  adsorption–

1 desorption isotherm characteristic of mesoporous materials are obtained for the  
2 material Chol-MSMs, this data and the XRD study suggest that Chol-MSMs synthesized  
3 by a co-condensation route has a worm-like mesostructure and form aggregates as can  
4 be observed by TEM (Figure S2). In comparison to Chol-SBA-15 material, Chol-MSMs  
5 possesses higher  $S_{\text{BET}}$  ( $670 \text{ m}^2 \text{ g}^{-1}$ ), comparable pore volume ( $0.43 \text{ cm}^3 \text{ g}^{-1}$ ) and smaller  
6 BBJ pore diameter ( $26 \text{ \AA}$ ) (See Figures 2B and S3). Based on the nitrogen content  
7 obtained by elemental analysis the quantity of molecules attached to the mesoporous  
8 SBA-15 was calculated to be  $0.81 \text{ mmol g}^{-1}$  ( $L_0 = \%N/\text{nitrogen molecular weight}$ ). Taking  
9 into account  $L_0$  and  $S_{\text{BET}}$  of the mesoporous silica, the average surface density,  $d$ , of  
10 attached molecules and the average intermolecular distance were calculated as  $0.77$   
11  $\text{molecules/nm}^2$  and  $1.14 \text{ nm}$ , respectively. Similarly, this data calculated for Chol-HMDS-  
12 SBA-15 are  $0.64 \text{ mmol g}^{-1}$  ligand content,  $0.60 \text{ molecules/nm}^2$  average surface density  
13 of attached molecules and  $1.29 \text{ nm}$  intermolecular distance. As expected the ligand  
14 content decreases since the silane ligand competes with the silylating agent, HMDS,  
15 used to mask the surface silanol groups. Finally, ligand content calculated for Chol-MSMs  
16 is  $0.96 \text{ mmol g}^{-1}$  with  $0.87 \text{ molecules/nm}^2$  average surface density of attached molecules  
17 and  $1.07 \text{ nm}$  intermolecular distance.



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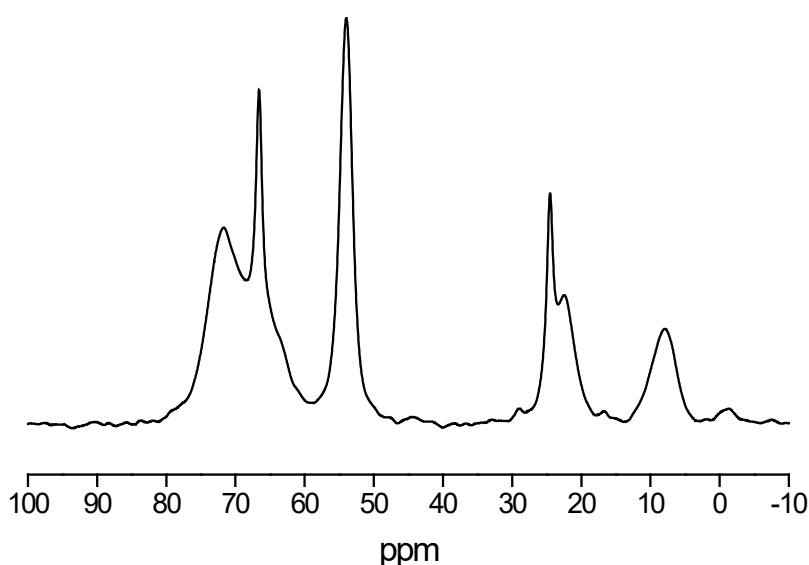


2

3 Figure 2. Nitrogen adsorption/desorption isotherms of (A) SBA-15 and Chol-SBA-15 and  
 4 (B) Chol-MSMs. Type IV isotherms typical of mesoporous silica are exhibited.

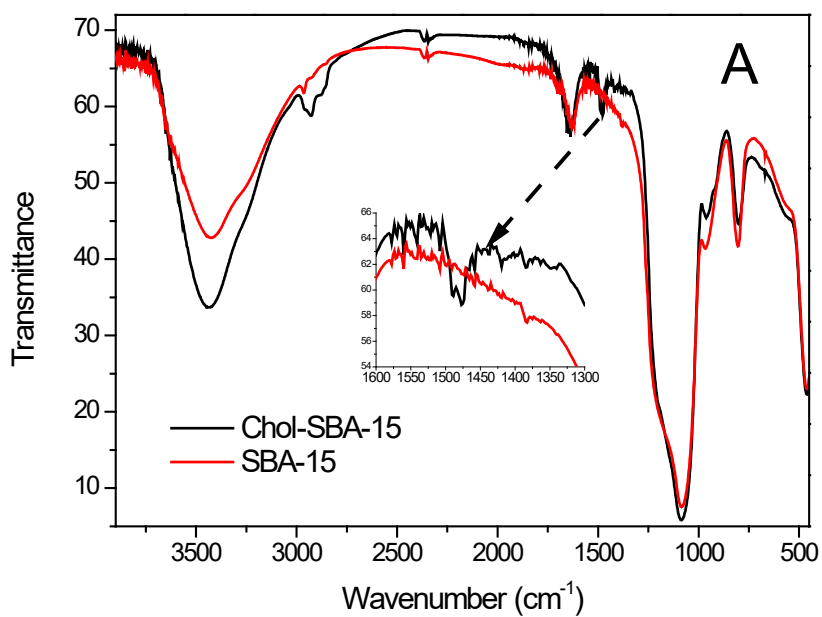
5 The  $^{13}\text{C}$  MAS NMR spectrum of Chol-SBA-15 (Figure 3) gives proof of the presence of the  
 6 ionic liquid function linked to the silica surface. The  $^{13}\text{C}$  CP MAS NMR spectrum of Chol-  
 7 SBA-15 exhibits signals at 8, 24 and 72 ppm due to the carbon atoms of the propyl chain  
 8  $-\text{Si}-\text{CH}_2-$ ,  $-\text{CH}_2-\text{CH}_2-\text{CH}_2-$  and  $-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{O}$ , respectively. The signal attributed to the  
 9 methylene group  $\text{O}-\text{CH}_2-\text{CHOH}-$  appears at 72 ppm (overlapped) and the signals due to  
 10 carbon atoms of the opened epoxide function appears at 66 and 72 ppm, the methyne

- 1 CH-OH and methylene N-CH<sub>2</sub>- groups, respectively. Finally, the intense resonance peak
- 2 at ca. 54 ppm indicates the presence of methyl groups attached to N.

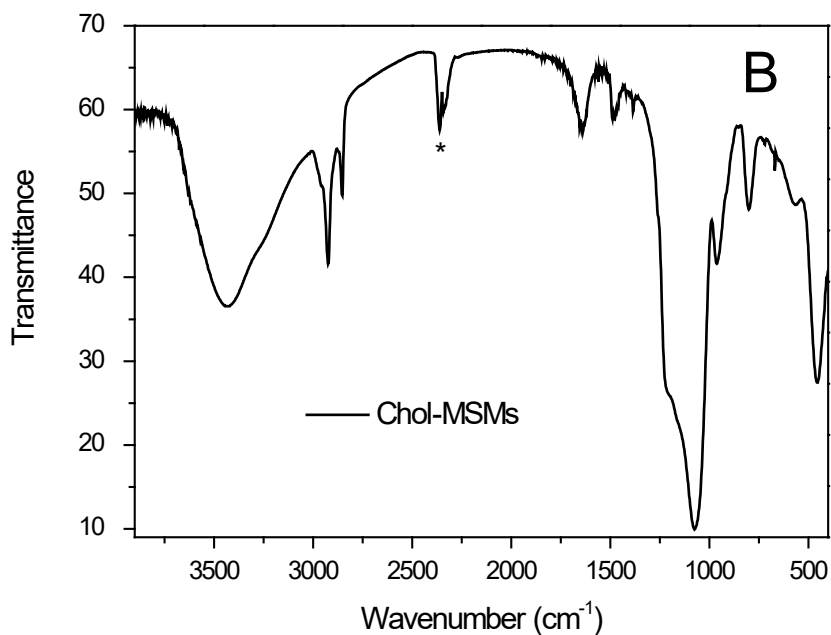


3  
4 Figure 3. <sup>13</sup>C CP MAS NMR of Chol-SBA-15

5 The FT-IR spectrum of mesoporous SBA-15 before and after functionalization are shown  
6 in Figure 4A and S4. The FTIR spectrum of SBA-15 shows characteristic bands at 3441  
7 cm<sup>-1</sup> assigned to O-H stretching vibrations and the remaining physisorbed water  
8 molecules, at 1629 cm<sup>-1</sup> due to deformation vibrations of the adsorbed water molecules  
9 and at 1082, 959 and 806 cm<sup>-1</sup> attributed to the Si-O stretching vibrations. Chol-SBA-15  
10 material displays additional bands at 2929 and 2878 cm<sup>-1</sup> due to the ν(C-H) stretching  
11 vibrations and at 1489, 1471 cm<sup>-1</sup> assigned to the bending vibrations of δ(C-H) of the  
12 alkyl chain. As can be seen in Figure 4B the FTIR spectrum recorded for Chol-MSMs  
13 shows similar bands supporting the presence of the ILs function.



1



2

3 Figure 4. (A) FTIR spectra of SBA-15 in comparison to Chol-SBA-15 (B) FTIR spectrum of  
 4 Chol-MSMs synthesized by co-condensation route \*atmospheric CO<sub>2</sub>

### 5 3.2. Catalytic tests

#### 6 3.2.1. Influence of reactants.

7 The Knoevenagel condensation between malononitrile or ethyl cyanoacetate and  
 8 benzaldehyde was carried out in a 50 mL reactor with 50 mg of catalyst, equivalent to

1 0.040 and 0.048 mmol of hydroxide choline units for Chol-SBA-15 and Chol-MSMs,  
2 respectively; and with equimolar amounts of reactants (11 mmol). The reactions results  
3 are summarized in Table 1. As can be seen, the catalytic system works excellently in  
4 malononitrile ( $pK_a = 9$ ) condensation with ethanol as solvent. The expected product is  
5 obtained quantitatively in a short time at room temperature using ethanol as solvent.  
6 The catalytic activity obtained for Chol-SBA-15 is higher than the results reported with  
7 MOF materials as  $\text{NH}_2\text{-MIL-53(Al)}$  [4] and with amine functionalized mesoporous  
8 material [18]. The conversion value decreases when using a less activated reactant, as  
9 ethyl cyanoacetate. To optimize the experimental conditions and to improve this result  
10 some extra experimental conditions have been tested.

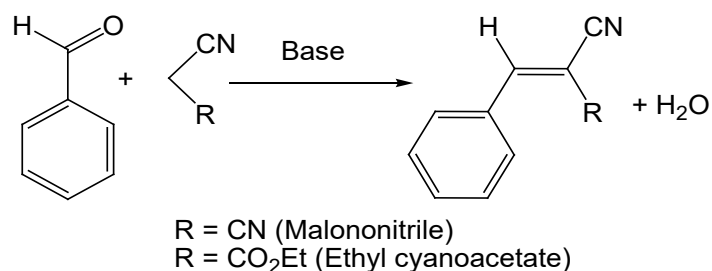
### 11 **3.2.2. Influence of reaction conditions.**

12 In the case of ethyl cyanoacetate ( $pK_a = 10.5$ ) the material Chol-SBA-15 showed its best  
13 result, 89 % conversion, at room temperature, using ethanol as solvent and increasing  
14 the reaction time to 24 h. This value decreases to 74 % when the reaction time decreases  
15 to 2 h even on increasing the working temperature at 60 °C. The effect of solvent was  
16 checked by using toluene, ethylene glycol/water and dichloromethane. As can be seen  
17 in table 1, polar solvents improve the conversion values in comparison to toluene, the  
18 conversion values go from 60% using toluene to 70% and 74% using dichloromethane  
19 and ethanol, respectively. The reaction was also tested in the absence of solvent. In this  
20 case, the yields obtained were lower.

### 21 **3.2.3. Influence of material**

22 As mentioned in the previous section two additional materials have been tested as  
23 catalysts in order to compare the results and the influence of the catalyst structure. The  
24 material Chol-HMDS-SBA-15 with capped silanol groups on the silica surface renders  
25 better results increasing the conversion (from 74% conversion using Chol-SBA-15 as  
26 catalyst to 90% for Chol-HMDS-SBA-15 catalyst). The material Chol-MSMs has proved to  
27 be the most efficient catalyst giving the desired product almost quantitatively (99% of  
28 conversion and 99% of selectivity towards ethyl 2-cyano-3-phenylacrylate in 2 h of  
29 reaction). Similar results were obtained with three-dimensional (3D) Zr(IV) MOFs  
30 containing amino groups [19].

31



Entry/Catalyst	Substrate	T (°C)	Solvent	Time (h)	% Conversion <sup>a</sup>
Chol-SBA-15	C≡NCH <sub>2</sub> C≡N	25	Ethanol	0.5	100
Chol-SBA-15	C≡NCH <sub>2</sub> CO <sub>2</sub> Et	25	Ethanol	24	89
Chol-SBA-15		60	Ethanol	2	74
Chol-SBA-15		60	Dichloromethane	2	70
Chol-SBA-15		60	Toluene	2	60
Chol-SBA-15		60	EG/H <sub>2</sub> O	2	71
Chol-SBA-15		25	Solvent less	24	51 <sup>d</sup>
Chol-SBA-15		60	solvent less	24	54 <sup>d</sup>
Chol-HMDS-SBA-15		60	Ethanol	2	90
Chol-MSMs		60	Ethanol	2	99

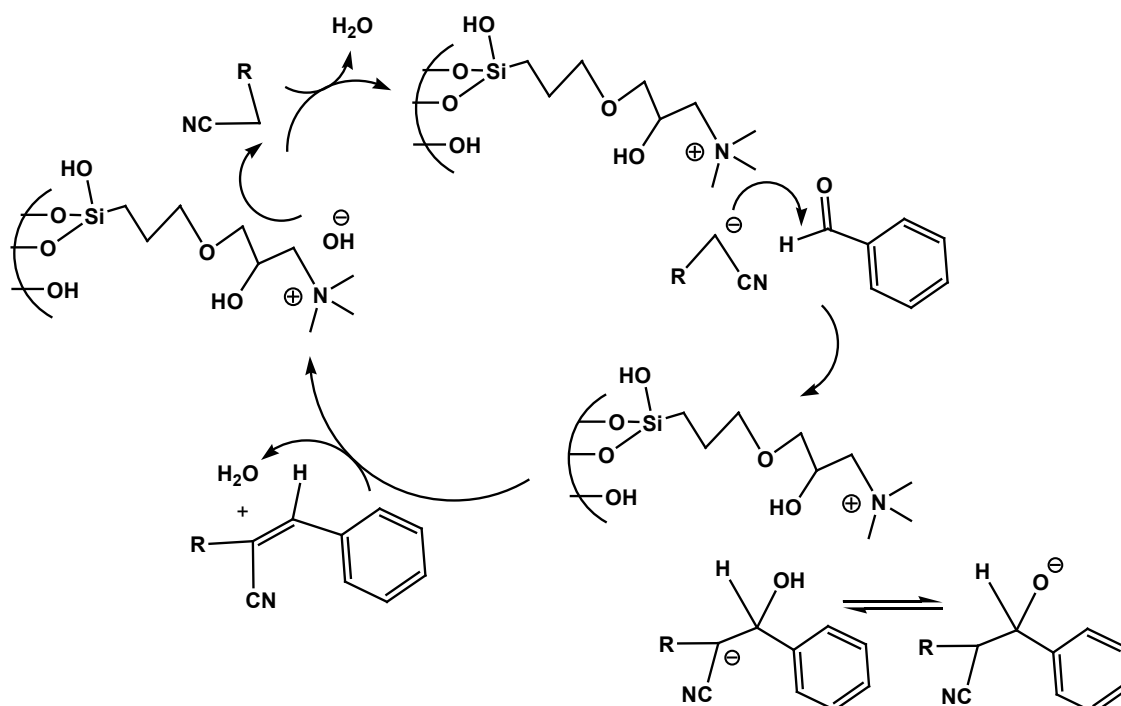
1 Table 1. Knoevenagel condensation reaction Conversion values for Chol-SBA-15. <sup>a</sup>Conversion vs  
2 malononitrile or ethyl cyanoacetate (GC values). Ethanol as solvent (with malononitrile 10mL  
3 and with ethyl cyanoacetate 5 mL).<sup>b</sup> Selectivity value is 99% towards 2-benzylidenemalononitrile  
4 or ethyl 2-cyano-3-phenylacrylate. <sup>c</sup> benzoic acid is observed as trace. <sup>d</sup>yield (product isolated  
5 and checked by <sup>1</sup>H-NMR).

6



### 3.2.4. Mechanism for the Knoevenagel condensation reaction

The effect of solvents, observed when using Chol-SBA-15 as catalysts, supports the existence of an ion-pair mechanism since activity increases in polar solvents as previously proposed in the literature for high order amines. The mechanism involves base abstraction of a proton from the methylene carbon and the formation of a carbanion, which attacks the carbonyl group forming an enol. The reaction finish with the formation of a double C=C and water release (see Scheme 3).



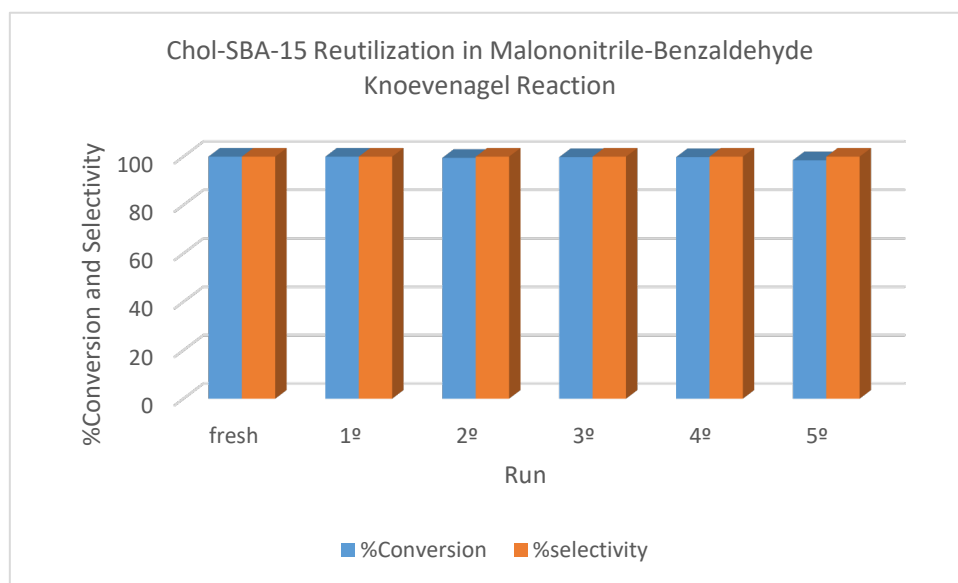
Scheme 3. Plausible ion-pair mechanism for the Knoevenagel condensation reaction.

Acid-base bifunctional inorganic catalysts have been reported to perform the reaction via this mechanism [20]. The proposed mechanism starts with the activation of the cyano compound by interaction of the nitrile group with the acid Lewis site, thereby facilitating abstraction of the proton from the methylene group and stabilizing the resultant carbanion. Angeletti et al. [21] proposed the involvement of neighbouring silanol groups in amorphous silica supports through the formation of hydrogen bonds and the improvement of reaction rate by strongly adsorbing water molecules produced by the reaction. Other studies proposed a different role for the silanol groups, due to their low  $pK_a$  value they can transfer a proton influencing greatly the mechanism; in the case of using primary amines, as basic functionalities, through the formation of an imine

1 intermediate [22]. The results summarized in Table 1 shows better conversion values by  
2 using Chol-HMDS-SBA-15 against Chol-SBA-15, which suggest an important decrease of  
3 base strength of the latter because of the interaction of hydroxide group and surface  
4 remaining silanol groups; as previously proposed by Corma and co-workers [10]. As  
5 discussed, the use of hexamethyldisilazane, as silylating agent, mask the silanol groups  
6 on the silica surface in Chol-HMDS-SBA-15 maintaining unaltered the pendant choline  
7 hydroxide function. Sangs et al. [11] observed an important decrease in activity for  
8 Knoevenagel ethyl cyanoacetate and benzaldehyde reaction when using silylated  
9 aminopropyl and dihydroimidazole functionalized SBA-15 in comparison to their  
10 unprotected analogues. In the case of aminopropyl functionalized SBA-15 they accepted  
11 the formation of an imine intermediate promoted by proton transfer from the silanol  
12 groups. In the case of dihydroimidazole functionalized SBA-15, a stronger base unable  
13 to form the imine intermediate, the activity decreases upon silylation was explained not  
14 only by the absence of cooperative acid silanols but also because of an increase of  
15 hydrophobic character of the environment of the anion making difficult its stabilization.  
16 In our materials, the presence of a hydroxyl group attached to the main alkyl chain could  
17 similarly guarantee the formation of hydrogen bonds with release water enhancing the  
18 nucleophilic addition of the anionic methylene compound. In addition, the presence of  
19 the ionic liquid tethered by a considerably long alkyl chain would avoid the negative  
20 effect that the hydrophobic surface could have in the anion stabilization. Finally, the  
21 influence of the support is evaluated by comparison with the mesoporous silica  
22 microspheres containing the same chemical functionality. The catalyst Chol-MSMs  
23 shows quantitative conversion of ethyl cyanoacetate under similar experimental  
24 conditions, which can be due to its to its better physical properties as higher surface  
25 area with comparable pore volume and more efficient dispersion in the solvent media.  
26 In addition, the functionalization procedure used guarantees higher ligand loading and  
27 hence higher amount of basic sites and the homogenous distribution of the basic  
28 functionalities throughout the material avoiding the concentration of functionalities on  
29 the pore mouth, as can take place, in the conventional post synthetic procedure used  
30 when synthesized Chol-SBA-15.

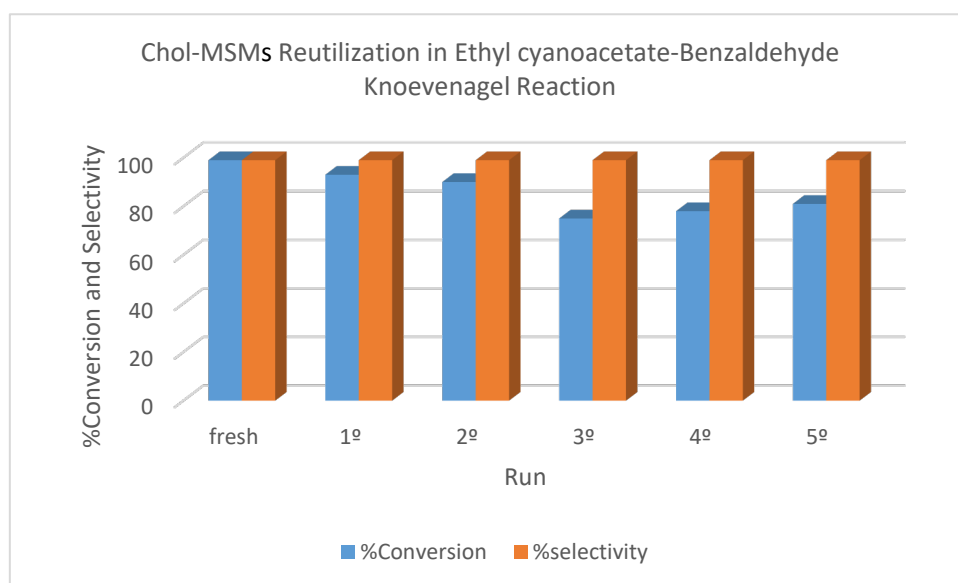
### 31 **3.2.5. Reusability Studies**

1 The reusability of the best catalyst systems has been studied. Chol-SBA-15 catalyst was  
2 tested for Knoevenagel reaction of benzaldehyde and malononitrile. The results of  
3 malononitrile conversion and 2-benzylidenemalononitrile yield for six consecutive  
4 catalytic runs are shown in Figure 5. As can be seen, both parameters remain practically  
5 unaltered with quantitative conversion of malononitrile to 2-benzylidenemalononitrile  
6 in all runs in comparison to fresh catalysts. The reusability value of a catalyst should be  
7 consistent with good chemical resistance of the structure against the reaction  
8 conditions, as observed in the FTIR spectrum of Chol-SBA-15 after six consecutive cycles.  
9 The FTIR spectrum of recovered and washed Chol-SBA-15 shows a similar IR pattern  
10 after the reactions (See Figure S5). Meanwhile, Chol-MSMs material was recovered for  
11 Knoevenagel reaction of benzaldehyde and ethyl cyanoacetate. The conversion and  
12 selectivity values for six consecutive catalytic runs are shown in Figure 6; the graph  
13 shows that conversion decreases in comparison to fresh catalyst but retain high  
14 selectivity. Since we assume that chemical resistance is adequate, as found for the Chol-  
15 SBA-15, this significant drop in activity could be due to the difficult mechanical recovery  
16 of the functionalized microspheres since they remain in suspension. This drawback could  
17 be overcome using mesoporous magnetic silica microspheres, which would improve  
18 their reutilization and make this material a better catalyst in comparison to SBA-15  
19 based catalysts [23].



20

1 Figure 5. Catalytic activity of Chol-SBA-15 in consecutive reaction cycles of Knoevenagel  
2 reaction.



3

4 Figure 6. Catalytic activity of Chol-MSMs in consecutive reaction cycles of Knoevenagel  
5 reaction.

#### 6 **4. Conclusions.**

7 We have presented the synthesis of mesoporous silica materials with the choline  
8 hydroxide function tethered to the silica surface by a new and efficient method inspired  
9 on the industrial production of this strong Brønsted base compound. These Brønsted  
10 base solid materials are very efficient catalysts in Knoevenagel condensation reaction  
11 through an ion-pair mechanism. The easy separation and recovery of the catalysts make  
12 them reusable for several times without loss of activity. The silica mesoporous  
13 microparticles functionalized with ionic liquid based on choline hydroxide unit has great  
14 potential for multiple applications and is superior to similarly functionalized SBA-15  
15 analogues.

16

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