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# Synthesis of 2,2,4-trimethyl-1,2-*H*-dihydroquinoline (TMQ) over selected organosulfonic acid silica catalysts: Selectivity aspects



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ARTICLE INFO	A B S T R A C T
<i>Keywords:</i> Skraup reaction Aniline Acetone Mesityl oxide TMQ	This paper presents investigation on the synthesis of 2,2,4-trimethyl-1,2- <i>H</i> -dihydroquinoline (TMQ) as a result of the reaction of aniline and both acetone and mesityl oxide in the presence of selected sulfonic acid silica catalysts. Condensation of aniline with acetone is very complex process with the formation of significant number of side products, both desirable and undesirable considering the final product (TMQ). In acidic conditions and elevated reaction temperature the reactivity of main raw materials (aniline, acetone) is significantly high, what causes the formation of many side by-products lowering the selectivity of this reaction. In this paper the reaction of aniline with acetone in the presence of heterogeneous acidic silica catalysts were investigated in more detail and discussed. The results were confirmed by GC/MS analysis, that the presence of TMQ isomers and other by-products significantly affected the formation of final product. The formation of previously not described

structural isomer of TMQ has been also demonstrated.

## 1. Introduction

Alkyl derivatives of 1,2-*H*-dihydroquinoline (1,2-DHQ) belong to a large group of quinoline derivatives of great practical importance. The most important representative of them is 2,2,4-trimethyl-1,2-*H*-dihydroquinoline known in the market under the acronime TMQ. 2,2,4-Trimethyl-1,2-dihydroquinoline, because of relatively low price and great ease of application, is considered as a very important and effective antooxidant in rubber technologies. The methods of the synthesis of 1,2-quinoline derivatives are based on cyclization reaction well known as Skraup reaction. More detailed studies led to the development of various Skraup-based modifications (Combes, Knorr, Doebner, Friedlander).

The main raw material used in the synthesis of 1,2-dihydroquinoline derivatives is aniline or its alkyl derivatives and detailed variants of the synthesis depend only on the kind of carbonyl component used. As a rule acetone is used, which as a result of sequence reaction condensed with aniline with the formation of 1,2-*H*-dihydroquinoline derivative, *i.e.* 2,2,4-trimethyl-1,2-*H*-dihydoquinoline (Scheme 1).

According to Scheme 1 TMQ is manufactured in technical scale. Skraup synthesis of TMQ was described for the first time in 1921 [1]. Later study allow confirmation its chemical structure [2–5]. The synthesis of 1,2-*H*-dihydroquinoline derivatives, according to Skraup method or its various modifications, are carried out mainly in the presence of homogeneous catalysts. As catalysts most frequently  $I_2$  [1], HCl [6–8], *p*-toluenesulfonic acid [9], fluorine acids [10,11] and Lewis acids [12-17] are used. Condensation of aniline with carbonyl compounds is also possible to perform in the presence of heterogeneous catalysts. It should be noted, however, that this issue has not been particularly more deeply examined, particularly with regard to the analysis of reaction selectivity, which is reflected in the relatively small number of reports on the subject. Shaikh described the study on condensation of aniline with carbonyl compounds with the use of various special catalysts with mesoporous structure, prepared in the reaction of thionyl chloride and mesoporous silicate [18]. At temperature of 80 °C, in the presence of toluene as a solvent, he obtained corresponding quinoline derivatives with the yields of  $57 \div 62$  wt%. Sidhe used the same catalyst in the reaction of acetylaniline with various ketones [19]. The yields of corresponding quinolines were from 50 to 80 wt%. In turn, Venkateswarlu as catalyst used Chloramine-T [20]. In the presence of acetonitryle as a solvent, in temperature of 80 °C, the yield of quinoline derivatives was 95 wt%. High yields of quinoline derivatives have been achieved in the reaction catalysed by heteropolyacids. Heravi in Friedlander modification of Skraup method (80 °C, 3 ÷ 5 h) obtained quinolines with the yield of 91 wt% [21]. Heteropolyacids, in particular phosphomolybdic acid, were used as catalysts in the study conducted by Chaskar [22].

Studies described above concerned very particular cases of

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Scheme 1. Synthesis pathway of 2,2,4-trimethyl-1,2-H-dihydrochinoline (TMQ) according to Skraup mechanism.

condensation of aniline with various carbonyl compounds leading to corresponding quinoline derivatives. Among of the described results, only a few of them describe the synthesis of 2,2,4-trimethyl-1,2-H-dihydroquinoline. Yadav described the synthesis of TMQ in the reaction of aniline with acetone in the presence of catalyst based on sesquisiloxane framework, functionalized by acidic sulfonic group [23]. At temperature of 80 °C he achieved quinoline with the yield of 90 wt%. Hegedüs used as catalyst klinoptilolite modified by sulfuric acid [24]. The reaction of aniline with acetone was conducted in temperature of 110 °C in the presence of toluene as a solvent. The amount of used catalyst was, however, very significant i.e. 4.3 g/g aniline. In above reaction conditions TMQ was achieved with the yield of 95 wt%. Methyl analog of TMQ was obtained in the reaction of 3-methylaniline with acetone in the presence of Amberlyst A15 as a catalyst [25]. The yield of MeTMQ was very high (93 wt%) but after long time of synthesis (48 h).

TMQ is considered as commercial product of great practical importance, but in none of the abovementioned papers on the synthesis of TMQ, did not provide more detailed information about characteristic of the post-synthesis mixture. These informations are useful for the assessment of the course of this very complex synthesis, especially the selectivity of the reaction of aniline with acetone catalysed by heterogeneous catalysts.

Owing to the relevance of TMQ and also its methyl analogues, we described the novel approach to the synthesis of important 1,2-DHQ derivatives with the use of selected sulfonic acid silica catalysts. The detailed structural analysis of reaction products have been presented for the first time.

## 2. Experimental

## 2.1. Materials

Aniline for synth. (99%), acetone puriss. p.a. (> 99.5%) and mesityl oxide for synth. were supplied by Aldrich (Poland). SBA-15 silicas were synthesized using a hydrothermal procedure. As the precursors were used: tetraethylorthosilicate (TEOS, 98%) supplied by Aldrich (Poland) as a silica source, nonionic triblock co-polymer Pluronic P123 [poly (ethylene oxide)-block-(poly(propylene oxide)-block-poly(ethylene oxide)], molecular weight = 5800, supplied by Aldrich (Poland) as a template, chlorotrimethylsilane puriss. (CTMS, 99%), phenyltriethoxysilane (PTES) for synth. and chlorosulfonic acid supplied by Aldrich (Poland) as functional modifiers. Distilled water, hydrochloric acid and dichloromethane puriss. p.a. were supplied by POCh (Poland).

# 2.2. Catalysts preparation

Mesoporous molecular sieves of SBA-15 were synthesized according to the method described in the literature with some modifications [26,27]. In a typical synthesis, P123 (4 g) was dissolved in an aqueous solution of HCl (1.6 M HCl, 150 g) at a room temperature, under vigorous stirring. Subsequently, a 8.5 g of TEOS was added to the above solution. The molar composition of the reactants used in these synthesis was 1 SiO<sub>2</sub>: 0.017 Pluronic P123: 5.88 HCl:192 H<sub>2</sub>O. After stirring at 40 °C for 2 h, the reaction mixture was transferred into a Teflon bottle and aged at 100 °C for 48 h under static conditions. The mixture was then allowed to cool to room temperature, and the solid, white product was filtered, dried at 110 °C for 12 h and calcined at 550 °C for 8 h (temperature gradient 5 °C/min). Typical yield of pure SBA-15 was 96 wt% based on used SiO<sub>2</sub>.

For the synthesis of organosulfonic acid functionalized silicas was applied post-synthesis method based on the work described by Mrowiec-Białoń (SBA-15) [28] and Karimi (SiO<sub>2</sub>) [29]. First, pure siliceous materials (SBA-15) were contacted with water steam for 2.5 h and subsequently calcined at 200 °C for 2 h. The nominal content of organic groups was 1.0 mmol g<sup>-1</sup>. All the operations were made under a nitrogen atmosphere. The synthesis pathway of the preparation of organosulfonic acid functionalized SBA-15 is presented in Fig. 1.

In a preparation of the SBA-15-propyl-SO<sub>3</sub>H catalyst, a mixture of corresponding silica and MPTMS in *n*-hexane was magnetically stirred for 15 min at room temperature, and then refluxed for 24 h at 45 °C (Fig. 1a); all the above operations were made under a nitrogen atmosphere. Then the reaction mixture was cooled, and the solvent was removed by evaporation and the product was dried at 60 °C for 24 h. After that mercaptopropyl groups were oxidized with 30% aqueous hydrogen peroxide solution under stirring at 40 °C for 24 h under nitrogen atmosphere. After filtration, the solid product was washed with deionized water. The material was filtered and washed several times with water and ethanol. The wet material (1.0 wt%) was suspended in 1 M H<sub>2</sub>SO<sub>4</sub> for 2 h. Finally the material was filtered, washed with water and ethanol, dried at 60 °C under vacuum overnight. The catalysts were denoted as SBA-15-Pr-SO3H. Using amorphous silicas in the place of SBA-15 corresponding organosulfonic acid modified silica catalysts were obtained and denoted as SiO<sub>2</sub>-Pr-SO<sub>3</sub>H.

The SBA-15-phenyl-SO<sub>3</sub>H catalyst were prepared by grafting of PTES over the silicas (Fig. 1b). The calcined SBA-15 material was refluxed with excess quantity of PTES dissolved in n-hexane under nitrogen atmosphere overnight for 24 h at 45 °C. Then the reaction mixture was cooled, then the solvent was removed by evaporation and the product was dried at 60 °C for 24 h. The obtained material further reacted with chlorosulfonic acid, which resulted in generating the phenyl sulfonic acid groups. The material was degassed at 130 °C under vacuum for 12 h and then 30 mL of CH<sub>2</sub>Cl<sub>2</sub> containing chlorosulfonic acid (1 mL) was slowly added at room temperature under nitrogen atmosphere. After 4 h of stirring, the suspension was slowly added to the mixture of water and ice (0 °C). After filtration, the solid product was washed with deionized water. Finally the powder product was dried at 60 °C under vacuum overnight. To improve the hydrophobicity of the catalyst's surface, methyl groups (nominal content of methyl groups was  $1 \text{ mmol g}^{-1}$ ) were introduced by grafting chlorotrimethylsilane (CTMS). The catalyst was denoted as SBA-15-Ph-SO<sub>3</sub>H(-CH<sub>3</sub>) (Fig. 1c).



Fig. 1. Scheme of the preparative pathway of organosulfonic acid modified SBA-15 catalysts: (a) SBA-15–Pr-SO<sub>3</sub>H and (b) SBA-15–Ph-SO<sub>3</sub>H(-CH<sub>3</sub>).

#### 2.3. General method for the synthesis of 1,2-dihydroquinoline derivatives

For the synthesis of TMQ 100 mL standard glass reactor equipped with mechanic stirrer, electronic temperature controller was used. The reactor was also equipped with acetone dispensing system connected with precise piston pump (Ismatec MCP-CPF IF60) and glass distillation kit contains short path distillation column (*c.a.* 10 cm length) connected with thermostatic mantle and cold water condenser for collecting of acetone vapors, released continuously during the synthesis.

In a typical synthesis 60 g (0.02 mol) aniline was placed to a 100 mL glass reactor containing 6 g of corresponding catalyst. The resulting suspension was agitated intensively (700 rpm), and after heating to desired temperature, acetone dosing was started. Dosing rate of acetone was set at a level, which allowed constant temperature of a reaction mixture. The dosing of acetone was complete after 5 h and the resulting suspension was cooled down to room temperature, filtered and obtained filtrate was analysed.

#### 2.4. Supports and catalysts characterization

*Texture*: Nitrogen adsorption and desorption isotherms were measured at 77 K with the Autosorb-1C Quantachrom sorption analyser. Specific surface area was calculated using the BET model. The BJH method was applied for determining the pore diameter.

*X-ray powder diffraction (XRD)* patterns of the SBA-15 materials were collected on a Siemens D5005 diffractometer using CuKa ( $\alpha = 0.154$  nm) radiation.

*NMR*: The <sup>29</sup>Si MAS NMR spectra were recorded with an AC200 Bruker spectrometer.

*Transmission electron microscopy (TEM)*: Transmission electron microscope (TEM) images were generated using a Jeol Jem 1200 EX II microscope operating at 80 kV. Prior to observation, the samples were ultrasonically dispersed in butanol and transferred to a holeycarbon coated copper grid (300 mesh).

*Scanning electron microscope (SEM)* images were generated using a Zeiss EVO 40 microscope. Micrographs were obtained at 20 kV. The samples were deposited on a sample holder with an adhesive carbon foil and sputtered with gold using Balzers SCD 050 sputter deposition equipment.

*FT-IR spectroscopy*: Infrared spectra (FT-IR) were recorded on a BRUKER VECTOR 22 spectrophotometer. All of the compounds were solid and solid state IR spectra were recorded using the KBr disk technique.

#### 2.5. Analysis of the reaction products

The composition of reaction products and identification of components was performed using GC/MS method on gas chromatograph 7890A (Agilent) equipped with mass detector Model 7000 (Agilent). The carrier gas was helium with flow rate maintained at  $1 \text{ mL ml}^{-1}$ . Inlet temperature was kept at 300 °C. The oven temperature was programmed from 70 °C (1 min) to 280 °C (30 min) with temperature progress 10 °C min<sup>-1</sup>. Injection sample was 0.5 µL. Quantitative analysis of TMQ in post-synthesis mixtures was based on external calibration (calibration curve) (Fig. S4, Supplementary information). For the preparation of calibration curve purified TMQ sample was used. For this purpose TMQ fraction was first separated by distillation and obtained raw TMO was purified by double crystallization (for details see Supplementary information). The structure of the obtained TMQ analytical sample was confirmed by H NMR spectroscopy (Fig. S5, Supplementary information). Recorded H NMR spectrum was identical to the TMQ spectrum published in the literature [30].

### 3. Results and discussion

#### 3.1. Characterisation of SBA-15

Textural properties of pure siliceous SBA-15 material were characterised by the low temperature N<sub>2</sub> adsorption–desorption, XRD and TEM techniques. According to the IUPAC classification, the SBA-15 material presents the adsorption–desorption isotherm of type IV (Fig. 2a), showing a sharp inflection (steep hysteresis of type H1) at a relative pressure around  $p/p_0 = 0.6 \div 0.8$  and narrow pore size distribution, which is characteristic of well-ordered mesoporous materials. The SBA-15 sample displays the BET specific area amounting to  $710 \text{ m}^2 \text{ g}^{-1}$ , pore volume of  $0.9 \text{ cm}^3 \text{ g}^{-1}$  and mean pore diameter of 5.6 nm (Table S1, Supplementary information).

The external surface area of this material was found be to very small (*i.e.* below  $10 \text{ m}^2 \text{ g}^{-1}$ ), suggesting that there is almost no macropores. In the XRD pattern of SBA-15, three peaks are observed, *i.e.* an intense peak at 0.96° and low-intensity peaks at 1.56° and 1.80° (Fig. 2b). These peaks are indexable as (1 0 0), (1 1 0) and (2 0 0) reflections, which are associated with *p6mm* hexagonal symmetry. Further evidence for a highly ordered hexagonal structure is provided by the transmission electron microscopy (TEM) micrograph, as shown in Fig. 2c.



Fig. 2. Characterization of the SBA-15 sieve; (a) N<sub>2</sub> adsorption (full dots) – desorption (open dots) isotherms, pore size distribution as well as (b) XRD pattern and (c) TEM images.



Fig. 3. N<sub>2</sub> (full dots) – desorption (open dots) isotherms and pore size distribution (inside) of (a) SBA-15–*Pr-SO*<sub>3</sub>*H*, (b) SBA-15–*Ph-SO*<sub>3</sub>*H*(-*CH*<sub>3</sub>), (c) SiO<sub>2</sub>-*Pr*–*SO*<sub>3</sub>*H*(1) and (d) SiO<sub>2</sub>–*Pr-SO*<sub>3</sub>*H*(2).

#### 3.2. Catalysts characterization

#### 3.2.1. Structure properties

Fig. 3 shows the  $N_2$  adsorption–desorption isotherms and pore size distributions recorded for organosulfonic acid SBA-15 as well as SiO<sub>2</sub> supported catalysts.

In the case of SBA-15 supported catalysts (Fig. 3a and b), the isotherms of type IV were obtained what confirmed the presence of ordered mesoporous structure. A steep capillary condensation step (p/  $p_0 = 0.6 \div 0.8$ ) is observed for both SBA-15 based samples, suggesting a presence of uniform-size pore system. The incorporation of sulphonyl groups does not produce changes in the characteristic shape of the isotherm with the exception of some reduction in the amount of adsorbed N<sub>2</sub> compared with pure SBA-15 carrier. As can be seen from Fig. 3a and b, the SBA-15-Pr-SO<sub>3</sub>H and SBA-15-Ph-SO<sub>3</sub>H(-CH<sub>3</sub>) catalysts have a narrow distribution of pores (d<sub>B,IH</sub>) with peak positions at 5.6 an 4.9 nm, respectively. Texture parameters of the studied catalysts are given in Table S1. There are some changes in the porous structure of the functionalized SBA-15 support in respect to the SBA-15 mesoporous material. The preparation of SBA-15-Pr-SO<sub>3</sub>H and SBA-15-Ph-SO<sub>3</sub>H (-CH<sub>3</sub>) catalysts is accompanied by two-fold decrease in S<sub>BET</sub> as well as in pore volume compared with pure SBA-15 carrier. Moreover, the immobilization of sulphonic groups onto the SBA-15 surface causes the increase of the average pore diameter by 0.4 and 0.7 nm for SBA-15-Pr-SO<sub>3</sub>H and SBA-15–Ph-SO<sub>3</sub>H(-CH<sub>3</sub>) samples, respectively.

The N<sub>2</sub> adsorption–desorption isotherms of SiO<sub>2</sub> supported systems are plotted in Fig. 3c and d. For both samples an isotherm of type I (according to IUPAC) was obtained, which is typical of microporous materials. The texture of SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(1)* catalyst and that of SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(2)* differs only slightly (Table S1). The SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(1)* and SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(2)* catalysts exhibit an S<sub>BET</sub> of 484 and 412 m<sup>2</sup> g<sup>-1</sup>, respectively. In the SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(1)* catalytic system, dominant are micropores with diameters of 2.6 nm (d<sub>DFT</sub>) and they are greater by about 1 nm as compared with the diameters of SiO<sub>2</sub>–*Pr-SO<sub>3</sub>H(2)* (d<sub>DFT</sub> = 1.6 nm). However, both catalysts have an average pore diameter of 2.3 nm. The pore volume of the catalysts ranges between 0.2 and 0.3 cm<sup>3</sup> g<sup>-1</sup>.

In order to further investigate the pore structure of the SBA-15 supported catalysts, they are also evaluated by transmission electron microscopy.

TEM images presented in Fig. 4a and b demonstrate the structure of the SBA-15–*Pr-SO*<sub>3</sub>*H* and SBA-15–*Ph-SO*<sub>3</sub>*H*(-*CH*<sub>3</sub>) catalysts, respectively. TEM images of both catalysts clearly show well-ordered hexagonal arrays with one-dimensional channels as well as parallel fringes corresponding to side-on projections of the hexagonal mesostructured. These results confirmed that the samples possess two-dimensional hexagonal mesoporous structure which is in good agreement with the N<sub>2</sub> sorption observations.

#### 3.2.2. Morphology characterisation (SEM)

The morphological characterization of the supports and the catalysts were performed using scanning electron microscopy (Figs. 5 and 6).

The SEM micrographs show that the particles of pure siliceous SBA-15 are mainly spherical-shaped (Fig. 5a). These particles have mostly a smooth surface, only few visible defects on the surface are observed. It also shows that micrometer-sized sphere particles had a relatively uniform size with a diameter of about ranges from 2 to 7  $\mu$ m and some of them are tended to adhere together.

As it was shown in Zhao et al. work the morphology of the SBA-15 can to be controlled by different synthesis conditions, *i.e.* condensation rate of silica species (pH and silica source), stirring rate, micelle shape, and inorganic species present [31]. The morphology of these materials is highly dependent on the energy of local curvature and the attainment of a lower local energy of curvature will result in a more curved morphology. The most common macroscopic structures of siliceous SBA-15



Fig. 4. TEM images of (a) SBA-15-Pr-SO<sub>3</sub>H and (b) SBA-15-Ph-SO<sub>3</sub>H(-CH<sub>3</sub>).

are a rod-like particles organized into the packages. The sphericalshaped morphology of SBA-15 could be obtained inter alia by incorporating co-surfactant e.g. cetyltrimethyl ammonium bromide (CTABr) [32] which lowers the local curvature energy and conduces to the formation of a sphere shape. Also, alcohols like *n*-butanol [33,34] and ethanol [35] were applied as co-solvents to synthesize spherical SBA-15 particles. Tetraethyl orthosilicate was also selected as the silica source to reduce the local energy of curvature; TEOS has slower condensation rates as compared to tetramethyl orthosilicate [36]. Ethanol plays a very important role in determining the characteristics of the SBA-15 particles because ethanol is one of the products formed during the sol-gel synthesis from TEOS. We believe, that even though, the synthesis of SBA-15 was conducted without any additional ethanol, the local concentration of alcohol from TEOS was high enough to decrease the local surface curvature energy and leads to the formation of curved morphologies of SBA-15 particles.

The SEM images of the SBA-15–Pr- $SO_3H$  catalysts represented that after the active groups immobilization, the morphological structure and the particle shapes did not change considerably. Only, slight morphological differences can be detected for the SBA-15 supported catalysts (Fig. 5b and c). It is found that both of the SBA-15 supported catalysts have partially spherical-shaped and partially a cubic-like morphology. Some irregular small and large particles shaped are also present and some defects on the surface are detected. Average grain size dominating in the SBA-15–Pr- $SO_3H$  catalyst approached 5 µm.

The morphology of SiO<sub>2</sub> based catalysts are illustrated in Fig. 6. Presented SEM images revealed that both SiO<sub>2</sub>-*Pr*-SO<sub>3</sub>*H*(1) and (b) SiO<sub>2</sub>-*Pr*-SO<sub>3</sub>*H*(2) samples are consisted of units with irregular shapes. It is clear that, the silica supported catalysts exhibit amorphous nature of the particles.



Fig. 5. SEM images of (a) SBA-15, (b) SBA-15-Pr-SO<sub>3</sub>H and (c) SBA-15-Ph-SO<sub>3</sub>H(-CH<sub>3</sub>).

3.2.3. Characterization of sulfonic acid-functionalized SBA-15 and  $\mathrm{SiO}_2$  catalysts

Qualitative identification of the active moieties in the materials was performed by FT-IR and spectroscopy (for details see Supplementary information). Fig. S1 illustrates the FT-IR spectra of the functionalized SBA-15 and SiO<sub>2</sub> materials in comparison to that of pure silica SBA-15 (Fig. S1a). Common to all samples are the bands at a frequency of 1220, 1070, 800, and  $450 \text{ cm}^{-1}$  which represent the typical Si–O–Si

stretching and bending vibrations of condensed silica network [37–39]. *Non*-condensed Si–OH groups were formed on the surface of all the samples as evidenced by the absorption bands around 960 cm<sup>-1</sup>. While the broad peak around  $3450 \text{ cm}^{-1}$  and the strong one around  $1640 \text{ cm}^{-1}$  are due to the stretching and bending vibrations of adsorbed H<sub>2</sub>O. The FT-IR spectra for the SBA-15–*Ph*-*SO*<sub>3</sub>*H*(*-CH*<sub>3</sub>) catalyst (as an representative example) and for the SiO<sub>2</sub>–*Pr*-*SO*<sub>3</sub>*H*(*2*) catalyst (as an representative example) are shown in Figs. S1b and S2, respectively.



Fig. 6. SEM images (a) SiO<sub>2</sub>-Pr-SO<sub>3</sub>H(1) and (b) SiO<sub>2</sub>-Pr-SO<sub>3</sub>H(2).



Scheme 2. Reaction pathway of the reaction of aniline with acetone.

The results revealed that SBA-15 and SiO<sub>2</sub> carriers were successfully functionalized by anchoring the active groups to the surface. After SBA-15 functionalization, the absorption peak were found at about 2942, 2938 and 2883 cm<sup>-1</sup> which could be attributed to stretching vibrations in C–H bonds of the alkyl groups. The spectrum of the SBA-15–Ph-SO<sub>3</sub>H (-CH<sub>3</sub>) material has peaks at 594 and 702 cm<sup>-1</sup> with medium intensity which are assigned to the out-of-plane bending of the para di-substituted aromatic ring as well as the bending vibration of the sulfonic acid group. In the case of  $SiO_2$ -Pr-SO<sub>3</sub>H(2) sample the propyl group attached to the surface of SiO<sub>2</sub> in can be identified by the methylene stretching bands also in the 2850-2950 cm<sup>-1</sup> region (2943 and  $2854 \text{ cm}^{-1}$ ). The peaks corresponding to the sulfonate groups stretching vibrations are normally observed in the range of 1000–1400  $\text{cm}^{-1}$ . These peaks cannot be resolved due to their overlapping with the absorbance of Si-O-Si stretch in 1000-1130 cm<sup>-1</sup> range and that of Si-CH<sub>2</sub>-R stretch in 1200–1250 cm<sup>-1</sup> range. However, in comparison to reference silica, the spectra of the sulfonic acid functionalized materials i.e. SBA-15-Ph-SO3H(-CH3) and SiO2-Pr-SO3H (2) have more pronounced peaks centered at about 1186 and 1099 cm<sup>-1</sup> and 1184 and 1096 cm<sup>-1</sup> respectively, which could be assigned to the symmetric and asymmetric stretching vibrations of the sulfonate moieties, respectively.

Therefore, the results above proved that SBA-15 and SiO<sub>2</sub> carriers were successfully functionalized with active groups. It is also worth noting that FT-IR spectra of the catalysts well supported that all thiol groups were converted to sulfonic groups through the lack of the peak at  $2580 \text{ cm}^{-1}$  which is ascribed to the stretching vibrations in S–H groups.

The SBA-15 surface modification process was further monitored by <sup>29</sup>Si MAS NMR. The <sup>29</sup>Si MAS NMR spectrum of SBA-15 sample (Fig. S3a) shows three distinct resonance peaks around the shifts of -92, -103 and -112 ppm. They are assigned to silicon groups, *i.e.* Qn  $(Q_n: Si(OSi)_n(OH)_{4-n}, n = 2 \div 4)$  in the following structures: geminal silanol species (OSi)<sub>2</sub>Si(OH)<sub>2</sub> (Q<sub>2</sub>), isolated silanol species (OSi)<sub>3</sub>SiOH (Q<sub>3</sub>) and finally the most polymerized Si(OSi)<sub>4</sub> (Q<sub>4</sub>) units, respectively [40,41]. As a result of the introduction of active groups, the solid state <sup>29</sup>Si MAS NMR spectrum of the SBA-15-Ph-SO<sub>3</sub>H(-CH<sub>3</sub>) shown in Fig. S3b (as a representative example) displayed different signal patterns when compared to the parent silica material. It shows a much higher intensity of Q<sub>4</sub> sites (-112 ppm) when compared to the parent SBA-15 silica (Fig. S3a). This indicates the positive effect of experimental conditions on the local structures of the silicate framework. In addition, new resonances at  $\delta=-82$  and  $-71\,ppm$  are observed which are corresponded to organosiloxane T<sub>m</sub> species (T<sub>m</sub>: R-Si(OSi)<sub>m</sub>(OH)<sub>3-</sub>  $m, m = 1 \div 3$ ), *i.e.* to T<sub>3</sub> and T<sub>2</sub> moieties, respectively. The appearance of T<sub>3</sub> and T<sub>2</sub> peaks confirms the formation of Si-C bonds in the SBA-15 materials.

#### 3.3. Synthesis of 2,2,4-trimethyl-1,2-H-dihydroquinoline (TMQ)

The synthesis of TMQ is very complex and multistage process. In the

key first stage of this process aniline react with protonated enol of acetone with the formation of aniline Schiff base commonly called as acetanil. In general, products of the reaction of aniline with acetone conducted in elevated temperatures are very complex mixtures contained and beside of starting raw materials (aniline, acetone) a significant number of side products are formed. One of them is the product of the reaction of one mole of aniline with one mole of acetone – acetanil. This reaction is considered as a main side reaction compared to self-condensation reaction of acetone into mesityl oxide.

More detailed analysis of the condensation of aniline with acetone indicate that in the post-synthesis mixtures, beside of monomeric TMQ, its oligomers are also present, mainly TMQ. From the application point of view, the presence of TMQ oligomers should be considered beneficial. The next step of the production of TMQ-based antioxidants is oligomerization of TMQ. In this context, TMQ dimer may be considered also as a one of desirable product of the reaction of aniline and acetone. The reaction pathway of the reaction of aniline with acetone in the presence of acid catalyst has been shown in Scheme 2. Table 1 represents the composition of post-synthesis mixtures obtained at reaction temperature of 180  $^{\circ}$ C.

In Table 1 only the main components were indicated, both aniline and the key reaction products. Several others by-products were collected and assigned as others. More detailed analysis of the reaction of aniline and acetone will be described and discussed later. It was observed that, in reaction temperature of 180 °C the conversion of aniline depended on the catalyst used, which was in the range of  $61.3 \div 71.7\%$ and selectivity to TMQ were 38.5 up to 57.2%. A little higher activity characterized both SBA-based catalysts. Content of TMQ in postsynthesis products were above 36 wt% and additionally noticeable higher amounts ( $4.72 \div 6.31$  wt%) of TMQ dimer were observed. In Table 2 the compositions of post-synthesis mixtures obtained at 160 °C were presented.

Conversion of aniline depending on the used catalyst, was 60.6–68.7%. Comparison the results presented in Tables 1 and 2 shows, that decreasing the reaction temperature resulted in a reduction of the

Table 1

The results of condensation of aniline with acetone at 180 °C. The composition of post-synthesis mixtures (wt%).

	SiO <sub>2</sub> – <i>Pr-SO<sub>3</sub>H</i> (1)	SiO <sub>2</sub> –Pr-SO <sub>3</sub> H (2)	SBA–Ph-SO <sub>3</sub> H (-CH <sub>3</sub> )	SBA–Pr-SO <sub>3</sub> H
Sample	1	2	3	4
Aniline	37.93	33.13	24.32	35.80
Acetanil	18.42	22.66	17.61	9.45
TMQ	33.02	24.82	36.92	36.65
DiTMQ	1.36	0.90	6.30	4.71
Others	9.27	18.49	14.85	13.39
C <sub>A</sub> , %	61.2	65.5	71.6	62.9
$S_{TMQ}$ , %	55.5	38.5	57.2	64.5

 $C_A$  – conversion of aniline;  $S_{\rm TMQ}$  – selectivity to TMQ (as a sum of TMQ and DiTMQ).

#### Table 2

The results of condensation of aniline with acetone at 160 °C. The composition of post-synthesis mixtures (wt%).

	SiO <sub>2</sub> – <i>Pr-SO</i> <sub>3</sub> H (1)	SiO <sub>2</sub> <i>Pr-SO</i> 3H (2)	SBA–Ph-SO <sub>3</sub> H (-CH <sub>3</sub> )	SBA–Pr-SO <sub>3</sub> H
Sample	5	6	7	8
Aniline	34.30	36.48	28,05	31.12
Acetanil	22.37	28.20	14,38	10.45
TMQ	29.19	21.69	32.23	32.06
DiTMQ	2.23	1.70	5.16	6.94
Others	11.91	12.07	20.18	19.43
C <sub>A</sub> , %	63,0	60,5	68,6	65,4
$S_{TMQ}$ , %	47.9	36.8	52.0	56.7

 $C_{\text{A}}$  – conversion of aniline;  $S_{\text{TMQ}}$  – selectivity to TMQ (as a sum of TMQ and DiTMQ).

selectivity. Selectivity to TMQ were 36.8-56.7%. The content of the main by-product (acetanil), depending on the used catalyst, decreased to 10.44-28.06 wt%. In the temperature of 160 °C a little higher activity characterized also both SBA-based catalysts. Content of TMQ in postsynthesis products were above 32 wt% and additionally noticeable higher amounts (5.17-6.95 wt%) of TMQ dimer were also observed. Analysing the results presented in Tables 1 and 2, it can be noticed that the key factor having a significant impact on the selectivity of the tested reaction is the textural character of the catalysts used in the research. Both types of catalysts (SBA and SiO<sub>2</sub>) are characterized by similar surface area. The presence of active SO<sub>3</sub>H groups makes them characterized by similar acidic strength. However, what distinguishes them is the significant difference in pore size diameters. Since the reaction product (TMQ) is a much larger molecule than started aniline, its formation, especially the last stage of this reaction, is more convenient in the presence of catalyst with a larger pore size containing acidic centres on its surface. This makes the SBA-based catalysts have noticeably higher selectivity to the final products. This is particularly evident in the case of the TMQ dimer, which in the presence of SBA-based catalysts is formed in an amount even three times higher as compared to SiO<sub>2</sub> based catalysts.

For the synthesis of TMQ also Doebner-Miller mechanism is postulated [42]. The key step according to this mechanism is aldol condensation of acetone with the formation of mesityl oxide. In the next step mesityl oxide reacts with protonated aniline and in the sequence of reaction, TMQ molecule is formed (Scheme 3).

In order to investigate this possible method of the synthesis of TMQ, the reaction of aniline with mesityl oxide as carbonyl donor was conducted. The reaction was carried out in the temperature of 180 °C in analogous procedure adopted for acetone as carbonyl donor with the use of mesityl oxide in 20% molar excess. The results were presented in Table 3.

For both used SiO<sub>2</sub> catalysts, a considerable differences were



**Scheme 3.** Synthesis pathway of 2,2,4-trimethyl-1,2-*H*-dihydrochinoline (TMQ) according to Doebner-Miller mechanism.

#### Table 3

The results of condensation	of aniline with	mesityl	oxide a	at 180 °C.	The	com-
position of post-synthesis mi	ixtures (wt%).					

	SiO <sub>2</sub> –Pr-SO <sub>3</sub> H (1)	SiO <sub>2</sub> –Pr-SO <sub>3</sub> H (2)	SBA–Ph-SO <sub>3</sub> H (-CH <sub>3</sub> )	SBA–Pr-SO <sub>3</sub> H
Sample	9	10	11	12
Mesityl oxide	4.02	4.91	0.20	0.81
Aniline	19.34	19.83	25.30	24.36
Acetanil	18.33	17.51	2.52	7.00
TMQ	15.08	9.74	30.89	30.00
DiTMQ	3.68	3.62	13.59	13.05
Others	39.55	44.39	27.50	24.77
C <sub>A</sub> , %	71.5	72.7	65.0	65.3
$S_{TMQ}$ , %	24.5	17.8	59.7	57.6

 $C_A$  – conversion of aniline;  $S_{\rm TMQ}$  – selectivity to TMQ (as a sum of TMQ and DiTMQ).

observed. Amorphous silica sulfonic catalysts are characterized be higher content of unreacted mesityl oxide, higher amount of aniline Schiff base (acetanil), but also significantly lower content of TMQ and TMQ dimer compared to SBA-based catalysts. This experimental data indicate lower catalytic activity of amorphous silica catalysts. Although the conversion of aniline was higher than over SBA-based catalysts  $(71.5 \div 72.7\%)$ , but the selectivity to desired 1,2-H-dihydrochinoline derivatives was very low and reached only 17.8 ÷ 24.5%. The effect of used catalyst on the selectivity is analogous to that of the reaction of aniline with acetone. Selectivity to TMQ and also to TMQ dimer is significantly higher for SBA-based catalysts. Analysing the results presented in Table 3, you can also see a another catalyst effect. The condensation of aniline with mesityl oxide in the presence of SiO<sub>2</sub>-based catalysts is characterized by a slightly higher conversion of aniline compared to SBA-based catalysts. However, the higher conversion value is due to the greater share of the main side reaction, *i.e.* the decomposition of mesityl oxide into acetone and the formation of acetanil. This effect can also be linked to the pore size diameter, which in the case of SiO<sub>2</sub> catalysts are significantly smaller.

## 3.4. Condensation of aniline with acetone - mechanistic study

Comparing the use of acetone and mesityl oxide as a carbonyl donors it may be concluded that in adopted reaction conditions the use of acetone is more beneficial. From mechanistic point of view, higher selectivity and the absence of mesityl oxide in post-synthesis mixtures indicates classical Skraup mechanism of the synthesis. On the other hand the presence of significant amount of acetanil in post-synthesis mixtures obtained with use of mesityl oxide indicates the course of mesityl oxide decomposition with release of acetone.

The results presented in Tables 1–3 indicate that the reaction of aniline with acetone in temperature range of  $160 \div 180$  °C is more complex than it was depicted in Scheme 1. In this paper the analysis of the reaction of aniline with acetone in more detail have been presented for the first time. This analysis was performed with the support of GC–MS (Fig. 7) spectrometry. Sample 7 was used as a reference sample of post-synthesis mixture obtained at 160 °C with the use of SBA–*Ph*-SO<sub>3</sub>H(-CH<sub>3</sub>) as a catalyst.

Most of the scientific literature presenting the study on Doebner i Doebner-Miller condensation processes, in particular concerning the synthesis of TMQ describe the course of this reaction in a simplified way. One of the main assumptions of this work is the analysis of the course of the synthesis of TMQ catalysed by heterogeneous silica sulfonic acid catalysts in more detail. GC chromatograms of post-synthesis products show that the reaction is more complex and, besides of the main and desired products, leads to many by-products. The key components, important for mechanistic analysis of studied reaction, were numbered and indicated in this chromatogram (Fig. 7). For this components MS spectra were recorded for identification purposes.



Scheme 4. Formation of by-products  $\mathbf{2}$  and  $\mathbf{3}$  in the reaction of aniline and acetone.

The main by-product of the reaction of aniline with acetone according to Skraup (Doebner) mechanism is aniline Schiff base (acetanil). In fact, this component was found in all obtained in this study post-synthesis products. In Scheme 1 acetanil is marked as component 2 (compound 1 – aniline). The presence of characteristic master ion 133 m/e and fragmentation ions at 118 and 103 m/e in MS spectrum confirms the presence of acetanil in post-synthesis products (see Supplementary informations). Component marked as **3** is formed from acetanil in an excess of acetone. The formation of components 1-3 is presented in Scheme 4.

Formation of component **3**, however, should be considered as unfavourable because it does not participate in the formation of TMQ. Component marked as **4** has been identified as the main product – TMQ. In the MS spectrum is presented the characteristic peak of 173 m/e, assigned to master ion, which confirm the presence of TMQ in postsynthesis products. Very close to compound **4** compound marked as **5** 

Scheme 5. Formation of TMQ structural isomers.

was recorded. The MS spectrum of this component is very similar to MS spectrum of TMQ. The analysis of possible course of studied reaction suggested that it may be a previously not described structural isomer of TMQ (isoTMQ). The formation of this isomer is presented in Scheme 5.

From the chemical point of view dehydration of 4-hydroxy byproduct leads mainly to TMQ 4, but formation of isoTMQ is also possible and this isomer is present in post-synthesis mixtures. In the application point of view, the presence of structural isomer of TMQ is beneficial. Analogously to TMQ it also forms the desired 1,2-dihydrochinoline oligomers.

Components marked as **6–8** are the result of subsequent reactions based on acetanil, TMQ and acetone. The formation of components **6** and **7** is presented in Scheme 6.

Component 6 is formed in the reaction of acetanil 2 with an excess of acetone. In turn, component 7 is formed in synchronous reaction of acetanil with aniline. Relatively higher amounts of component 6, compared to compound 7, in post-synthesis mixtures proves that the



Scheme 6. Formation of components 6 and 7.



Scheme 7. Decomposition of compound 7.

first reaction is more preferred, probably because of strong activating effect of  $N=C(CH_3)_2$  group in acetanil molecule. In contrast to compound **6**, which is one of the side products, compound **7** is also beneficial. In the adopted reaction conditions it decomposes with elimination of aniline molecule and formed TMQ molecule (Scheme 7).

The presence of characteristic master ion 133 m/e and fragmentation ions at 118 and 103 m/e in MS spectrum confirms the presence of compound **7** in post-synthesis products (see Supplementary informations).

Component marked as **8** has been identified as TMQ dimer. The presence of characteristic master ion 133 m/e and fragmentation ions at 118 and 103 m/e in MS spectrum confirms the presence of compound **7** in post-synthesis products (see Supplementary informations).

Analyzing the possible pathways of the synthesis of TMQ in the context of above described study may conclude that the reaction of aniline with acetone catalysed by heterogeneous acidic catalyst proceed in mixed Skraup/Doebner mechanism. According to Doebner mechanism the key step of this reaction is the formation of mesityl oxide. Because of large excess of acetone in this case the content of mesityl oxide in products should by significantly higher. GC analysis of postsynthesis products, however, showed that the contents of mesityl oxide was only at traces level. It may suggest Skraup mechanism of this reaction. On the other hand, condensation of aniline with mesityl oxide leads to the formation of TMQ, but with lower efficiency. The content of mesityl oxide in post-synthesis mixtures was in range of  $4.0 \div 4.9 \text{ wt\%}$ , but only for silica-based catalysts. For SBA-based catalysts there's only  $0.2 \div 0.8$  wt%. Relatively high amounts of acetanil showed that in the reaction mixtures a specific equilibrium between acetone, mesityl oxide and aniline was observed.

## 4. Conclusions

In this paper, we investigated the reaction of aniline with acetone and mesityl oxide as a model carbonyl donor in acid catalysed Skrauptype condensation. As catalysts two type of organosulfonic modified silicas (amorphous and well-ordered) were applied. The reaction of aniline with acetone in the presence of heterogeneous acidic silica catalysts were investigated in more detail and discussed. We've found out that in acidic reaction conditions and elevated reaction temperature the reactivity of main raw materials (aniline, acetone) is significantly high, what causes the formation of many side by-products lowering the selectivity of this reaction. This reaction, leading to important 1,2-*H*-dihydochinoline derivative (TMQ), was then studied paying particular attention to formation of key side products, both desirable and undesirable considering the final product. Above detailed analysis of the selectivity of this reaction was made for the first time. Moreover the formation of not previously not described structural isomer of TMQ has been also demonstrated and analytically confirmed.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.mcat.2018.05.016.

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