



## Synthesis of chalcones catalyzed by aminopropylated silica sol–gel under solvent-free conditions

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### ABSTRACT

Aminopropylated nanosilica was prepared by a simple sol–gel process from tetraethyl orthosilicate (TEOS) and then it was functionalized with different amounts of 3-aminopropyltriethoxysilane (APS) under toluene reflux. The prepared solids were characterized by means of XRD, FT-IR, TGA–DTA, SEM–EDS, and TEM. Their textural properties were determined by adsorption–desorption isotherms of N<sub>2</sub> at 77 K. It was proved that the amount of APS used in the preparation process had a great influence on the physicochemical properties of the hybrid organic–inorganic solid materials. The materials were used as catalyst in the Claisen–Schmidt preparation of chalcones for the reaction of substituted acetophenones and benzaldehydes under solvent-free conditions. The result showed that the presence of a high amount of aminopropyl groups was important for a very good performance of the catalyst in the substrate conversion. Also, the influence of different groups in the aromatic ring of acetophenones and benzaldehydes was investigated. In all cases, coproduct formation was not observed; the catalysts were recovered and can be recycled twice without appreciable loss of reactivity.

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## 1. Introduction

Chalcones are a family of aromatic ketones with two aromatic groups bridged by an enone linkage (Ar–COCH=CH–Ar'). They have attracted increasing attention due to numerous pharmacological applications. Chalcones are the main precursors for the biosynthesis of flavonoids, which are frequent components of the human diet [1]. For example, Licochalcone A isolated from the roots of *Glycyrrhiza inflata* (licorice) has in vitro and in vivo antimalarial [2] and antileishmanial activity [3], and 3-methoxy-4-hydroxyoncocarpin isolated from the roots of *Lonchocarpus utilis* inhibits NADH:ubiquinone oxidoreductase activity (Fig. 1) [4].

Compounds with the backbone of chalcones, which possess various biological activities such as antimicrobial [5], anti-inflammatory [6], antiplatelet [7], antimalarial [8], anticancer [9], antileishmanial [10], antioxidant [11], antifungal [12], and inhibition of leukotriene B<sub>4</sub> [13], have been reported. Also some chalcones exhibit allelopathic activity [14], and many chalcones are used as agrochemicals, therefore chlorochalcones are a potent insect antifeedant [15,16].

Chalcone is commonly synthesized via the Claisen–Schmidt aldol condensation between acetophenone and benzaldehyde. This reaction is catalyzed by bases and acids under homogeneous conditions. Wang et al. [17] used aminopropylated silica containing mesopores prepared by a simple sol–gel process with tetraethyl orthosilicate and aminopropyltriethoxysilane under strong acidic condition. The materials were used as catalysts in the Claisen–Schmidt condensation in the liquid phase. The results showed that the presence of an appropriate amount of aminopropyl groups and narrowly distributed mesopores was important for good performance of the catalysts.

The condensation reaction in basic medium is usually carried out in the presence of sodium hydroxide, potassium hydroxide or alkali alcoholate [18,19], and the acid-catalyzed methodologies include the use of dry HCl [20], Lewis acid as TiCl<sub>4</sub> [21], *p*-toluenesulfonic acid [22], and more recently BF<sub>3</sub>–Et<sub>2</sub>O [23]. There are many drawbacks under homogeneous conditions such as catalysis recovery and waste-disposal problems.

In this aspect, a heterogeneous catalyst is considered as an eco-friendly alternative. Industry favors catalytic processes in view of easy handling, simple work-up and regenerability [24]. Also green chemistry provides a good and eco-friendly method for the organic synthesis under solvent-free conditions.

In relation to catalytic materials, the application of nanoscale materials and structures, usually ranging from 1 to 100 nm, is an

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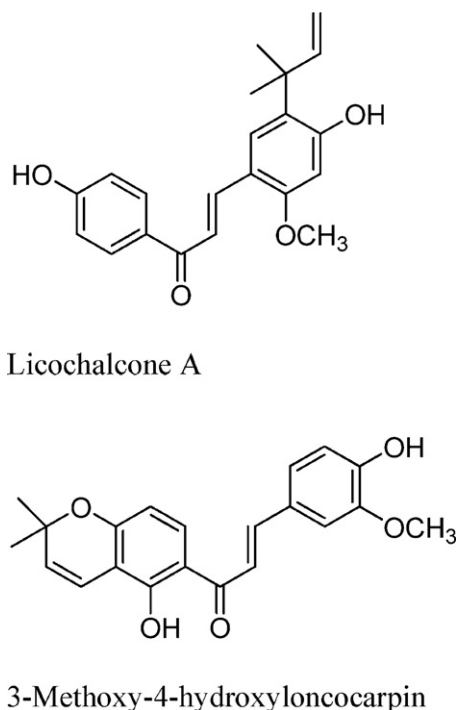


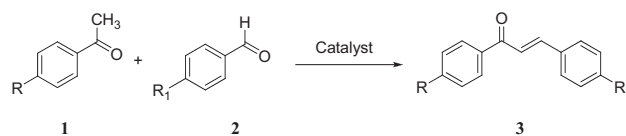
Fig. 1. Naturally occurring chalcones.

emerging area of nanoscience and nanotechnology. Nanomaterials may provide solutions to technological and environmental challenges in the areas of solar energy conversion, catalysis, medicine, and water treatment [25,26]. This increasing demand must be accompanied by “green” synthesis methods as was mentioned previously. In the global efforts to reduce generated hazardous waste, green chemistry and chemical processes are progressively integrating with modern developments in science and industry. Implementation of these sustainable processes should adopt the 12 fundamental principles of green chemistry [27–31]. These principles are geared to guide in minimizing the use of unsafe products and maximizing the efficiency of chemical processes. Hence, many synthetic routes or chemical processes should address these principles using environmentally benign solvents and nontoxic chemicals [27].

On the other hand, nanomaterials often show unique and considerably changed physical, chemical and biological properties compared to their macro-scaled counterparts [32].

In this way, as a potential alternative, heterogeneous acid or basic catalysts for chalcone synthesis, for example, alkaline-doped carbons [33], zeolites [34], alumina [35], magnesium oxide [36], hydrotalcites [37], natural phosphates modified with sodium nitrate or potassium fluoride [38], potassium hydroxide impregnated on silica gel [39], acid montmorillonites [40], silica–sulphuric acid [41], zinc chloride and microwave irradiation [42], commercial acid clays [43], and metal nanoparticles [44], have received much attention over the last two decades. Recently, the use of acidic IL (ionic liquid) as catalyst for chalcone synthesis has been reported because of its benign nature as solvent and its ability to dissolve a wide range of compounds, but the high cost, viscosity and issues related to its separation, especially when the product is a high-boiling liquid or a solid, limit its use [45,46].

Another clean alternative is the use of amino- or diamino-modified porous materials over different supports, for example, mesoporous silica, SBA-15 materials and zeolites. These materials were used for the synthesis of flavanones via chalcones [47,48], Knoevenagel condensation [49], Michael additions [50], and the



Scheme 1. Chalcone synthesis by Claisen–Schmidt procedure.

nitroaldol reactions [51]. We have recently shown that amine-functionalized silica sol–gel is a very effective catalyst for the transesterification reaction of  $\beta$ -ketoesters in heterogeneous conditions using toluene as reaction solvent [17,52,53].

Here we report our recent results on the efficient synthesis of chalcones by the Claisen–Schmidt condensation reaction under solvent-free conditions catalyzed by aminopropylated silica sol–gel materials. The materials were prepared by a simple functionalization method without the addition of any pore-directing agents. The catalytic efficiency of the aminopropylated silica sol–gel is discussed for the Claisen–Schmidt condensation between substituted benzaldehydes and substituted acetophenones in the absence of solvent (Scheme 1).

## 2. Materials and methodology

### 2.1. Materials and reagents

All solvents and chemicals were commercially available and used without further purification unless otherwise stated.

### 2.2. Catalysis synthesis

#### 2.2.1. Silica preparation

Silica (SI) preparation by the sol–gel technique: all the experiments were made with a final molar ratio of tetraethylorthosilicate (TEOS), TEOS/EtOH/H<sub>2</sub>O, equal to 1:1:4, using AcOH as catalyst. The TEOS–EtOH–AcOH sols were stirred at atmospheric pressure at room temperature (r.t.), for 30 min. Then, the hydrolysis process began with the slow addition of distilled water. After water addition, gelation of the sols was carried out at r.t., and the wet gels were then aged in the same medium until dry silica particles were obtained. These solids were washed with distilled water, and subsequently dried at 20 °C.

#### 2.3. Functionalized silica

The catalysts were prepared by grafting 3-aminopropyltrimethoxysilane (APS) onto the silica sol–gel prepared previously [54,55]. One gram of SI was refluxed in dry toluene solution (50 ml) containing the corresponding amount of APS (see Table 1), at 110 °C for 5 h. The catalysts were recovered by filtration after washing in dry toluene (20 ml), ethyl ether (20 ml) and dichloromethane (20 ml). The catalysts were dried in an oven at 100 °C and stored for later use. The nomenclature of samples is listed in Table 1 according to the APS amount.

### 2.4. Catalyst characterization

#### 2.4.1. Fourier transformed infrared spectroscopy (FT-IR)

Bruker IFS 66 equipment, pellets with BrK, and a measuring range of 400–1500 cm<sup>-1</sup> were used to obtain the FT-IR spectra of the solid samples.

#### 2.4.2. Electron microscopies

The scanning electron microscopy (SEM) analysis was carried out with a scanning electron microscope Philips 515, with energy dispersive analyzer (EDAX-Phoenix). For the transmission electron

**Table 1**  
Nomenclature of synthesized silica and APS perceptual amount on silica surface.

Entry	Nomenclature of samples	APS (ml)	First dried (100 °C) in N <sub>2</sub> atmosphere before APS contact (g)	Second dried (100 °C) in N <sub>2</sub> atmosphere after APS contact (g)	% APS on surface silica
1	SI	0			
2	SI-A	0.25	0.1533	0.1746	8.52
3	SI-B	0.5	0.1659	0.1989	6.6
4	SI-C	0.75	0.1596	0.2195	7.98
5	SI-D	1.0	0.1685	0.3616	19.31
6	SI-E	1.5	0.1675	0.4400	18.16
7	SI-F	2.0	0.1679	0.9255	37.88
8	SI-G	3.0	0.1601	1.8574	56.57

microscopy (TEM and EDX) study, a JEOL transmission electron microscope, JEM-2010 model, was used.

#### 2.4.3. XRD analyses

Power XRD patterns were recorded on the same samples that had been analyzed by FT-IR. The equipment used was a Phillips PW-1732 with built-in recorder, using Cu K $\alpha$  radiation, nickel filter, 20 mA and 40 kV in the high voltage source, and scanning angle between 5 and 60° of 2 $\theta$  at a scanning rate of 2° per min.

#### 2.4.4. Potentiometric titration

A 0.05 ml portion of *n*-butylamine (0.1 N), in acetonitrile, was added to a known mass of solid (between 0.1 and 0.05 g) using acetonitrile as solvent, and stirred for 3 h. Later, the suspension was titrated with the same base at 0.05 ml/min. The electrode potential variation was measured with an Instrumentalia S.R.L. digital pH meter, using a double junction electrode. The acidic properties of the samples measured by this technique enable the evaluation of the number of acid sites and their acid strength. In order to interpret the results, it is suggested that the initial electrode potential (*E*) indicates the maximum acid strength of the surface sites, and the values (meq/g solid), where the plateau is reached, indicate the total number of acid sites. The acid strength of surface sites can be assigned according to the following ranges: very strong site, *E* > 100 mV, strong site, 0 < *E* < 100 mV; weak site, -100 < *E* < 0 mV, and very weak site, *E* < -100 mV.

#### 2.4.5. Textural properties

The specific surface areas (*S*<sub>BET</sub>) were determined by the nitrogen adsorption/desorption technique using Micromeritics Accusorb 2100E equipment (Table 1).

#### 2.4.6. Thermal analysis

The TG-DTA measurements of the solid samples were performed in a Shimadzu DT 50 thermal analyzer. The thermogravimetry and differential thermal analysis experiments were performed under argon and nitrogen, respectively, using 20–25 mg samples and a heating rate of 10 °C/min. Quartz cells were used as sample holders with Al<sub>2</sub>O<sub>3</sub> as reference. The studied temperature range was 25–700 °C.

### 2.5. Catalytic reaction procedure

#### 2.5.1. Chalcone preparation study

The catalytic chalcone synthesis was performed in a sealed tube immersed in a thermostated bath with magnetic stirrer under solvent-free conditions. A mixture of the corresponding aldehyde (1.3 mmol), acetophenone (1 mmol) and catalyst (100 mg) was warmed at the corresponding temperature. Aliquots of the reaction mixture were withdrawn at intervals of time. Each sample was approximately diluted with 1 ml of ethanol. Conversions were obtained with the analysis performed with a Varian GC 3400 instru-

ment. The capillary column was a 30 m Chromopack CP Sil 8 CB, whose diameter was 0.32 mm. The identification of products was performed with GC-MS (detector HP 5971). The conversion is expressed in terms of amount of chalcone in wt.%.

#### 2.5.2. Typical procedure for chalcone synthesis

Chalcone synthesis was performed in a sealed tube under solvent-free conditions. A mixture of the corresponding aldehyde (1.3 mmol), acetophenone (1 mmol) and catalyst (100 mg) was warmed at 140 °C for 4 h. The reaction mixture was diluted with hot toluene (10 ml), the catalyst was filtered off, and then the solution was washed, dried with anhydrous Na<sub>2</sub>SO<sub>4</sub>, the solvent was evaporated, and the residue purified by column chromatography (silica gel, ethyl acetate:hexanes) to afford pure chalcones. All the yields were calculated from isolated products. <sup>13</sup>C NMR and <sup>1</sup>H NMR spectra were recorded at room temperature on Bruker Avance DPX-400 spectrometers using TMS as internal standard. The catalyst was recycled by filtration followed by washing with toluene (2 × 5 ml), dried under vacuum and then reused. The spectral data of isolated compounds are listed below.

**Chalcone:** <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  8.10 (2H, dd, *J*: 8.2, *J*: 1.8, H-2', H-6'), 7.94 (1H, d, *J*: 16, H-3), 7.59–7.52 (6H, m, H-2, H-3', H-4', H-5', H-2'', H-6''), 7.43–7.41 (3H, H-4'', H-5'', H-6'').

<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz): 190.4 (CO), 144.9 (C-3), 138.5 (C-1'), 134.7 (C-1''), 132.9 (C-4'), 130.7 (C-3', C-5')\*, 128.7 (C-3'', C-5''), 128.6 (C-2'', C-6'')\*, 128.5 (C-2', C-6')\*, 128.4 (C4''), 122.5 (C2). They can be interchanged.

**4-Methylchalcone:** <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  = 8.03 (2H, dd, *J*: 8, 1.8, H-2', H-6'), 7.86 (d, 1H, *J*: 16, H-3), 7.62–7.45 (m, 6H, H-2, H-3', H-4', H-5', H-2'', H-6''), 7.10 (d, 2H, *J*: 8, H-3'', H-5''), 2.34 (CH<sub>3</sub>).

<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz):  $\delta$  = 190.5 (CO), 144.9 (C-3), 138.6 (C-1'), 138.4 (C4''), 132.9 (C-4'), 131.7 (C-1''), 130.9 (C-3', C-5'), 128.9 (C-3'', C-5''), 128.6 (C-2'', C-6'')\*, 128.5 (C-2', C-6')\*, 122.5 (C2), 21.4 (CH<sub>3</sub>). They can be interchanged.

**4-Chlorochalcone:** <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  = 8.1 (2H, dd, *J*: 8, 1.8, H-2', H-6'), 7.85 (d, 1H, *J*: 16, H-3), 7.73–7.59 (m, 6H, H-2, H-3', H-4', H-5', H-2'', H-6''), 7.35 (d, 2H, *J*: 8, H-3'', H-5'').

<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz):  $\delta$  = 190.2 (CO), 143.2 (C-3), 138.0 (C-1'), 136.4 (C4''), 133.4 (C-4'), 132.8 (C-1''), 129.5 (C-3', C-5')\*, 129.2 (C-3'', C-5''), 128.6 (C-2'', C-6'')\*, 128.5 (C-2', C-6')\*, 122.5 (C2). They can be interchanged.

**4-Methoxychalcone:** <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  = 8.0 (2H, dd, *J*: 8, 1.9, H-2', H-6'), 7.71 (d, 1H, *J*: 16, H-3), 7.3–7.7 (m, 6H, H-2, H-3', H-4', H-5', H-2'', H-6''), 6.93 (d, 2H, *J*: 8, H-3'', H-5''), 3.85 (s, 3H, -OCH<sub>3</sub>).

<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz):  $\delta$  = 190.4 (CO), 161.5 (C-4''), 144.5 (C-3), 138.5 (C-1'), 132.4 (C-4'), 130.4 (C-2'', C-6''), 128.5 (C-3', C-5')\*, 128.4 (C-2', C-6')\*, 127.7 (C-1''), 119.5 (C-2), 114.7 (C-3'', C-5''), 55.2 (-OCH<sub>3</sub>). They can be interchanged.

**4-Hydroxychalcone:** <sup>1</sup>H NMR (DMSO d-6, 400 MHz):  $\delta$  = 10.1 (sa, 1H, OH), 8.11 (2H, dd, *J*: 8, 1.8, H-2', H-6'), 7.81–7.57 (m, 7H, H-2, H-3 H-3', H-4', H-5', H-2'', H-6''), 6.88 (d, 2H, *J*: 8, H-3'', H-5'').

**Table 2**  
Textural properties of functionalized nano-silicas.

Sample	BET surface area (m <sup>2</sup> /g)	t-Plot micropore area (m <sup>2</sup> /g)	BET adsorption average pore width (Å)	BJH adsorption average pore width (Å)	t-Plot micropore volume (m <sup>3</sup> /g)
SI	459	88	67.3	67.3	0.037
SI-A	209	232	106.7	106.7	−0.015
SI-B	106	123	133.3	122.3	−0.011
SI-C	45	59	172.3	142.5	−0.008
SI-D	54	78	140.2	140.2	−0.014
SI-E	46	40	170.7	178.7	0.001
SI-F	5	3	9.4	9.4	0.001
SI-G	5	2	8.6	7.3	0.001

<sup>13</sup>C NMR (DMSO d-6, 100 MHz):  $\delta$  = 188.8 (CO), 160.5 (C-4''), 144.6 (C-3), 138.0 (C-1'), 132.6 (C-4'), 130.8 (C-2'', C-6''), 128.6 (C-3', C-5')\*, 128.5 (C-2', C-6')\*, 125.7 (C-1''), 118.5 (C-2), 115.8 (C-3'', C-5''). They can be interchanged.

<sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz): 7.95 (2H, d, J: 8, H-2', H-6'), 7.81 (1H, d, J: 16, H-3), 7.55–7.40 (m, 3H, H-2, H-2''), 6.99–6.81 (m, 5H, H-3', H-5', H-3'', H-5'', H-4'').

<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz):  $\delta$  = 189.8 (CO), 144.5 (C-3), 143.6 (C-1''), 135.6 (C-4'), 135.0 (C-1'), 130.3 (C-2'', C-6''), 129.3 (C-2', C-6')\*, 128.9 (C-3', C-5')\*, 128.6 (C-3'', C-5'')\*, 128.4 (C-4'')\*, 122.4 (C-2), 21.6 (−CH<sub>3</sub>). They can be interchanged.

<sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  = 7.85 (1H, d, J: 16, H-3), 7.70 (d, J: 8, H-2', H-6') 7.65–7.49 (m, 5H, H-2, H-2'', H-6'', H-3', H-5'), 7.15–7.28 (m, 3H, H-3'', H-4'', H-5'').

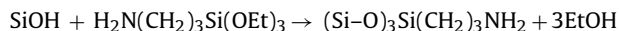
<sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz):  $\delta$  = 189.1 (CO), 145.5 (C-3), 139.2 (C-1'), 136.4 (C-4'), 135.1 (C-1''), 134.8 (C-4''), 130.8 (C-3', C-5'), 129.5 (C-3'', C-5'')\*, 129.7 (C-2', C-6')\*, 128.5 (C-2'', C-6''), 121.8 (C-2). They can be interchanged.

### 3. Results and discussion

#### 3.1. Silica characterization

The interface involving silica surface plays an important role in the adsorption process. The surface characteristics of the adsorbate determine the nature of the bonding between adsorbate and adsorbent. Different techniques are in use to characterize the surface of the adsorbents. To investigate the behavior of porous silica coated with siloxane polymers, Gilpin et al. [56] used the nitrogen adsorption technique for the surface area and porosity of silica. On thermal treatment the hydrophilic surface gradually changes to hydrophobic surface by irreversible elimination of a pair of adjacent hydroxyls [57,58].

The APS was used for the surface modification of hydrophilic silica obtained via sol–gel by grafting. The functionalization process occurs as shown in the following equation:



The equation is a very simplified version of the inclusion of APS ethoxy-type groups on the silica surface. The modification of the silica surface using APS consumes three silanol groups and generates a terminal amino group.

It is important to mention that the amount of APS in the functionalization process and during the washing and drying of samples had a great influence on the textural properties of the hybrid organic–inorganic materials. The samples prepared by TEOS hydrolysis and with different amounts of APS (Table 1) had a narrow pore size distribution structure and a very different surface area and pore volume depending on the APS content (Table 2), as it were obtained in previous results [54,55,59,60]. In relation to that reaction, the  $S_{\text{BET}}$  decreases from 459 m<sup>2</sup>/g (SI) to 5 m<sup>2</sup>/g (SI-G) because of the reaction between APS and TEOS, and steric effects due to their

structure (Tables 1 and 2, respectively) [61]. Regarding the textural properties, the surface area of bulk and supported acid samples determined from N<sub>2</sub> adsorption–desorption isotherms using BET and BJH methods, together with the t-plot micropore area, BET adsorption average pore width, BJH adsorption average pore width and the t-plot micropore volume, are shown in Table 2, as was mentioned previously. In all cases the values are close to the experimental error of the methods used. Although the same samples show negative adsorption data, attributed to the agglomeration of APS and the possible highly hygroscopic nature of silica, there could be electronic delocalization that repulses the nitrogen molecules, generating gas desorption, and very different  $S_{\text{BET}}$  results without any relation between the APS amount and surface area. In addition, according to the surface microvalues calculated using the t-plot method (Table 2), the total surface area comes from a micro and mesoporous structure depending on the APS amount.

According to the results of textural properties, XRD patterns of the samples do not present a crystalline structure (not shown here). This may be due to the presence of high APS agglomeration without interaction with the support [54,55]. The sample with out APS does not show crystalline structure.

In relation to the acidic properties, the curves obtained for sample leaching, by means of potentiometric titration with *n*-butylamine, are not shown in this paper [53]. At this point, it is interesting to comment that the development of a potentiometric method was thought of taking into account that acid and basic functions of a solid are not properly defined thermodynamically. Moreover, an indicator test such as the Hammett's method, though considered as a reference technique, is difficult to apply to certain solids. The method used here is based on the observation that the potential difference is mainly determined by the acidic environment around the electrode membrane. The measured electrode potential is an indicator of the acidic properties of dispersed solid particles. The different samples were titrated with *n*-butylamine in order to compare their acidities. Although all samples exhibited weak sites, SI showed higher acidity than SI-A (200 mV) to SI-G (−200 mV). It is evident from this result that the grafting process leads to amine groups of APS attached to the surface of SI acidic sites.

On the other hand, near-IR spectra of water adsorbed on silica are also used for the study of the surface behavior of silica. Silanols are proposed to be the water adsorption sites [58–66]. This model can also explain the hydrophobic character of silica with low silanol densities. From intensity measurement of near-IR diffuse-reflectance spectra, Klier et al. [58] claimed the existence of SiOH–OH<sub>2</sub> complexes with about one half of the silanols as “BET monolayer” on Hisil 233 silica. Additional water adsorption takes place around adsorbed water molecules rather than on free silanols, because such clusters would be energetically more favorable. Yamauchi and Hondo [66] obtained more accurate IR spectra of the silanols and the adsorbed water on a silica gel. They suggested that water would settle only on part of the silanols at first as SiOH–OH<sub>2</sub> complexes, where the water hydroxyl would absorb

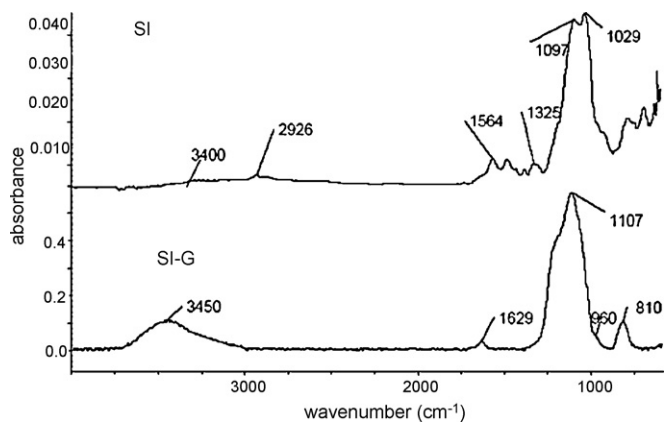


Fig. 2. FTIR of Si and SI-G samples.

at  $5270\text{ cm}^{-1}$ . A second water molecule absorbing at  $5150\text{ cm}^{-1}$  would then settle on the previous silanol water. In accordance with these concepts, Fig. 2 shows the main features of pure silica (SI), and functionalized (SI-G) absorption bands. For unchanged silica, at  $3450\text{ cm}^{-1}$  a band due to the OH bonds of silanol groups exists. Also, bands for symmetrical and asymmetrical vibration of the Si–O are located at  $810$  and  $1107\text{ cm}^{-1}$ , respectively. A small shoulder observed at about  $960\text{ cm}^{-1}$  is assigned to the Si–OH groups. The band at  $1629\text{ cm}^{-1}$  is attributed to bending Si–O–H silica silanol groups. Functionalized silica shows a moderately different behavior from that of previous FTIR spectrum, the disappearance of the band at  $3450\text{ cm}^{-1}$  and a low broad band near  $3400\text{ cm}^{-1}$ , which is related to the tension of primary amine groups. Also, bands appear at  $2926$  and  $1097\text{ cm}^{-1}$ , corresponding to vibration groups of C–H and Si–O–C tension bands of the ethoxy group, respectively. At  $1564\text{ cm}^{-1}$  the band assigned to the deformation of the NH plane is observed, and at  $1325\text{ cm}^{-1}$  the bending band of C–N appears [67].

These results suggest a mechanism of nucleophilic substitution, as has been mentioned in previous work [59,60]. It may be suggested that the results obtained for the reaction over functionalized SI could be because of this mechanism [52], which could be due to the Si–O–Si group formed on the surface inducing an interaction between silanol groups and the APS, and leads to the formation of two residual ethoxy groups. Also, the functionalization process did not eliminate surface silanol groups completely and afforded a certain degree of hydrophilicity to silica, which can be explained by the steric agent effect. This would act as an *umbrella*, protecting the surface silanol groups from the attack of polar solvents and therefore reduces the wettability of silica [57,59,60]. This is consistent with the results obtained by the FTIR spectrum of SI-G (Si–O–C group at  $1097\text{ cm}^{-1}$ ).

In addition, TGA–DTA techniques to verify the presence of OH groups on bulk and functionalized silica (SI and SI-G samples) were applied. It is observed that at low temperatures (less than  $50^\circ\text{C}$ ), loss of moisture results (ambient water taken by both solids). The greatest weight losses are at over  $120^\circ\text{C}$  and  $450^\circ\text{C}$ , respectively. Below  $200^\circ\text{C}$ , the weight loss is attributable to the evaporation of water and the volatilization of organic material as thermal decomposition of the remains of solvents in both solids. Between  $200$  and  $300^\circ\text{C}$ , weight loss is attributed to the combustion of organic compounds that are part of the silica network (SI and SI-G). The weight loss around  $450^\circ\text{C}$  is due to the complete carbonization of organic compounds in the functionalized sample (SI-G).

In Fig. 3a, the micrographs of SI are shown. The magnification used in both cases corresponds to  $200\text{ nm}$  and  $50\text{ nm}$ , respectively. From this it can be inferred that SI has a small particle size (near  $12\text{ nm}$  in diameter) with a spherical shape. Based on this uniformity in morphology, SI was chosen to perform the grafting with

Table 3

Chalcone synthesis using different synthesized silicas as catalyst.

Entry	Catalyst	Yields of chalcone (%)
1	None	5
2	SI	38
3	SI-A	27
4	SI-B	21
5	SI-C	41
6	SI-D	39
7	SI-E	74
8	SI-F	75
9	SI-G	87

<sup>a</sup>Reaction conditions: acetophenone (1 mmol), benzaldehyde (1.3 mmol), catalyst (0.100 g), solvent-free, 4 h.

APS. In Fig. 3b, TEM micrographs of the synthesized functionalized silicas (SI-C, SI-E, and SI-G) are shown. In these micrographs it can be observed that silicas with APS in their structure have larger particles and agglomeration areas in comparison to SI. The agglomeration is independent of the quantity of APS incorporated during the functionalization process, which may be due to the reaction of the OH surface with the APS.

### 3.2. Catalytic tests

#### 3.2.1. Catalytic activity in the presence of the silica sol–gel (SI) support

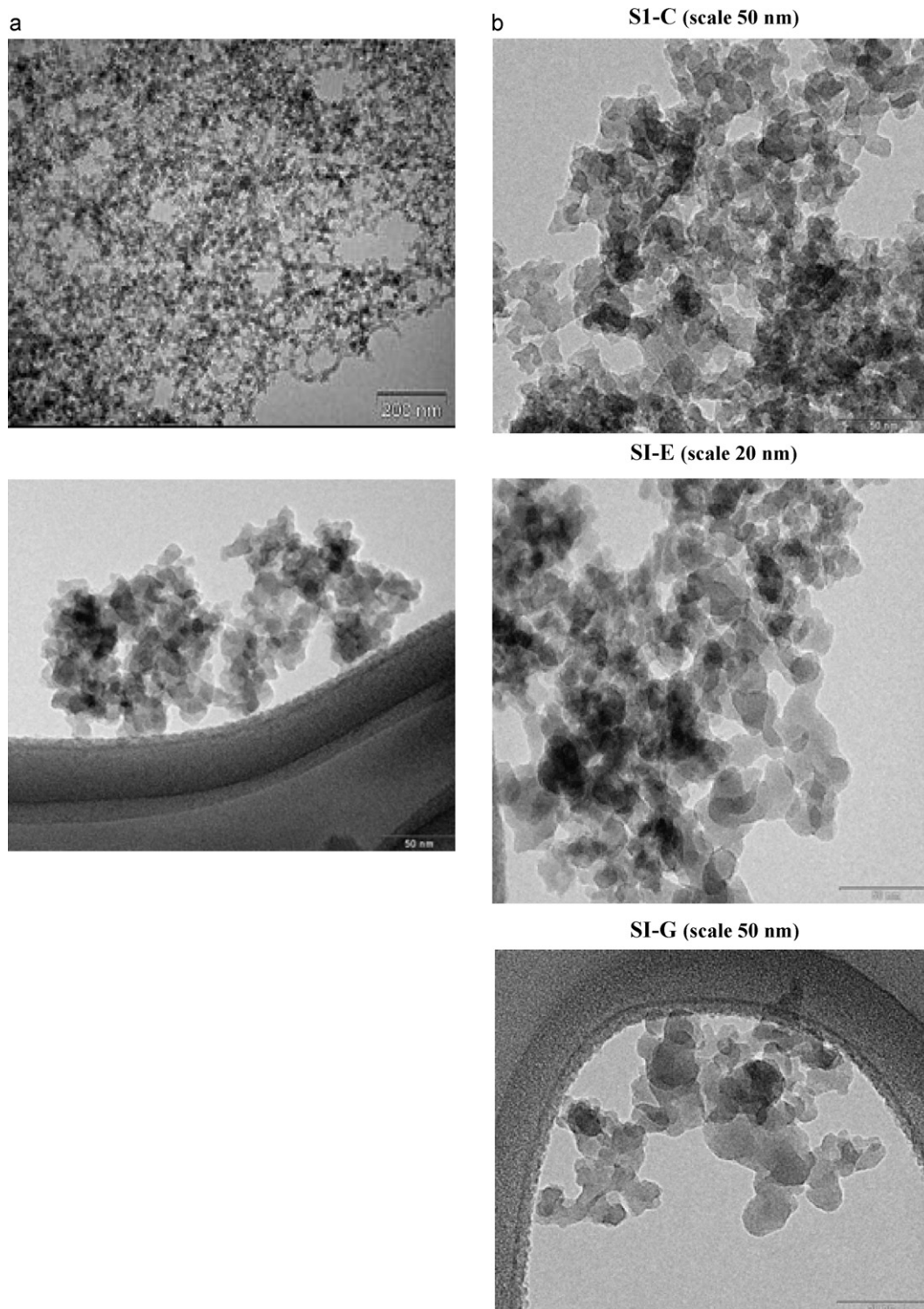
The Claisen–Schmidt synthesis of chalcones involving the condensation of acetophenone and benzaldehyde is illustrated in the reaction Scheme 1.

Before attempting a detailed catalytic work, a noncatalytic reaction between acetophenone and benzaldehyde was examined, and it was observed that under the experimental condition ( $140^\circ\text{C}$ , 4 h), only 5% formation of chalcone was detected, indicating that from a practical point of view the reaction is not taking place in the absence of a catalyst (Table 3, entry 1).

The Claisen–Schmidt condensation of benzaldehydes and acetophenones was reported to be catalyzed by acid or bases [18–23]. Pure silica sol–gel (SI) was first tested for the catalytic condensation between benzaldehyde and acetophenone without solvent at  $140^\circ\text{C}$  for 4 h. The GC yield of chalcone was 38% and no other side products were observed, indicating that the Cannizzaro reaction of benzaldehyde, condensation of acetophenone or aldehyde oxidation did not take place under their reaction conditions. The GC–MS analysis confirms that, under our experimental conditions, trans-chalcone is obtained selectively (MS *m/s*: 208, ( $\text{M}^+$ ), 179, 103, 77 (100), 65, 51. The result indicated that silica sol–gel (SI) showed poor activity to chalcone (38%, Table 2, entry 2). This result revealed that SI acts not only as a support but also as an acid–base bifunctional catalyst. The conversion over this solid is due to coordinate-assisted condensation of acetophenone with benzaldehyde for the presence of basic and acid sites on the surface of the silica sol–gel, as shown in Scheme 2.

#### 3.2.2. Influence of aminopropyl group loading

The catalytic activity of aminopropylated silica sol–gel prepared with different amounts of APS is displayed in Table 3. The reaction was studied at  $140^\circ\text{C}$ , using a ratio of benzaldehyde:acetophenone of 1:1.3, and an amount of catalyst of 100 mg, the reaction time was of 4 h. The catalyst samples were called SI-A, SI-B, SI-C, SI-D, SI-E, SI-F and SI-G, and the amounts of APS used during the functionalization are indicated in Table 1. From this table, it can be observed that the catalysts SI-E, SI-F and SI-G, which contain greater amounts of APS, show very high chalcone yields (see Table 3, entries: 7:74%; 8: 75%, and 9: 87%, respectively).

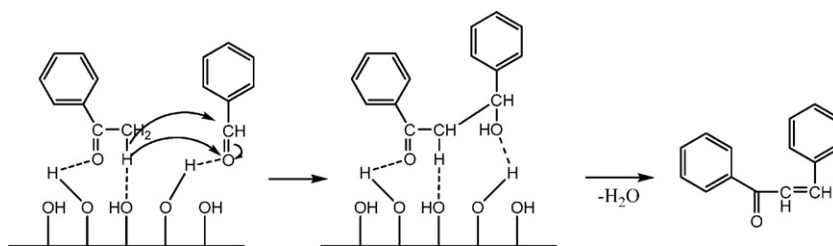


**Fig. 3.** TEM micrographs of (a) SI sample and (b) SI-C, SI-E and SI-G samples.

In contrast, the yields of catalysts SI-A, SI-B, SI-C and SI-D, which contain low amounts of amino groups, decreased dramatically (see Table 3, entries: 3: 27%; 4: 21%; 5: 41%, and 6: 39%, respectively). Since the best catalyst was SI-G, it was used to continue with our investigation for obtaining better chalcone yields. In these cases it can be observed that SI-A and SI-B have yielded less chalcone than SI, which could be due to SBET and the amount of APS on the silica surface.

### 3.2.3. Effect of reaction temperature and time on catalyst performance

The effect of temperature plays an important role in the catalytic synthesis of chalcones. It was examined in the temperature range between 120 and 150 °C, in the absence of solvent, on the SI-G catalyst, and the results are illustrated in Fig. 4. Temperature increase leads to a higher chalcone yield. The yield of chalcone for a reaction time of 4 h at 120 °C is only 38%, whereas at 140 °C the conversion



**Scheme 2.** Proposal mechanism of chalcone synthesis catalyzed by silica sol-gel (SI).

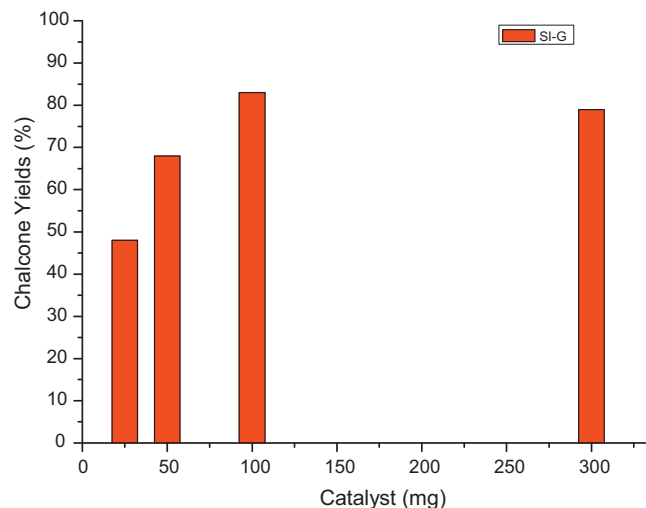
is 83%, which is 3.0 times higher than at 120 °C. For the same time of 4 h, an increase of only 3% is observed when the temperature is raised from 140 to 150 °C. For this reason, 140 °C was employed as the ideal temperature to continue with the analysis of other reaction variables. However, the catalytic performance of catalyst SI-G as a function of the reaction time in the condensation of benzaldehyde and acetophenone was studied at three temperatures (120, 140 and 150 °C) under solvent-free conditions (Fig. 4). The catalytic activity for the three temperatures was found to increase rapidly with the reaction time up to 4 h, and then remains almost constant. As reported by Wang et al. [17], the constant value is probably due to the blockage of the catalytic center by the high concentration of chalcone.

### 3.2.4. Effect of the amount of catalyst

The optimal reaction conditions (benzaldehyde 1 mmol, acetophenone 1.3 mmol, a temperature of 140 °C and 4 h) were used for the next experiment. Different amounts of the SI-G catalyst were tested (25, 50, 100 and 300 mg). The results show that 100 mg is an optimal quantity of catalyst to obtain the best yields (see Fig. 5, column 3: 83%). When the experiment was carried out employing 300 mg of SI-G catalyst, a yield of 79% was obtained and a small amount of an unidentified secondary product was detected. Perhaps this behavior could be due to the % APS in this sample.

### 3.2.5. Reuse of the catalyst

The reuse of catalysts is central to their utility. In order to investigate the reusable properties of the aminopropylated silica sol-gel catalysts, recycle experiments were conducted and the results are shown in Fig. 6. After reaction, the catalyst was recycled by washing with hot toluene (2 × 7 ml), dried under vacuum at 50 °C for 5 h and then reused. The better two catalysts, SI-F and SI-G, were used for this test. They were reused twice, and it was observed that there

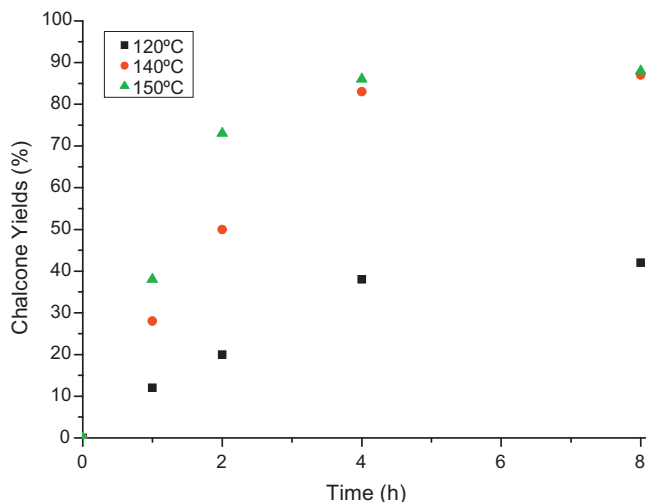


**Fig. 5.** Effect of the catalyst amount.

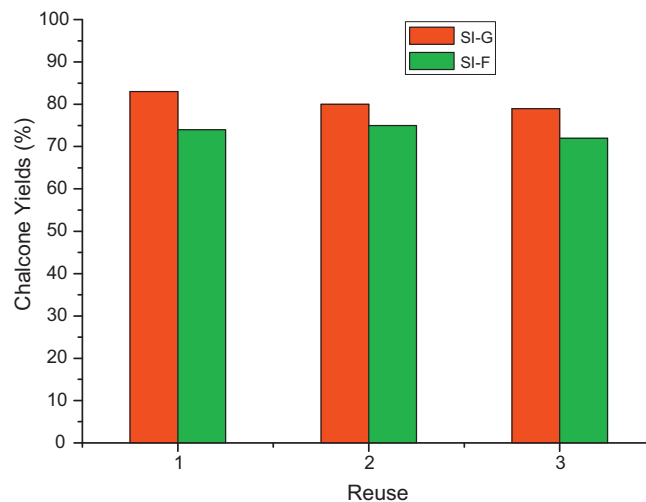
was a minor loss in catalyst weight during each recycles (total loss 12%). For the SI-F catalyst, the isolated yields of chalcone were 74%, 75% and 72%, and for SI-G 83, 80% and 79%, which showed, under these conditions, the good reusability of this catalyst.

### 3.2.6. Reaction mechanism

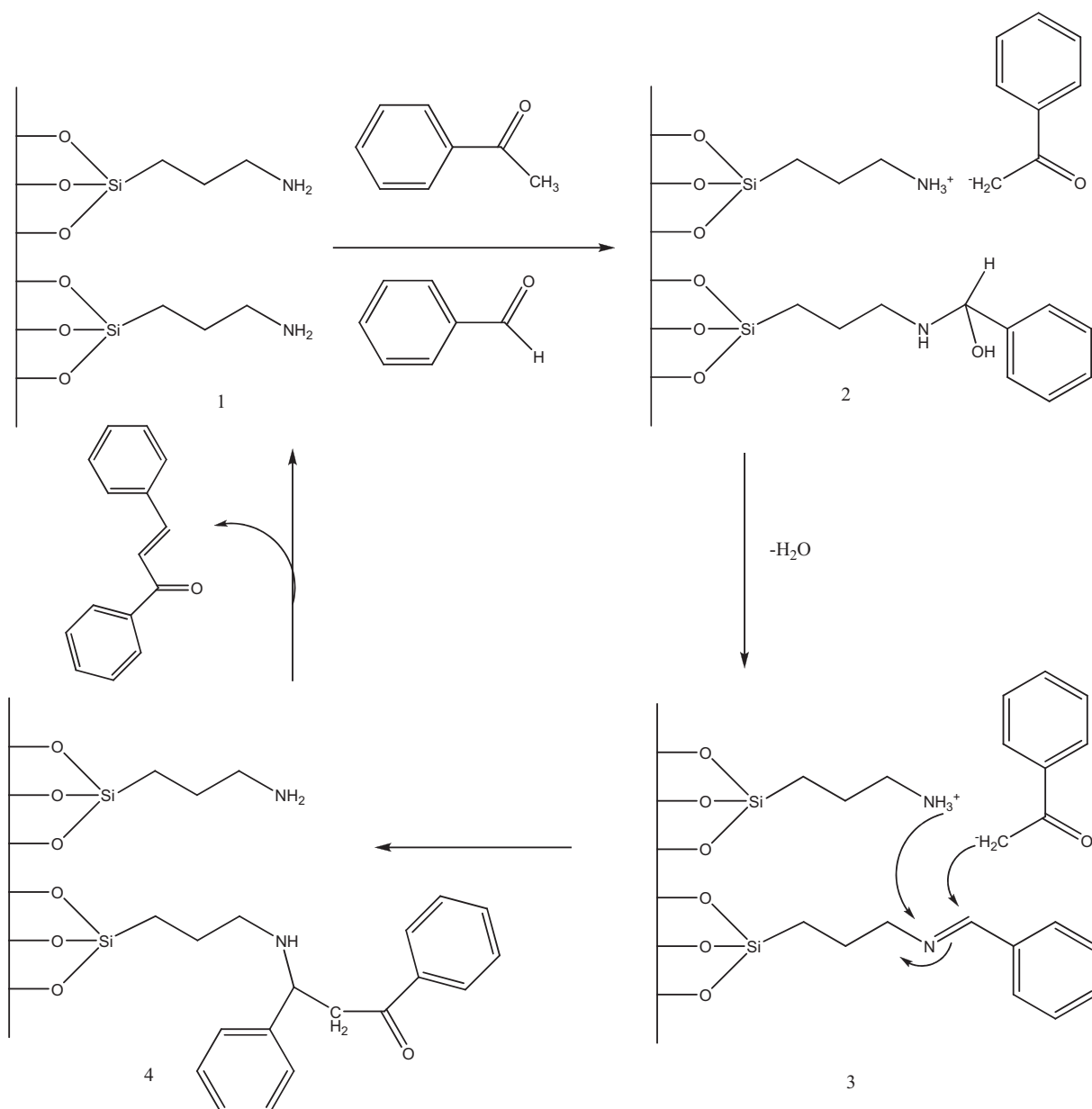
The Claisen–Schmidt condensation of benzaldehydes and acetophenones has been studied under acidic or basic conditions. Wang and Cheng [48] described an alternative mechanism to the classic basic catalyst procedure. This rationalization is carried out for the reaction of benzaldehyde and 2'-hydroxyacetophenone



**Fig. 4.** Effect of reaction temperature on the catalytic performance.



**Fig. 6.** Reuse of SI-F and SI-G catalysts.



**Scheme 3.** Proposal mechanism of chalcone synthesis catalyzed by aminopropylated silica sol-gel.

assisted by aminopropylated mesoporous silica. Our experimental results for the reaction of benzaldehyde and acetophenone are in accordance with this mechanism. The modified reaction mechanism is shown in **Scheme 3**. Over the aminopropylated silica sol-gel catalyst, the benzaldehyde molecules and the amino groups form the C=N imine species, which was then attracted by the anion of acetophenone to produce the corresponding adduct. The first step of imine formation is the attack by the nucleophilic amine on the carbonyl. Rapid proton transference results in a carbinolamine. The carbinolamine reacts to form imine by loss of water. The imine intermediate is attacked by the acetophenone anion and one proton is incorporated to form the intermediate 4. Finally the intermediate 4 forms chalcone and the catalysts are regenerated.

### 3.2.7. Preparation of substituted chalcones

To explore the general validity of the process previously described, a series of chalcone derivatives were prepared under the optimal conditions. The reactivity of different aryl-benzaldehydes and methyl aryl-ketones was tested under the same conditions

(140 °C, benzaldehyde/acetophenone ratio 1.3/1, catalyst 100 mg, and 240 min). Results of the obtained yields are listed in **Table 3**. The results showed that, in general, the reactions were clean and products were isolated by liquid column chromatography in pure form without further purification ( $^1\text{H}$  and  $^{13}\text{C}$  NMR). The reaction is very selective and no competitive side reactions such as product decomposition, acetophenone condensation, Cannizzaro's reaction, etc., were observed (GC).

Finally, we studied the influence of the substituting groups on the aromatic ring of acetophenones and benzaldehydes. The reactions of aldehydes bearing electron-donating groups such as -Me, -OMe and -OH gave yields similar to those of the corresponding reaction with unsubstituted benzaldehyde (**Table 4**, entries 2: 83%, 3: 83%, and 4: 84%, respectively).

The presence of electron-withdrawing groups in acetophenone such as -Cl gave a comparable rate of condensation, even when the aldehyde contains an electron-withdrawing group such as -Cl, presumably due to ease of formation of the enolate anion in the first step (see **Table 4**, entries 5: 88% and 7: 89%). The physical



**Table 4**  
Synthesis of chalcones by aminopropyl-functionalized silica sol–gel<sup>a</sup>.

Entry	Product	R	R <sub>1</sub>	Yields (%) <sup>b</sup>
1	3a	H	H	87
2	3b	H	–CH <sub>3</sub>	83
3	3c	H	–OCH <sub>3</sub>	83
4	3d	H	–OH	84
5	3e	H	–Cl	88
6	3f	–CH <sub>3</sub>	H	90
7	3g	–Cl	H	89

<sup>a</sup> Reaction conditions: acetophenone (1 mmol), benzaldehyde (1.3 mmol), Si-G catalyst (0.100 g), solvent-free, 4 h.

<sup>b</sup> Calculated yield based on isolated product.

properties were determined and the structures were confirmed by <sup>1</sup>H and <sup>13</sup>C NMR spectra. The <sup>1</sup>H NMR spectral data indicated that the compounds were geometrically pure and confirmed that the ethylene moiety in the enone linkage is in *trans* conformation ( $J_{\text{H}\alpha\text{-H}\beta} = 15\text{--}16\text{ Hz}$ ) with an *s-trans* conformation around the C–C bond [47].

#### 4. Conclusions

In the present work we reported the preparation, characterization, and a catalytic study of various synthesized aminopropylated silica sol–gel catalysts with different amino group loadings. The materials were an efficient basic catalyst for the synthesis of chalcones via the Claisen–Schmidt condensations. The optimal conversion was obtained for the amino-functionalized silica sol–gel (S-G: 3 ml APS per 1 g silica (56.57% APS)), and a decreasing amount of APS goes to the detriment of the conversion. The substituting groups in the aromatic rings have no great effect on the catalytic performance in Claisen–Schmidt condensation under solvent-free conditions. We have demonstrated that hybrid materials based on silica gel provide efficient, selective, inexpensive, and eco-friendly solvent-free catalysts for the synthesis of various examples of chalcones, and the analytical analysis confirmed their structures. These catalysts can be recycled twice without appreciable loss of reactivity. Simplicity of the operation coupled with simple work-up and the environmentally benign nature of the reaction would allow their application to a variety of substrates. The application of these catalysts to other reactions would be of further interest.

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