Hierarchical micro-/macroporous TS-1 zeolite epoxidation catalyst prepared by steam assisted crystallization

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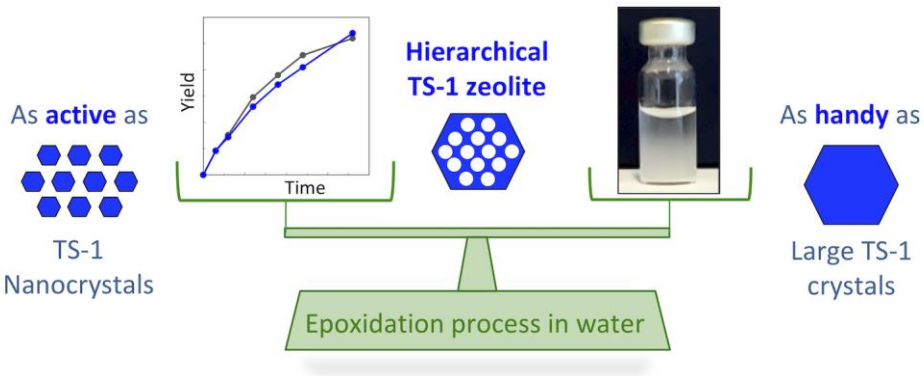
Abstract

Mesoporous Ti–SiO_2 nanoparticles were prepared under alkaline conditions in the presence of a surfactant and were subsequently converted into a hierarchical micro-/macroporous TS-1 zeolite with large crystal size using steam assisted crystallization. In this procedure, the precursor nanoparticles were used both as macroporous hard template and as Si and Ti sources. The secondary macroporosity is a reminiscence of the nanoparticles which undergo dissolution and recrystallization upon steaming. The obtained catalyst has structural properties comparable to benchmark TS-1. We show that the successful conversion of the amorphous material into a fully crystalline catalyst stands for its excellent catalytic performance in aqueous media. Besides, the combination of large crystal size with a hierarchical pore structure ensures easy catalyst handling and processing without compromising on the catalytic activity.

Keywords: hierarchically porous zeolite, TS-1, macroporous material, steam assisted crystallization, epoxidation



1. Introduction

Titanium silicalite-1 (TS-1) zeolite [1] is an important functional material that has been used for the past decades as a selective oxidation catalyst, *e.g.* in olefin epoxidation [2]. While preserving the MFI type structure that ensures its remarkable activity, it is desirable to design new TS-1 based catalysts for specific catalytic applications and reactor configurations.

On the one hand, catalytic performance is strongly limited by the slow diffusion of reactants and products in the micropores of the zeolite [3–6]. In some cases, the molecules cannot enter the microporosity and are thus restrained to the external surface. Therefore, strategies are put in place to enhance the surface-to-volume ratio of the catalyst, *i.e.* to reduce the diffusion path length within the inorganic walls and/or to increase the external surface area [3]. Thus, TS-1 can be shaped [7] as nano-sheets [8], pillared materials [9], membranes [10], hollow crystals [11,12], etc. Another way out is to add a secondary porosity, with benefits in terms of active site accessibility. While this strategy has been extensively investigated for micro-/mesoporous TS-1 [13–20], fewer studies focused on the incorporation of macropores inside the framework and on their impact on the catalytic performance [21–24]. More simply, the crystals size can be reduced in order to increase the catalytic performance.

On the second hand, the handling of small zeolite nanocrystals is complicated because such colloidal objects are refractory to mechanical recovery by filtration or decantation. Zeolite nanocrystals cannot be implemented in fixed bed flow reactor as their packing would result in an excessive pressure drop. Therefore, another objective of the modification of TS-1 materials is to obtain larger objects which fully benefit from the advantages of heterogeneous catalysts in terms of recoverability and reusability. Thus, TS-1 material can be prepared in the form of hierarchically porous microparticles [25,26] or even self-standing monoliths [27]. Alternatively, the nanosized crystals can be dispersed onto a porous support, *e.g.* diatomites [28].

Considering the above, it is highly desirable to obtain large crystals while preserving a high surface-to-volume ratio. The *Steam Assisted Crystallisation* (SAC) method, also called *Dry Gel Conversion* (DGC), has become a popular procedure to prepare hierarchically porous zeolites with a good control

on texture and particle size [29–34]. In this method, an amorphous (mixed) oxide is prepared in the form of a dry gel and treated under hydrothermal conditions in the presence of a structure-directing agent and of steam. Upon steaming, the crystallization of the zeolite has been suggested to proceed via an oriented attachment route, which consists in the aggregation and alignment of tiny crystallites that form bigger crystals [30]. According to this proposed mechanism, the technique therefore differs from the hydrothermal synthesis of zeolites, the latter involving the crystallization route by nucleation and growth in liquid phase water. The particle size can be tuned by varying the temperature and crystallization time, whereas the porosity is typically controlled in the mesoporous range by the addition of templates – *e.g.* organosilanes – that prevent the fusion of the crystallites, or by leveraging on the grinding and drying steps of the gel prior to autoclaving [33]. Alternatively, Schwieger and co-workers showed that mesoporous silica and metallosilicate nanoparticles could be used both as hard template and precursors in the synthesis of micro-/macroporous zeolitic materials by SAC, respectively [35–37].

Herein, we propose to combine titanium and silicon precursors in the synthesis of amorphous Ti–SiO_2 nanoparticles and to use the latters in the preparation of hierarchical TS-1 material featuring both a micro-/macroporosity and large crystal size. We aim to demonstrate that controlling the incorporation of titanium during the preparation of the precursor particles prior to the thermal treatment allows obtaining TS-1 presenting both proper Ti speciation in the MFI-type structure and a secondary intracrystalline macroporosity. The successful conversion of the amorphous material into crystalline TS-1 is exploited in the catalytic conversion of allyl alcohol into glycidol in water, and compared to the benchmark microporous TS-1 catalyst.

2. Experimental

2.1. Preparation of the materials

2.1.1. Preparation of the reference catalyst (TS-1 nanocrystals)

Benchmark TS-1 (‘**TS-1**’) was prepared with a Ti loading of 1.8% (here and after the loading is expressed as mol Ti / (mol Ti + mol Si) × 100 %) using titanium isopropoxide (TiiP) and tetraethyl

orthosilicate (TEOS) as Ti and Si sources, respectively, and tetrapropylammonium hydroxide (TPAOH) as structure directing agent [38]. The detailed preparation procedure is available in the Supplementary material.

2.1.2. Preparation of the hierarchical micro-/macroporous TS-1

The micro-/macroporous TS-1 (denoted as '**TS-1_MAC**') was prepared by adapting the procedure of Machoke *et al.* for the preparation of macroporous silicalite [35]. First, mesoporous Ti–SiO_2 particles, denoted '**MSTP**', were synthesized as follows: 1 g of hexadecyltrimethylammonium bromide (CTAB, Alfa Aesar, 98%) was added to 140 ml distilled H_2O and 480 ml EtOH under stirring. After 10 min stirring, 24 ml of 25% (w/w) aqueous NH_3 (Merck) was added (Solution A). In a separate vessel, 3.130 g TEOS and 0.097 g titanium butoxide (1.8% at. Ti) (TiBuO, Sigma-Aldrich, 97%) were mixed in 5 ml EtOH under vigorous stirring and then stirred for 1h at room temperature (Solution B). This mixing of the Si and Ti precursors was essential to ensure the incorporation of titanium into the silica nanoparticles. Thereafter, solution B was added dropwise to solution A, resulting in a clear yellowish solution. After 10 min stirring at room temperature, a white precipitate appeared and the solution was further stirred for 2h. The precipitate was subsequently recovered by filtration, washed with distilled H_2O and dried overnight at 75°C. Finally, CTAB was removed by calcination at 550°C for 6h (5°C/min). In the second step, 250 mg of **MSTP** was impregnated with 0.34 ml 40% (w/w) aqueous TPAOH (TPAOH/SiO_2 molar ratio of 0.16) in a crucible and homogenised with a spatula. The mixture was then put to rest for 24h. After that time, a solidified paste was obtained. Using 0.34 ml of 40% (w/w) aq. TPAOH, the nominal V_{MSTP} to (V_{MSTP} + V_{TPAOH}) ratio was of 0.74, corresponding to a close-packing arrangement of the MSTP particles in the solid mixture. The solid was crushed manually into small pieces and transferred into a 70 ml teflon-lined stainless steel autoclave containing 20 ml of distilled H_2O in a separate vessel. After 96h SAC at 130°C, the solid was successively washed with distilled water and EtOH so as to facilitate drying without altering the porosity. It was then dried at 75°C overnight and finally calcined at 550°C for 5h (5°C/min).

2.2. Characterization of the materials

The Ti content of the materials was measured by ICP-AES on an ICP 6500 instrument (Thermo Scientific Instrument) after dissolution of the samples by sodium peroxide fusion. XPS experiments were carried out using an SSX 100/206 spectrometer (Surface Science Instruments, USA) with Al-Kα radiation operated at 10 kV and 20 mA. The binding energy scale was calibrated on the Si 2p peak, fixed at 103.5 eV [39]. The quantification of Ti in Ti–O–Si and Ti–O–Ti was based on the decomposition of the $2p_{3/2}$ peak at approximately 460.0 and 458.5 eV, respectively [40,41]. Si was quantified on the basis of the Si 2p peak at 103.5 eV [39]. Powder X-ray diffraction (PXRD) patterns were recorded at room temperature with a D8 ADVANCE Bruker diffractometer equipped with a LYNXEYE XE-T detector, using copper Kα radiation (λ = 1.5406 Å) in a 2θ range of 5–80° (step = 0.02°, time per step = 0.15 s). The X-ray source was operated with a tension of 40 kV and a current of 30 mA. For display, the diffractograms were normalized by the most intense diffraction peak. The relative crystallinity of the catalysts was estimated by a simple calculation based on the intensity of diffraction peaks in the diffractograms (see details in supplementary materials, Figure S1). The DR UV-VIS spectra were recorded on a Shimadzu UV-3600 Plus UV–Vis–NIR Spectrophotometer with a Harrick single-beam Praying Mantis Diffuse Reflectance collection system. The spectra were recorded at room temperature in 20000–50000 cm^{-1} range. A Spectralon® Diffuse Reflectance Standard was used to measure the background spectra. The DR UV-VIS spectra were background corrected, normalized by the most intense absorption band, and the Kubelka Munk function was used to display the data. The DRIFT spectra were recorded using an Equinox 55 spectrometer (Bruker) equipped with a DRIFT cell in order to degas the sample *in situ* (air, 200°C) prior to measurement. The spectra were recorded between 4000 and 800 cm^{-1} with a resolution of 2 cm^{-1} and normalized by the most intense absorption band. Scanning electron microscopy (SEM) images were taken using a JEOL 7600F microscope with a 1–5 kV voltage. Samples were pre-treated with a gold sputter coating of 15 nm carried out under vacuum with a Sputter Metal 208 HR (Cressington). Textural properties were determined from N_2 adsorption/desorption isotherms at -196°C using a Tristar 3000 instrument (Micromeritics, USA). Prior to measurement, the samples were degassed overnight under vacuum at 150°C. The BET specific surface area of **MSTP** was evaluated in the 0.05–0.3 P/P_0 range. For hierarchical zeolites, the external specific surface area – which includes the specific surface area of mesopores –was evaluated by the slope of the line drawn in the

linear portion of the t-plot in the 3.5–5 Å thickness range; the micropore volume was given by the intercept. The total pore volume was measured at $P/P_0 = 0.98$. The pore size distribution was obtained from the adsorption branch using the BJH method.

2.3. Catalytic tests

The catalytic performance was evaluated in water for the epoxidation of allyl alcohol with hydrogen peroxide as the oxidant. The reaction was carried out in a two-necked round-bottomed glass reactor at 45°C, equipped with a magnetic stirrer and a rubber septum. In a typical run, 0.528 g (0.9 M) allyl alcohol (Acros Organics, 99%), 0.037 g (0.05 M) Butan-1-ol (Sigma-Aldrich, ≥ 99.4%) – used as the internal standard – and 50 mg (5 $g.L^{-1}$) catalyst were pre-mixed in 9.152 g of distilled H_2O and stirred for 10 min. To start the reaction, 0.204 g (0.18 M) of 30% (w/w) aqueous H_2O_2 was added and the mixture was allowed to react for 3 h. The product formation was followed by collecting aliquots at regular time intervals and by analysing them in gas chromatography, using a Varian CP-3800 chromatograph equipped with a FID detector and a capillary column (BR-5, 30 m, 0.32 mm i.d., 1.0 μm film thickness). Prior to injection, water was removed by an extraction step with ethyl acetate (50:50 v/v).

3. Results and discussion

The materials were first analysed by PXRD in order to evaluate the bulk phase crystallinity. The diffractogram of the starting material **MSTP** does not show any peak, confirming the amorphous nature of these Ti–SiO_2 particles. The **TS-1_MAC** catalyst exhibited the crystalline MFI-type structure identical to **TS-1** zeolite (**Figure 1a**). This result demonstrates that the formation of the zeolitic framework in **TS-1_MAC** occurred during the steaming step. **TS-1** prepared by such hydrothermal route typically have a high degree of crystallinity (here estimated to reach 97%, see **Figure S1**, supplementary material) [38]. For **TS-1_MAC** the degree of crystallinity was also high (94%), confirming that both catalysts are very similar in terms of crystallinity. Importantly, no TiO_2 anatase – having a signature peak at $2\theta = 25°$ [42,43] – was detected in the zeolite samples, thereby excluding the presence of large crystalline TiO_2 domains in the materials.

In order to have deeper insight into the incorporation of titanium in the materials, an elemental analysis was first carried out by ICP-AES and revealed that the experimental Ti content was respectively of 1.6% and 1.7% for **TS-1** and **TS-1_MAC** catalysts (**Table 1**), thus close to the nominal loading. Further investigations by XPS analysis allowed to determine the Ti concentration at the surface as well as the quality of the Ti dispersion (**Table 1** and **Figure S2**, Supplementary material). For both zeolitic catalysts, the surface composition matched closely the bulk content, indicating a homogeneous Ti incorporation throughout the material. On the opposite, the surface Ti content was very low in the starting material **MSTP**, highlighting the fact that Ti is poorly dispersed in the amorphous dry gel, with presumably a gradient of concentration and high Ti content in the bulk of the materials. After applying the SAC procedure, however, a homogeneous zeolitic material is obtained.

Table 1. Percentage of Ti species (mol Ti / (mol Ti + mol Si) × 100 %) in the catalysts (bulk composition, ICP-AES) and at the catalyst surface (from XPS)

	Bulk Ti %[a]	**Surf. Ti %**	**Surf. Ti–O–Si %**	**% Ti–O–Si**[b]
TS-1	1.6 (1.8)	1.3	1.2	90
TS-1_MAC	1.7 (1.8)	1.7	1.1	66
MSTP	n.m. – (1.8)	0.3	–[c]	–

[a] Nominal composition calculated from the precise amounts of precursors actually used in each synthesis is given in brackets. [b] % Ti–O–Si = (Surf. Ti–O–Si % / Surf. Ti %) × 100. [c] The amount of titanium at the surface was too low for this sample to allow a proper decomposition of the Ti 2p peak.

The third column of **Table 1** indicates the fraction of Ti species that are truly dispersed in the silica matrix, forming Ti–O–Si bonds, as determined by the decomposition of the Ti 2p peak [44]. The catalyst prepared by SAC shows a relatively lower Ti dispersion as compared to **TS-1**. As no TiO_2 anatase was detected by PXRD (**Figure 1a**), the fraction that is not well incorporated in the silica matrix is assigned to extra-framework Ti species in 5- and 6-coordination states, possibly in the form of Ti oligomers [45]. This is also suggested by the UV-visible spectrum of the **TS-1_MAC** catalyst (**Figure 1b**), which shows a minor contribution of highly coordinated Ti species in the region between 250 and 300 nm. Nevertheless, the main absorption band for this catalyst is found in the 200–210 nm range – as in **TS-1** – which corresponds to highly dispersed tetrahedral Ti species inside the framework. As a comparison,

the XPS spectrum of **MSTP** shows a Ti $2p_{3/2}$ peak at 458.9 eV (see **Figure S2c**, Supplementary material), suggesting a major contribution from Ti–O–Ti bonds present in polymeric Ti oxide species. This result is further supported by the UV-visible spectrum, which exhibits a much higher contribution of highly coordinated Ti species for **MSTP**, which is a clear indication of the poor dispersion of Ti in this starting material. For this sample, the absorption in the region above 300 nm may not exclude the presence of TiO_2 anatase [46,47]. Yet, these clusters would be too small to be detected by PXRD. In any case, the extra-framework Ti species are converted into framework Ti species by the SAC treatment [14].

In SEM, **TS-1_MAC** appeared as holed crystals with size in the 1.5–2 μm range (**Figure 2c–d**), thus ~ 15 times larger than the typical nano-sized crystals of **TS-1** which show dimensions between 100 and 150 nm (**Figure 2a**) [38]. The synthesis of **TS-1_MAC** was reproduced three times and the resulting solids showed no difference either in terms of crystal size or morphology. **TS-1_MAC** crystals are smaller than the Ti-free silicalite-1 crystals prepared by Machoke et al. (*ca.* 4 μm) [35], which suggests a lower rate of crystallization in the presence of titanium [38]. This assumption is further supported by the fact that the crystallization did not occur when performing the SAC at 110°C, as indicated for silicalite-1 [35]. In the present case, the crystallisation step had to be carried out at 130°C to obtain the crystalline TS-1. One attempt was made to increase the temperature to 160°C, but in this case the crystals were too small to properly incorporate the macropores. Each embedded macropore in **TS-1_MAC** has a pore opening between 200 and 300 nm. These macropores are a reminiscence of the individual **MSTP** particles (see **Figure 2b**) which have an average diameter of *ca.* 450 nm and serve both as a precursor for the TS-1 crystallization and as a hard template.

Considering the above results as well as the mechanism of crystallization by the oriented-attachment route proposed by Song *et al.* [30], **Scheme 1** presents a suggested formation mechanism for **TS-1_MAC** crystals. Each crystal is formed by a hard templating route, in which the embedded macropores result from the dissolution-recrystallization of the amorphous **MSTP** particles upon steaming in the presence of the structure directing agent [35]. During this key step, the poorly dispersed Ti species in the amorphous precursor particles are incorporated in the zeolitic framework in a 4-

coordination mode. The crystals then grow *via* the oriented attachment of tiny crystallites, themselves originating from tiny particulates formed by the disassembly of the amorphous dry-gel [30].

In N_2 physisorption, the isotherms of the **MSTP** solid revealed the presence of supermicropores formed upon templating with CTAB. Yet, no micropores were found on the t-plot. After the SAC treatment, **TS-1_MAC** expectedly showed a Type I isotherm characteristic of microporous solids, and very close to the **TS-1** sample (**Figure 3**). The micropore volume V_μ is similar in both catalysts (**Table 2**). Although the macropores of **TS-1_MAC** fall off the measurment range of the N_2 physisorption technique, the forced closure of the isotherm upon desorption at P/P_0 of 0.4–0.5 due to the tensile stress effect [48] suggests also the presence of mesopores smaller than 3.8 nm in the pore walls of the material, as reported in the literature [35,49] (see also inset of **Figure 3**). The large N_2 uptake at high P/P_0 in this sample is assigned to interparticular voids between the crystals (~ 40–50 nm). The external surface area of **TS-1** nanosized crystals was of 130 $m^2.g^{-1}$. Importantly, despite the much larger crystal size of **TS-1_MAC**, the external surface area reached 150 $m^2.g^{-1}$ (**Table 2**), thanks to the surface area generated by the additional porosity.

Table 2. Textural properties of the catalysts

	S_{ext} ($m^2.g^{-1}$)[a]	V_μ ($cm^3.g^{-1}$)[a]	V_p ($cm^3.g^{-1}$)[b]
TS-1	130	0.15	0.43
TS-1_MAC	150	0.14	0.23
MSTP	610[c]	0	0.40

[a]Micropore volume and external surface area calculated from the t-plot. [b]Measured at $P/P_0 = 0.98$. [c]For this mesoporous sample, the external surface area is evaluated by the BET method (0.05–0.3 P/P_0 range).

The catalytic performance of **TS-1_MAC** was evaluated for the epoxidation of allyl alcohol to glycidol in water with H_2O_2 as the oxidizing agent. Such conditions allow to properly assess the successful crystallization of the zeolite, as amorphous Ti–SiO_2 materials are known to be inactive in water [50]. It should be noted that allyl alcohol is small enough to enter the micropore network. From the kinetic curves presented in **Figure 4** – showing the glycidol production over time – almost no activity was observed when testing the amorphous **MSTP** starting material. Indeed, it is well known that amorphous Ti–SiO_2 catalysts are sensitive to the presence of H_2O molecules [50], leading to strong deactivation issues in the presence of large amounts of water [51]. Besides, XPS and UV-visible spectroscopy showed that Ti was poorly dispersed in the **MSTP** sample (*vide supra*). On the opposite, **TS-1_MAC** was highly active as it showed similar performance as the benchmark **TS-1**. Thus, starting from an inactive Ti-SiO_2 material, an active epoxidation catalyst is obtained using SAC. The high activity of this material can be ascribed to the successful formation of the MFI crystal structure upon steaming (see **Figure 1**). Indeed, the incorporation of single site Ti in the crystalline framework during the dissolution-recrystallization step accounts for the formation of the active sites, and the MFI structure is known to confer an intrinsic resistance towards deactivation in water.

Both **TS-1** and **TS-1_MAC** exhibit comparable performance, not only in terms of glycidol production and full selectivity towards the epoxide [52], but also as regard to their turnover frequency (TOF). Yet, increasing the particle size gives a competitive advantage by reducing the energy cost for separation by facilitating the catalyst recovery by centrifugation or filtration. For example, the sedimentation behaviour was qualitatively assessed for both **TS-1_MAC** and **TS-1** and we showed that

the former could be separated much faster (see inset of **Figure 4**). Zuo *et al*. have shown, however, that the turnover frequency decreases when increasing the crystal size of non-hierarchical TS-1, because the external surface areas was lowered (85 and 145 $m^2.g^{-1}$ for crystal size of 1200 and 200 nm, respectively) [53]. In our system, the key factor is that the additional porosity of **TS-1_MAC** allows to overcome this limitation. While switching from ~100 nm **TS-1** particles to ~1500 nm crystals of **TS-1_MAC**, a high external surface area is maintained (S_{ext} = 130 $m^2.g^{-1}$ and 150 $m^2.g^{-1}$ respectively). Additionally, the diffusion path length between the intracrystalline macropores of **TS-1_MAC** is comparable to the size of single **TS-1** crystals, which implies that mass transfer in the microporous walls of both materials should also be similar.

To address the role of the steaming treatment on the surface composition, DRIFT measurements were carried out on degassed **TS-1** and **TS-1_MAC** samples. The results suggested that the **TS-1_MAC** catalyst possessed a lower silanol content than the benchmark **TS-1** catalyst (**Figure S3**). This is presumably a result of the presence of TPAOH around the **MSTP** particles during the steaming treatment, as recently suggested by Rodenas *et al*.[54] Such reduction of the number of defect sites (*i.e.* it lowers the amount of surface hydroxyl groups) was reported to increase the surface hydrophobicity, which itself influences the catalyst selectivity. Nevertheless, here, the slight difference in the number of defect sites appeared to have no effect, as **TS-1** and **TS-1_MAC** were both fully selective towards the epoxide product.

The beneficial effect of the introduction of a hierarchical porosity in TS-1 on the catalytic performance was previously reported for micro-/mesoporous TS-1. In order to compare **TS-1_MAC** to such type of catalyst, a micro-/mesoporous TS-1 – denoted **TS-1_MES** – was synthesized with the same structure and composition according to a typical procedure from the literature (**Figure S4**, see Supplementary material for detailed synthesis procedure and full characterization) [32]. We confirm the validity of such approach, as this catalyst showed slightly higher performance than **TS-1** and **TS-1_MAC** (**Figure 4**) while exhibiting a settling velocity comparable to **TS-1_MAC** due to their similar crystal size (see **Figure S4e–f**). The higher performance of **TS-1_MES** results from the increased pore volume (0.41 $cm^3.g^{-1}$) and external surface area (180 $m^2.g^{-1}$) owing to the additional presence of

mesopores (see Figure S2d). It should be noted however that this synthesis involves the use of a sacrificial soft templating agent, whereas the SAC method does not require any additional template. Besides, the amount of TPAOH used here remains quite low (TPAOH/Si ≈ 0.16) compared to other hierarchical TS-1 (TPAOH/Si = 0.21 for **TS-1_MES** [32]) and conventional TS-1 (TPAOH/Si = 0.41 [38]). These two characteristics may contribute to reduce the cost of fabrication of the catalyst, which is of outmost importance for the industrial use of TS-1 based catalysts [55].

4. Conclusion

Herein, we show that combining titanium and silicon precursors in the preparation of amorphous Ti–SiO_2 nanoparticles followed by steam assisted crystallization in the presence of TPAOH allowed obtaining a micro-/macroporous titanosilicate zeolite with the MFI-type structure. The crystals of this new macro-microporous TS-1 catalyst are about 15 times larger than the nanosized TS-1 benchmark. Yet their external surface area remained relatively high, owing to the presence of the macropores. This catalyst performed as well as the nanosized TS-1 zeolite in the epoxidation of allyl alcohol in water. The larger crystal size ensures an easier recovery of the material and may also provide a series of advantages for industrial applications, such as the prevention of plugging in fixed-bed reactors and the safer handling of the catalyst during the loading and unloading operations.

Appendices

Detailed synthesis procedures for **TS-1** and **T-1_MES** as well as additional figures are presented in the Supplementary material.

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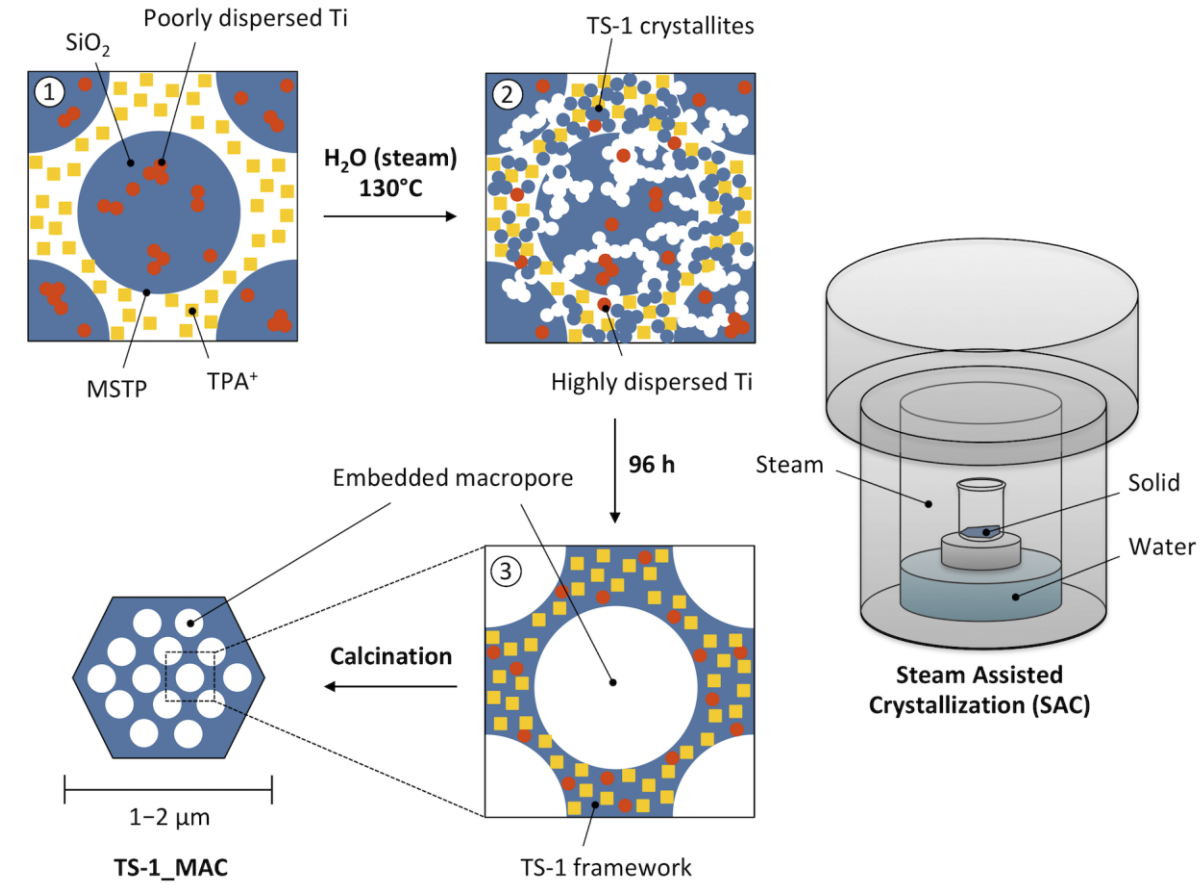
Figure 1. a) Normalized PXRD patterns of the zeolitic catalysts; diffractogram of amorphous **MSTP** is shown for comparison; b) Normalized DR UV-visible spectra of the catalysts (F(R) is the Kubelka-Munk function) and of the starting material **MSTP**.

Figure 2. SEM image of a) **TS-1**, b) **MSTP**, and c–d) **TS-1_MAC**.

Scheme 1. Proposed mechanism of formation of **TS-1_MAC**. In step 1, the **MSTP** particles are surrounded by the zeolite structure directing agent. In step (2), the dissolution-recrystallization proceeds in the presence of the SDA upon steaming to form tiny particulates that gradually transform into nanocrystallites, which further undergo oriented assembly into aggregates around the precursor particles to form bigger crystals. In step (3), the hierarchical zeolite framework is fully crystallized and displays embedded macropores.

Figure 3. N_2 adsorption-desorption isotherms of the materials. Desorption PSDs of **TS-1** and **TS-1_MAC** are shown in inset.

Figure 4. Kinetic data for the conversion of allyl alcohol into glycidol in H_2O using aqueous solution of hydrogen peroxide as oxidizing agent. The initial turnover frequency (TOF) was approximated by the glycidol production after 15 min reaction time and normalized by the amount of active Ti (see "Surf. Ti–O–Si %" in **Table 1**). No other product was detected by GC and the mass balance was always close to 100%. Experimental conditions: T = 45°C, [Allyl alcohol] = 0.9 $mol.l^{-1}$, [H_2O_2] = 0.18 $mol.l^{-1}$. In inset is shown a picture illustrating the fact that the **TS-1_MAC** sample settles faster than **TS-1** in water. The picture was taken 2h after sonicating the catalyst suspension (20 $g.l^{-1}$) for 30 min; it shows that **TS-1_MAC** has almost fully settled at the bottom of the vial, while **TS-1** is still mainly in suspension.



Scheme 1.

Figure 1.

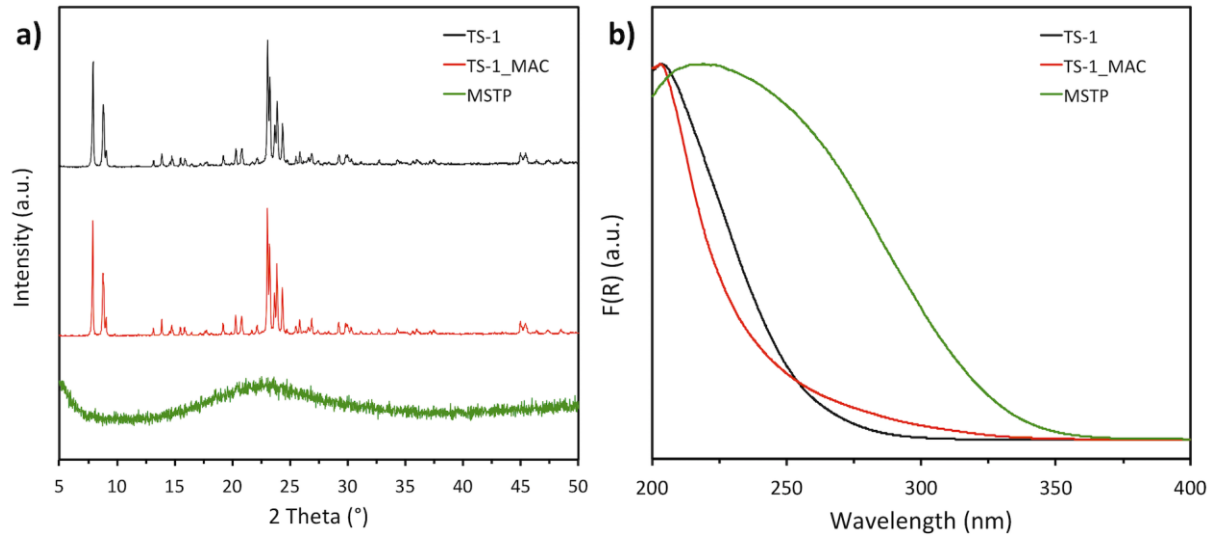


Figure 1

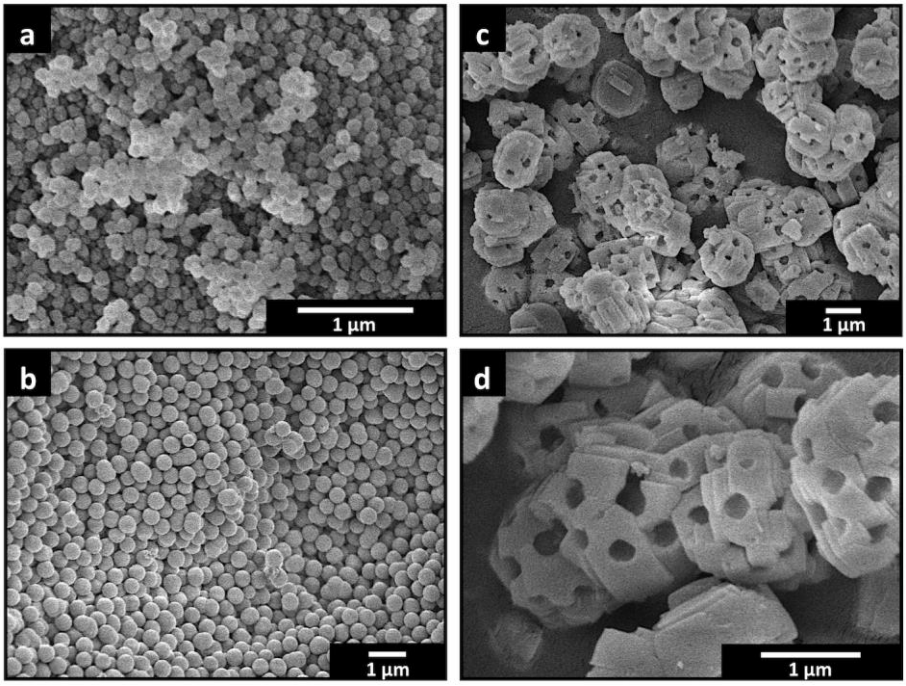


Figure 2.

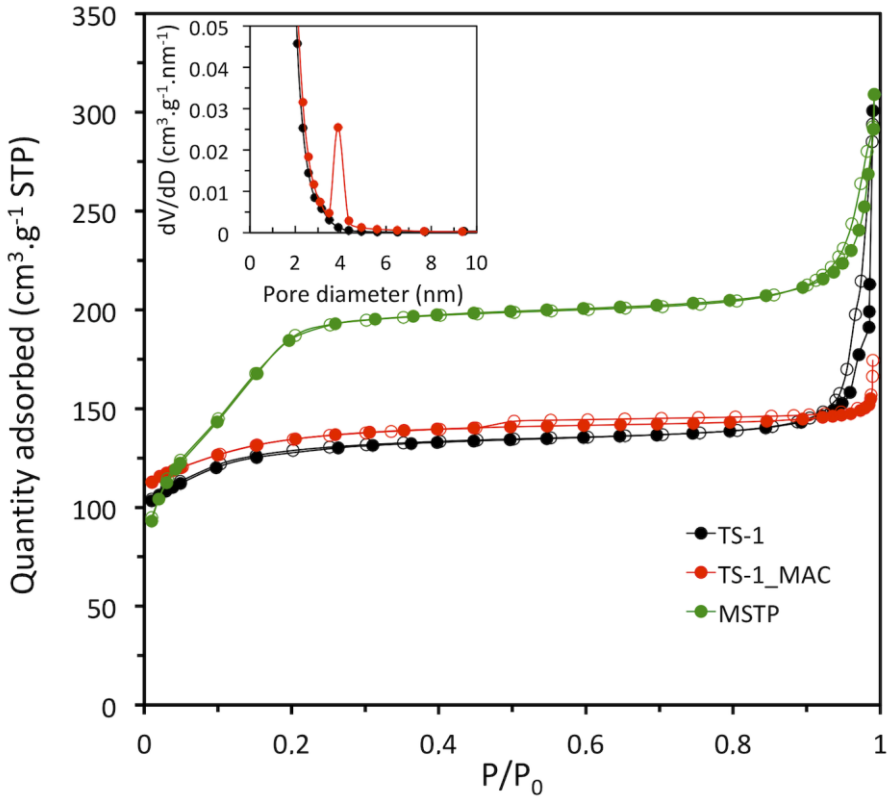


Figure 3.

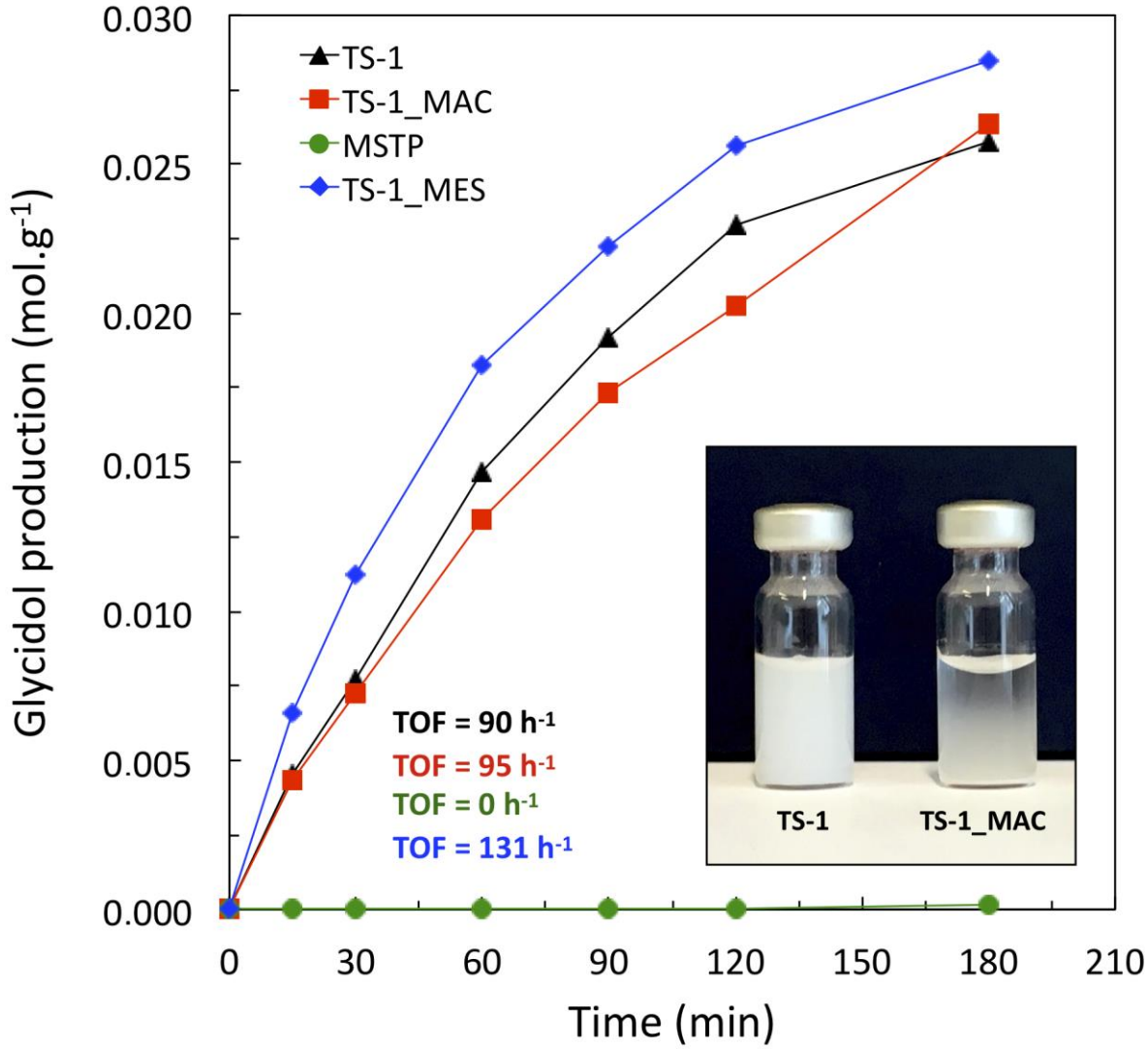

0.030
0.025
0.020
0.015
0.010
0.005
0.000
Glycidol production (mol.g-1)
TS-1
TS-1_MAC
MSTP
TS-1_MES
TOF = 90 h-1
TOF = 95 h-1
TOF = 0 h-1
TOF = 131 h-1
TS-1
TS-1_MAC
0
30
60
90
120
150
180
210
Time (min)

Figure 4.

Hierarchical micro-/macroporous TS-1 zeolite epoxidation catalyst prepared by steam assisted crystallization

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Supplementary material

Materials

Preparation of the reference catalysts

TS-1 [1]. 0.55 g of titanium isopropoxide (TiiP, Acros Organics, ≥ 98%), the titanium precursor, was first solubilized in 5 g of ^{i}PrOH (VWR) (Solution A). In a separate vessel, 22.5 g of tetraethyl orthosilicate (TEOS, Sigma-Aldrich, 98%), the silicon precursor, was mixed with 16.41 g of 40% (w/w) aqueous tetrapropylammonium hydroxide (TPAOH, Merck) and 9.84 g of distilled H_2O (Solution B). Both solutions were stirred for 5 min at room temperature. Solution A was then added dropwise to Solution B, and the turbid mixture was stirred for 15 min until a clear yellowish solution was obtained. After that time, 5.47 g of TPAOH (40% w/w aq.) diluted in 38.28 g of distilled H_2O was added. The initial gel composition was 1 SiO_2: 0.018 TiO_2: 0.40 TPAOH: 32 H_2O with a Ti loading of 1.8% (mol Ti / (mol Ti + mol Si) × 100 %). The solution was kept under stirring at 75°C for 2–3h – in order to reduce the volume of the solution by evaporation of the alcohol. Then, 30 g of distilled H_2O was added and the diluted gel was transferred into a 70 ml teflon-lined stainless steel autoclave for 24 h at 160°C. After rapid cooling, the formed white precipitate was isolated by centrifugation, thoroughly washed with distilled H_2O until neutral pH, dried in air at room temperature for 72 h, and finally calcined at 550°C for 5 h (5°C/min).

TS-1_MES [2,3]**.** This catalyst was obtained via a two-step procedure: (i) a solution composed by 3.12 g of TEOS, 0.271 g of hexadecyltrimethoxysilane (HTS, Sigma-Aldrich, ≥ 85%) and 0.0748 g of TiiP in 10 g of EtOH (VWR) (Solution A) was added dropwise to another solution prepared by mixing 1.6 g of 40% (w/w) aqueous TPAOH with 2 g of EtOH and kept under stirring for 1h (Solution B). The resulting clear yellow solution of composition 1 SiO_2: 0.018 TiO_2: 0.21 TPAOH: 0.05 HTS: 4 H_2O: 17 EtOH (1.7% Ti loading) was further stirred for 1h and eventually left for evaporation in the fume hood. (ii) after 2–3h, a wet soft gel started to form. This gel was grinded into small pieces and then left to dry for 24h. The resulting dry gel was subsequently transferred into a 70 ml teflon-lined stainless steel autoclave filled with 3.75 ml of H_2O. The autoclave was then sealed and kept in the oven at 160°C for 48h. Afterwards, it was rapidly cooled to room temperature with cold water and opened. The solid material was consecutively washed with deionized H_2O and small amounts of EtOH in order to facilitate the drying step without altering the texture. Thereafter, it was left in air for 72h and finally calcined at 550°C for 5h (5°C/min) to remove the organics.

Additional figures

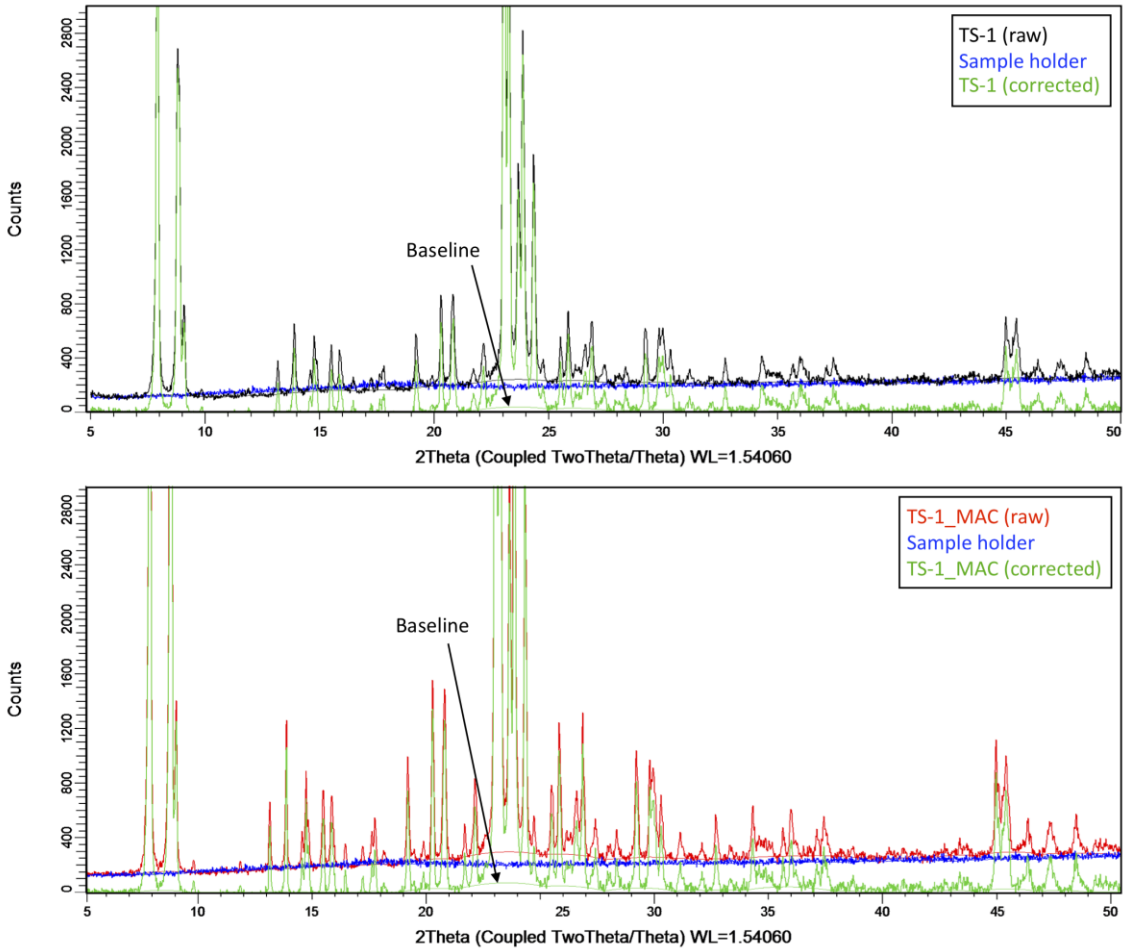

Figure S1. Calculation of the degree of crystallinity for the **TS-1** and **TS-1_MAC** catalysts according to the DIFFRAC.EVA software. Raw PXRD patterns are identical to **Figure 1a**. Prior to calculation, the diffractograms (black or red) were corrected by subtracting the signal of the sample holder (blue line) to get the green line. The degree of crystallinity, expressed in %, was obtained by calculating the ratio between the area under the diffraction peaks relative to the baseline automatically generated by the Bruker software (DIFFRAC.EVA) and the total peak area relative to the zero-signal.

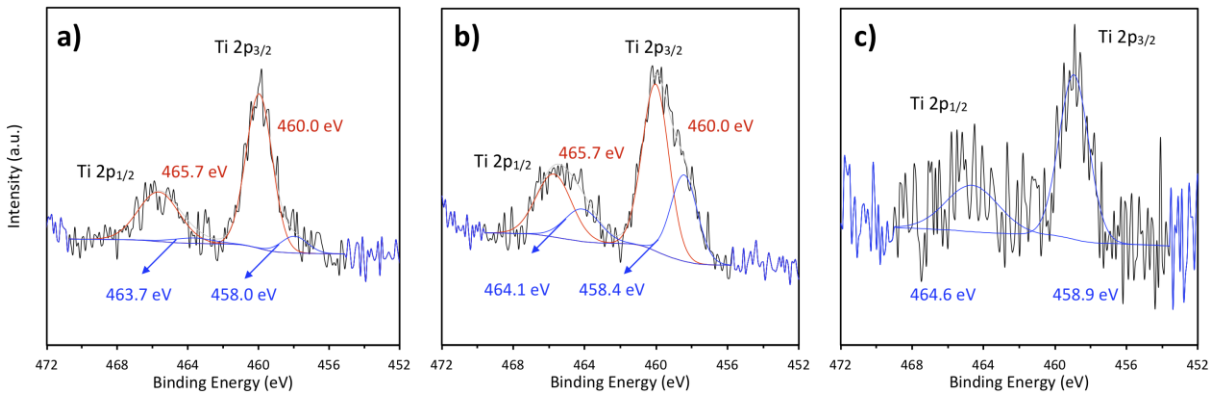

Figure S2. Decomposition of the XPS Ti 2p spectrum of a) **TS-1**, b) **TS-1_MAC** and c) **MSTP**. The position of the Ti $2p_{3/2}$ peak on the spectrum of **MSTP** suggests the majority of the titanium species at the surface are poorly dispersed (*i.e.* Ti–O–Ti bonds).

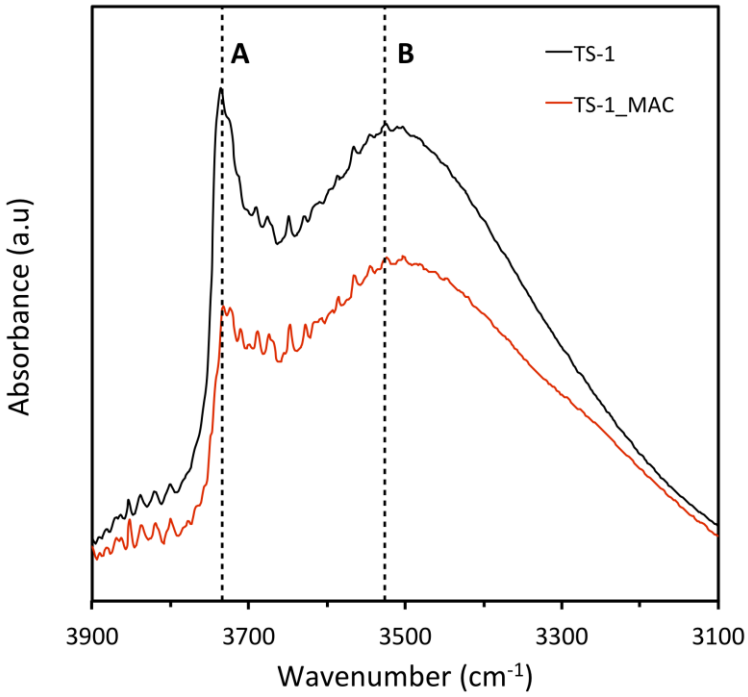

Figure S3. Normalized DRIFT spectra of the degassed **TS-1** and **TS_1_MAC** samples in the 3100–3900 cm^{-1} range. The absorption band around 3740 cm^{-1} (A) is due to isolated silanol groups, whereas the broad band centered around 3540 cm^{-1} (B) is due to H-bonded hydroxyl groups [4].

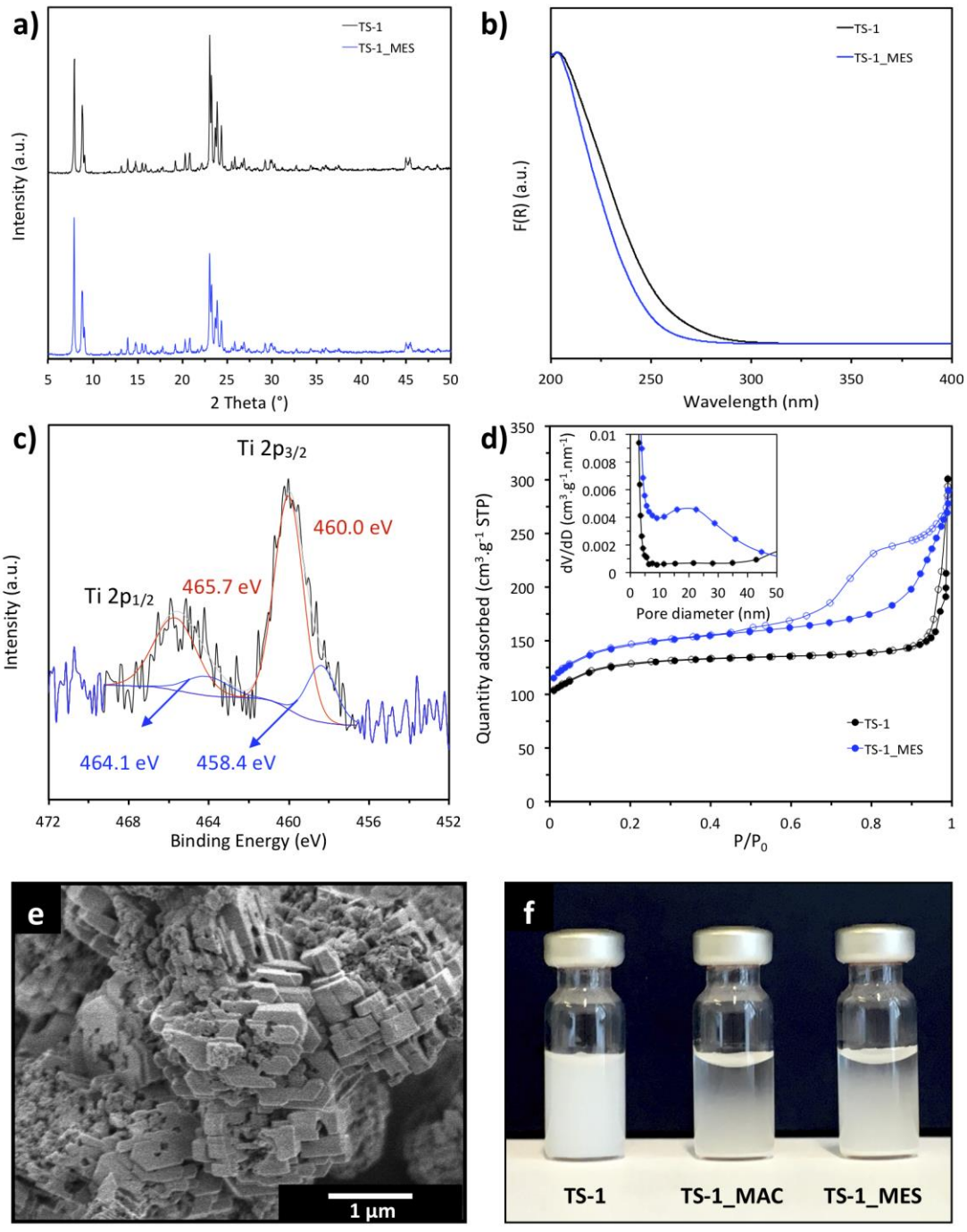

Figure S4. Characterization of the **TS-1_MES** catalyst synthesized following the procedure of Kong *et al.* [2]. a) Normalized PXRD patterns ; b) Normalized UV-visible spectra ; c) Decomposition of the XPS Ti 2p spectrum of **TS-1_MES**. For this sample, the bulk and surface Ti contents were 1.7% and 1.5%, respectively. The surface Ti–O–Si content of this sample was 1.2% ; d) N_2 adsorption-desorption isotherms (in inset are shown the adsorption PSD). The external surface area of **TS-1_MES** was 180 $m^2.g^{-1}$; the pore volume measured at $P/P_0 = 0.98$ was 0.41 $cm^3.g^{-1}$ whereas the micropore volume found by the t-plot method was 0.15 $cm^3.g^{-1}$. The adsorption PSD shows the presence of ~20 nm mesopores, which are also evidenced by the hysteresis loop of the type IV isotherm ; e) SEM micrograph and f) picture illustrating the settling velocity of **TS-1_MES** (20 $g.l^{-1}$ suspension) compared to **TS-1** and **TS-1_MAC**. The picture was taken 2h after sonicating the catalyst suspension for 30 min.

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