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Multifunctional Catalysis Promoted by Solvent Effects: Ti-MCM41 for a One-Pot, Four-Step, Epoxidation−Rearrangement−Oxidation−Decarboxylation Reaction Sequence on Stilbenes and Styrenes

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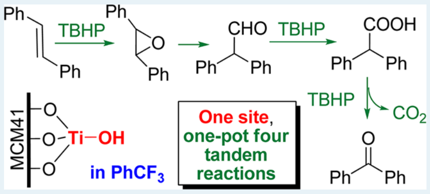
Supporting Information

ABSTRACT: Titanium sites grafted on several siliceous supports are able to act as multifunctional catalytic centers, activating *tert*-butyl hydroperoxide for oxidation reactions, as redox centers, and promoting rearrangements, as Lewis acids. In the one-pot, four-step conversion of stilbene into benzophenone, the best results were obtained over Ti-MCM41. Under suitable conditions, the catalyst promotes a tandem sequence: alkene epoxidation, epoxide rearrangement, aldehyde oxidation, and oxidative decarboxylation. α,α,α-Trifluorotoluene and a fluorinated glycerol-derived solvent were the optimal solvents for this tandem process, due to their polar aprotic character that allows the efficient oxidation reactions and a poor coordinating ability to prevent any deactivation of the Lewis acid character of the sites. The result of the tandem sequence of reactions is a ketone with loss of a carbon atom that, depending on the starting alkene, is the same result as that of an ozonolysis but under safer and milder conditions. Interesting and new insights on the mechanism of the different reactions involved are also described.



KEYWORDS: *multifunctional catalysis, titanium catalysts, epoxidation, epoxide rearrangement, oxidative decarboxylation, tandem catalysis*

INTRODUCTION

The cleavage of alkenes to the corresponding carbonyl or carboxylic compounds is a widely used method in organic synthesis, in particular as a strategy to introduce oxygen functionalities in molecules. These reactions can be carried out by both chemical and enzymatic methods.[1,2] The most popular chemical method is ozonolysis, although it is not free from risks mainly in large scales. Other chemical methods are based on the use of oxidants in stoichiometric or even overstoichiometric amounts, leading to the formation of high amounts of concomitants byproducts. On the other hand, enzymatic methods are suitable for a limited number of molecules and, although further developments are envisaged, they still lack of broad applicability to families of organic compounds. In this regard, the development of chemical strategies based on the use of environmentally benign oxidants is a matter of interest. Oxygen has been shown to cleave double bonds adjacent to phenyl or naphthyl groups in the presence of *N*-hydroxyphthalimide.[3]

From the seminal work of Noyori and co-workers,[4] hydrogen peroxide has been used, combined with tungstates and molybdates in the synthesis of adipic acid.[5−8] Then, several second- and third-row transition metals (in particular, Ru, Os, and W) have shown good performances as catalytically active centers for the cleavage of alkenes, since they undergo oxidation to the related metal-oxo species, which are, in turn, able to perform oxidative cleavage.[5] First-row transition metals, on the contrary, although they often present a lower oxidative-cleavage capability, involve different reaction mechanisms and are particularly suitable to be heterogenized by deposition onto solid supports or by insertion into porous matrices. Nonheme iron complexes, both in homogeneous and heterogeneous phase, have been also used for the cleavage of styrene, β-methylstyrene, and stilbene, leading to benzaldehyde in all cases when the reaction was carried out in acetonitrile,[9] or to benzaldehyde dimethyl acetal when using methanol as a solvent.[10] In the last case, it was proposed that the opening of the epoxide with methanol is the key step for the double bond cleavage. The carboxylic acid was obtained with aqueous TBHP as the oxidant and $FeCl_3$/NaOH as the catalyst.[11] Again, the main oxidation product obtained in the aerobic oxidation of styrene over supported nanocrystalline gold was benzaldehyde, with lower amounts of the desired epoxide.[12] Benzaldehyde and benzoic acid were also important side products in the epoxidation of *trans*-stilbene over catalytically active cobalt-substituted TUD-1 (Co-TUD-1) using molecular oxygen.[13]

Titanium-containing heterogeneous catalysts have been used in the synthesis of adipic acid with *tert*-butylhydroperoxide (TBHP) as the terminal oxidant. The cleavage took place through the formation of the diol and it was necessary to use

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Table 1. Textural Properties and Ti Content of the Pristine Silica Supports and of the Final Grafted Catalysts

support	S_A (m^2 g^{-1})	V_p^{tot} (mL g^{-1})	D_p[a] (nm)	Ti grafted precursor	Ti content[b] (wt %)	UV max[c] (nm)
MCM41	960	0.75	3.7			
Ti-MCM41	930	0.70	3.6	$Ti(Cp)_2Cl_2$	1.70	224
Ti-MCM41[d]	919	0.64	3.4	$Ti(Cp)_2Cl_2$	1.59	220
HMS	920	1.04	4.4			
Ti-HMS	905	0.99	4.3	$Ti(Cp)_2Cl_2$	1.74	247
SBA15	601	1.00	9.2			
Ti-SBA15	514	0.91	9.1	$Ti(Cp)_2Cl_2$	1.80	229
SiO_2 (Merck)	512	0.82	6.3			
Ti-SiO_2	485	0.72	6.0	$Ti(O^iPr)_4$	0.96	285

[a] Pore diameter (determined by Broekhoff and de Boer method). [b] Ti content was determined by ICP-AES. [c] DRS-UV−vis maximum absorption (full DRS-UV−vis spectra are available as Supporting Information). [d] Catalyst after 2 catalytic cycles. The solid underwent calcination in air at 500 °C after each recover.

Ti−Al−SBA15, a bifunctional catalyst with both redox and acid sites, because monofunctional Ti-SBA15 led exclusively to the epoxide.[14] Titanium in an aluminophosphate framework (Ti-AlPO) was able to convert cyclohexene into adipic acid with hydrogen peroxide, thanks to a combination of radical and concerted oxidation mechanism.[15] Previously, TS-1 and TS-2 zeotypes exhibited high activity in the conversion of α-methylstyrene into acetophenone or of styrene into benzaldehyde in the presence of aqueous hydrogen peroxide, by exploiting the oxidizing and Lewis-acid character of Ti(IV) sites.[16,17] Again, Ti, in the form of TiO_2/SiO_2 system, was active in the conversion of styrene into benzaldehyde in the presence of molecular oxygen at 10 bar, via a diol and cleavage reaction pathway.[18]

Single-site heterogeneous catalysts prepared by grafting titanium precursors onto mesoporous silica materials have provided interesting results in the epoxidation of alkenes,[19] because the pore size in the range of mesopores helps to circumvent the steric limitations often found in microporous zeolites and the dispersion of titanium sites can be easily modulated through the careful dosing of the metal precursor during the synthesis. Precursors such as $Ti(O^iPr)_4$ and titanocene derivatives were used to prepare this kind of catalysts, leading to good results in the epoxidation of several alkenes in the presence of TBHP[20−23] or hydrogen peroxide.[24−26] The cleavage of α-methylstyrene to acetophenone has been described in the epoxidation with hydrogen peroxide in acetonitrile catalyzed by Ti-containing zeolites.[27] In this case, it was proposed that the epoxide is opened by hydrogen peroxide to yield a hydroperoxide intermediate that is then transformed into the acetophenone via Grob fragmentation. Consistently with this mechanism, alkyl hydroperoxides were not suitable oxidants for these reactions because they are worse nucleophiles and hardly open epoxides. However, in some cases, non-negligible traces of benzaldehyde have been detected in the epoxidation of styrene with alkyl hydroperoxides under anhydrous conditions,[28−30] indicating that another mechanism must operate. In this manuscript, we explored the behavior of several substituted styrenes and stilbenes with TBHP, in the absence of water or nucleophilic alcohols, using different Ti-silica catalysts obtained by grafting the catalytically active centers onto various mesoporous solids. The use of anhydrous TBHP is important to reduce the undesired hydrolysis of Ti−O−Si bonds and hence to minimize the risk of leaching of the active Ti sites out of the catalysts.[31] It is then shown how the proper choice of the reaction conditions makes these systems capable to act as one-pot multistep catalysts, where the redox and acid character of Ti(IV) sites on silica are expressed at best.

■ RESULTS AND DISCUSSION

Properties of the Grafted Catalysts. Three mesoporous supports (MCM41, HMS, SBA15), with different textural properties (Table 1), were used for grafting of bis-[(cyclopentadienyl)dichlorotitanium(IV)], $Ti(Cp)_2Cl_2$, using the method previously described by Oldroyd et al.[32] In the grafting procedure, however, pyridine was used instead of triethylamine as basic additive. Nonordered amorphous Merck silica was used as support for the grafting of $Ti(O^iPr)_4$.[28]

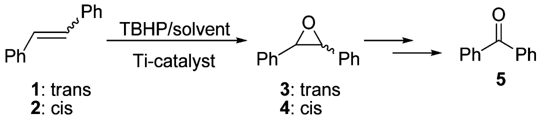
The Ti content for the three ordered mesoporous catalysts is around 1.7−1.8 wt %, whereas for the nonordered Ti-SiO_2 material is 0.96 wt %. Such relevant difference is justified to get a comparable surface dispersion of titanium between Ti-MCM41 and Ti-SiO_2. In fact, taking into account the lower specific surface area of the latter and considering the surface density of Ti sites per square nanometer, one finds 0.22 and 0.24 Ti atoms nm^{-2}, for Ti-MCM41 and Ti-SiO_2, respectively. Actually, the concentration and dispersion of the Ti sites on the surface proved to be a very important parameter in related solids.[24,33] For this reason, the loading of Ti on amorphous silica was tuned in order to approach such value.

The grafting of titanocene on mesostructured silicas led to a decrease in specific surface area, that is more marked for Ti-SBA15 (ca. 15%) and less important for Ti-MCM41 and Ti-HMS (<5%). This behavior is consistent with the data reported in previous studies, as it is due to the deposition of titanium species onto the internal surface of the porous solids, and it also suggests a partial plugging of the microporous fraction of the SBA15 network.[23,34] The evaluation of the X-ray diffraction patterns (see the Supporting Information) of the ordered mesoporous catalysts show that their structure was maintained after the grafting. The use of pyridine instead of triethylamine, as a base to favor the grafting, in fact, minimizes the damages to the mesoporous ordered structure of the material, as the former is less aggressive than the latter against the siliceous walls of the support.

The UV−vis diffuse reflectance spectroscopy (DRS) gives an indication about the degree of dispersion of the Ti(IV) sites on the silica supports. The maxima of absorption profiles of Ti-MCM41 and Ti-SBA15 (Table 1) show that in these solids the active sites are rather evenly dispersed on the silica surface, mainly as isolated centers (Ti maxima < 230 nm). On the other hand, the presence of absorption features above 240 nm has been attributed to an incipient oligomerization of Ti(IV) species into small Ti−O−Ti domains.[35] This is the case of Ti-HMS that shows a broader band with a maximum at 247 nm, assigned to the presence of Ti−O−Ti dimeric species. However, UV studies on model titanium-silsesquioxanes[36] have shown that monomeric Ti species can absorb at longer wavelengths, depending on the coordination sphere of Ti (tetrahedral or octahedral) and the number of bonds to the silica surface (monopodal, bipodal, and tripodal species). In particular, the maximum at 285 nm of Ti-SiO_2 is compatible with octahedral monopodal species. Nevertheless, taking into account the entire DRS UV−vis spectra (see the Supporting Information), the presence of a separate TiO_2 phase (in particular anatase) can be ruled out, as no important absorption bands were recorded in the range 350−400 nm.[37]

Reaction of Stilbenes. In order to test the behavior of these catalysts, we first studied the oxidation of *trans*-stilbene (**1**) with an excess of anhydrous TBHP (6 equiv) in various solvents, keeping the reaction mixture temperature at 75 °C (Scheme 1). Table 2 summarizes the results obtained over four different catalysts. First, acetonitrile was the solvent of choice, as it showed optimal performance in the selective epoxidation of functionalized alkenes with TBHP.[22,23,29,38] In such solvent, the primary product of the reaction observed at short reaction times was the corresponding *trans*-stilbene epoxide (**3**), as expected. This product is due to epoxidation of the C═C double bond catalyzed by titanium(IV) centers in the presence of alkyl hydroperoxides and such behavior is fully consistent with several previous observations.[32,39] In addition, thanks the use of anhydrous TBHP, the reaction proceeded mainly following a heterolytic oxidation pathway and hence with a good selectivity to the desired epoxide. However, at longer reaction times (72 h), the reaction proceeded further and the major observed product was surprisingly benzophenone (**5**). In particular, Ti-SBA15 was less selective as catalyst than Ti-HMS and Ti-MCM41, both for stilbene conversion and selectivity to benzophenone (50 vs 67−68% after 72 h).

Scheme 1. Ti Catalyzed Reaction of Stilbenes with *tert*-Butyl Hydroperoxide



The formation of **5** from **3** requires the migration of a phenyl group in a rearrangement-type reaction, probably catalyzed by acidic centers, and the loss of one carbon atom. The rearrangement of stilbene epoxide, with migration of phenyl groups, has been described over strong Brønsted or Lewis acid centers, such as Nafion or chromium(V) oxoporphyrins.[40,41] Analogously, minor amounts of **5** during the epoxidation of *trans*-stilbene **1** have been detected in several cases over other classes of catalysts.[42−44] Moreover, some decades ago, the noncatalyzed oxidation with O_2 of **1** and thermal rearrangement to **5** was proposed as a potential process for the production of benzophenone from stilbene,[45] even though it cannot be considered commercially and environmentally sustainable according to today's standards.

In terms of activity for *trans*-stilbene conversion, expressed as turnover number after 24 h of reaction, Ti-HMS, Ti-MCM41 and Ti-SiO_2 showed good results, especially in acetonitrile (Table 2). Nevertheless, aiming at enhancing and maximizing the multistep formation of benzophenone, the selectivity to the desired final product has to be taken into account, and other solvents were tested. It is indeed well-known that the solvent plays an important and sometimes decisive role in the behavior of catalysts.[46] Solvent effects have been studied in several oxidation reactions, including the epoxidation of styrene.[47−51]

Over Ti-HMS, three aprotic solvents, to prevent the possibility of epoxide ring opening, with different polar character were also tested, namely ethyl acetate, 1,2-dichloroethane and toluene (the reaction mixture was kept at 75 °C for all solvents). Stilbene (**1**) conversions depend on the nature of the solvent and the lowest values were reached in toluene. The need of polar aprotic solvents as ideal reaction media for the epoxidation of alkenes in the presence of TBHP over mesoporous titanosilicates is widely accepted and it has been confirmed by several experimental evidence.[52] So, the poor performance of toluene (the solvent with the lowest E_T^N value,[53] Table 2) in terms of conversion was not unexpected and, in fact, the conversion after 24 h correlates very well with the polarity of the solvent (Figure 1) in reactions catalyzed by Ti-

Table 2. Results Obtained from the Oxidation of *trans*-Stilbene (1) with TBHP[a]

			% conv (% select)[b]		TON[c]	productivity[d]
catalyst	solvent	E_T^N	24 h	72 h	24 h	72 h
Ti-SBA15	CH_3CN	0.460	70 (18)	89 (50)	18	11.6
Ti-HMS	CH_3CN	0.460	87 (40)	99 (67)	23	17.9
	AcOEt	0.228	62 (20)	98 (46)	17	12.2
	$PhCH_3$	0.099	54 (9)	58 (86)	15	13.5
	$ClCH_2CH_2Cl$	0.327	74 (55)	88 (94)	20	22.3
Ti-MCM41	CH_3CN	0.460	85 (37)	98 (68)	23	18.4
	AcOEt	0.228	55 (22)	99 (46)	15	12.6
	$ClCH_2CH_2Cl$	0.327	79 (58)	92 (97)	22	24.6
	$PhCF_3$	0.241	86 (63)	93 (96)	24	24.6
Ti-SiO_2[e]	CH_3CN	0.460	76 (35)	77 (45)	21	9.6
	AcOEt	0.228	15 (13)	nd	4	nd
	$PhCF_3$	0.241	46 (94)	52 (94)	13	13.5

[a]Reaction conditions: 0.49 mmol stilbene, 50 mg catalyst, 6 equiv TBHP, 75 °C. [b]Conversion of stilbene and selectivity (in parentheses) to benzophenone (**5**), determined by GC. [c]Turnover number (mol converted stilbene mol^{-1} total Ti in the catalyst) after 24 h reaction. [d]mol of benzophenone (**5**) produced mol^{-1} total Ti in the catalyst. [e]88.7 mg of catalysts were used.

HMS and Ti-MCM41, that arguably show the most similar sites, as shown by DRS-UV.

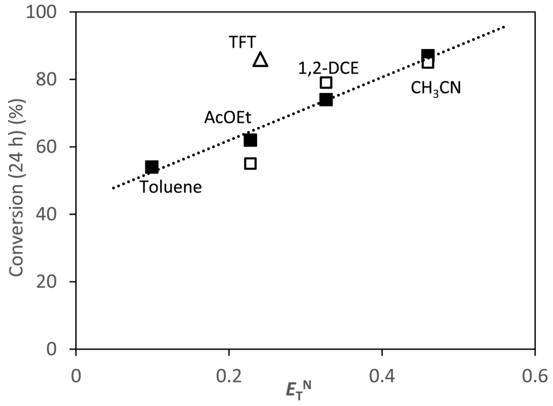


Figure 1. Correlation between the stilbene conversion after 24 h (data from Table 2) catalyzed by Ti-HMS (■, $r = 0.9924$) and Ti-MCM41 (open symbols, $r = 0.9463$ with the seven square points) and the polarity of the solvent (E_T^N parameter).

Selectivity to benzophenone (**5**) was strongly affected too by the nature of the solvent and it decreased in the order 1,2-dichloroethane (94%) > toluene (86%) > acetonitrile (67%) > ethyl acetate (46%). In previous works, it was shown that there exists a close relationship between acidity of the titanium catalytic center and both epoxidation (with H_2O_2 or TBHP) and epoxide opening activity,[23,54,55] and this effect depends on the structure of the catalytic sites. Indeed, solvents with high coordinating ability likely reduce the acidity of the catalytic centers lowering catalytic activity and, in particular, the acid-promoted rearrangement, first step in the formation of benzophenone. Differences in Gutmann donor number (D_N) values[56,57] support this hypothesis and qualitatively agree with the selectivity order: 1,2- dichloroethane (0.0) < toluene (0.1) < acetonitrile (14.1) < ethyl acetate (17.1). The order of global activity for the transformation of **1** into **5** can be therefore seen as the balance between the two main features of the solvent: a marked polar aprotic character, that is optimal for the stilbene epoxidation step, and a limited coordinating ability, that is good to enhance the acid-promoted rearrangement at the Ti(IV) site. The good performance of 1,2-dichloroethane was also demonstrated in the case of Ti-MCM41 (Table 2), with also slightly better conversion and selectivity than Ti-HMS. In this case, the same considerations about the influence of the solvents are valid, as above.

In principle, a solvent with aprotic polar character, but with no coordinating ability and even lower polarizability than 1,2-dichloroethane should enhance further the activity and selectivity to benzophenone. *α,α,α*-Trifluorotoluene possesses solvent properties that are comparable to those of dichloromethane, but with a remarkably lower volatility and a reduced toxicity. Thanks to the presence of fluorine atoms, $PhCF_3$ shows an intermediate polarity between ethyl acetate and 1,2-dichloroethane ($E_T^N = 0.241$, Table 2)[58] does not undergo oxidation at the benzylic positions and the highly electron-withdrawing character of the trifluoromethyl group prevents any electrophilic attack on the aromatic ring. Such relatively uncommon reaction medium is attracting a growing interest as a less hazardous alternative to chlorinated organic solvents for reactions where the Lewis character of the catalyst has to be enhanced.[59] Confirming this hypothesis, *α,α,α*-trifluorotoluene proved to be the best solvent to promote the cleavage of the double bond (Table 2). However, the correlation between conversion and E_T^N is not so good with this solvent (Figure 1), as the yield obtained was higher than expected, in agreement with an influence of other solvation mechanisms. In fact, the use of mixtures of this solvent with toluene was highly detrimental, and only a 10% of toluene was enough to reduce significantly both conversion and selectivity. Moreover, taking into account the higher boiling point of $PhCF_3$, it was possible to run the reaction at higher reflux temperature (102 °C) and this led to improved benzophenone yields, nearly to quantitative in only 24 h (Table 3).

Table 3. Results Obtained from the Oxidation of *trans*-Stilbene (1) over Ti-MCM41 in Fluorinated Solvents[a]

solvent	*T* (°C)	*t* (h)	% conversion[b]	% selectivity[c]
$PhCF_3$	60	1	7	0
		24	46	4[d]
		120	46	72
	80	24	86	63
		72	93	96
	102	1	82	29[d]
		24	98	97
$PhCH_3$	110	1	40	0[d]
		24	48	71
3F03F[e]	110	1	9	11
		24	41	90
		48	60	93
3F13F[e]	110	1	46	9[d]
		24	96	92
		48	99	99

[a]Reaction conditions: 0.49 mmol of stilbene, 50 mg Ti-MCM41, 6 equiv TBHP. [b]Determined by GC. [c]Selectivity to benzophenone (**5**). [d]Aldehyde was the main product. [e]See ref 60.

Following such strategy, other fluorinated solvents were then tested, namely two ethers of glycerol with 2,2,2-trifluoroethyl chains (Figure 2), labeled as 3F03F and 3F13F[60] (Table 3).

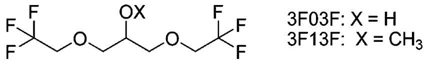


Figure 2. Glycerol-derived fluorinated solvents.

However, only 3F13F was able to provide high benzophenone yields at temperatures over 110 °C. Both solvents, *α,α,α*-trifluorotoluene and 3F13F, are polar enough (E_T^N values: $PhCF_3 = 0.24$, 3F13F = 0.55) to allow dissolution of reagents and to carry out the epoxidation step, but their low basicity and polarizability, due to the presence of fluorinated chains, make them poor solvating agents for the Ti(IV) acid sites. This does not hinder the effective acidity of the catalysts. On the other hand, the protic character of 3F03F reduced the epoxidation yield, perhaps also because of the possible oxidation of the solvent. Nevertheless, the selectivity to benzophenone was also high, showing that acidity is not reduced. In spite of the excellent results reached with the glycerol-derived 3F13F, the commercial and more easily available $PhCF_3$ was used to explore the behavior of other alkenes.

By comparing the performance of the catalysts obtained from four supports with different textural properties (Tables 1 and 2), it appears that the best results in terms of productivity to **5**

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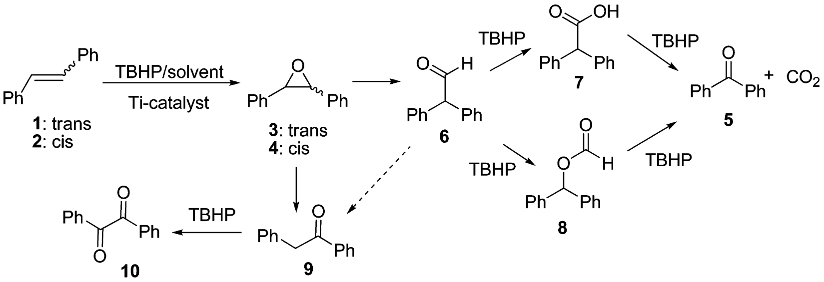
Scheme 2. Mechanism of the Tandem Multistep Reactions over Stilbenes[a]



[a]The dashed arrow indicates a pathway not described previously.

per Ti site were attained on Ti-MCM41 and Ti-HMS, which are solids derived from high-surface area ordered mesoporous silica materials. Indeed, stilbene molecules can freely enter and be accommodated within the mesopore network of molecular sieves whose pores are wider than 3 nm,[32] so the mean pore diameter was not a major limiting factor in defining catalyst reactivity. Conversely, the higher the specific surface area of the support, the more dispersed the Ti(IV) sites are on the silica materials. A better site isolation leads to a more marked acid character of the Ti(IV) centers and hence a better activity in acid-catalyzed rearrangement reactions.[23,54] In addition, a higher dispersion of Ti(IV) sites on the silica surface renders the catalyst less prone to deactivation. In fact, single-site Ti-silica catalysts usually lose their activity due to the gradual agglomeration of isolated Ti(IV) centers into larger TiO_2-like domains, able to homolytically decompose the oxidant and also with lower Lewis acidity.[61] Therefore, the higher the dispersion of Ti centers in the catalyst, the less the catalyst suffers from deactivation during the reaction, although this is controlled also by the role of the solvent, as can be seen by the results with Ti-SiO_2. At short reaction time, stilbene conversion is higher in acetonitrile, better solvent for epoxidation, whereas the selectivity to benzophenone is much better in trifluorotoluene, as the Lewis acidity is boosted in this solvent. However, in both cases the catalyst is deactivated and the reactions stop and do not proceed further after 24 h, in contrast with the results obtained with the crystalline mesoporous solids. For these reasons, the order of productivity to the desired product **5** for the four solids can be depicted as follows: Ti-MCM41 ≈ Ti-HMS > Ti-SBA15 > Ti-SiO_2 (that is a nonordered amorphous mesoporous solid).

Exploiting the promising reaction conditions over Ti-MCM41, at 102 °C in $PhCF_3$, an overall isolated yield of 82% to benzophenone (**5**) could be obtained starting from a larger amount (2.0 mmol) of *trans*-stilbene, via a one-pot, multistep transformation.

Analogously, a series of tests were run on *cis*-stilbene (**2**) (Scheme 1), in order to investigate the potential influence of *cis*−*trans* configuration of the substrate on the reaction performance. Nevertheless, no remarkable differences were detected with respect to the behavior already observed for *trans*-stilbene (**1**), in terms of activity and selectivity. Under optimized conditions, *cis*-stilbene yielded a 96% of benzophenone with a complete conversion of the alkene after 24 h. This is a non-negligible result, since *cis*-stilbene epoxide is typically far less reactive than *trans*-stilbene epoxide in epoxide ring opening reactions promoted by homogeneous or heterogeneous acid sites.[62] In this case, on the contrary, either *cis*- or *trans*-isomers gave rise to the same product in a similar way.

Finally, a study has been performed on the Ti-MCM41 catalyst to investigate the catalyst recyclability. The solid can be recovered and reused in new catalytic runs, but a careful filtration, washing with methanol and calcination under air at 500 °C was necessary to recover the pristine activity and remove the organic deposits on the catalyst surface (2.8 wt %, according to TGA measurements of weight loss between 100 and 800 °C, compared to the one of fresh Ti-MCM41). After this treatment, the initial catalytic activity was recovered in large part, as the conversion after 24 h is 83%, in $PhCF_3$. Conversely, without such intermediate treatment, the conversion after 24 h was 6% only and calcination at 300 °C (as in the activation of the fresh catalyst) improves conversion only up to 26% after 24 h. A thorough removal by calcination of the organic deposits that gradually foul the catalyst surface is thus necessary. The textural properties (Table 1) of the catalyst after two cycles shows that a small loss of specific pore volume took place due to a minor loss of mesostructure order, but no relevant damage or collapse of the mesoporous network was observed. In terms of spectroscopic characterization, even though the absorption maximum did not changed its position (Table 1), a gradual agglomeration of the isolated Ti(IV) sites into larger TiO_2-like domains occurred and was revealed by the increase of absorption shoulders around 350−400 nm (see Supporting Information). These factors may account for the slight loss in performance observed after two catalytic cycles and they are consistent with the previous observations by some of us in recycled Ti-containing silica epoxidation catalysts when TBHP or H_2O_2 were used as an oxidant.[23,26]

Reaction Mechanism. Diphenylacetaldehyde (**6**) and benzophenone (**5**) were the main products in all the cases. Scheme 2 shows the mechanism going from epoxide to benzophenone. This mechanism includes an acid-promoted rearrangement of the epoxide (**3**) to diphenylacetaldehyde (**6**). From this aldehyde, benzophenone can be obtained after loss of one carbon atom by decarbonylation, either through the oxidation to diphenylacetic acid (**7**) and subsequent decarboxylation, or through the formation of diphenylmethyl formate (**8**), result of a Baeyer−Villiger oxidation. The evolution of CO_2 in the final step was experimentally observed and measured quantitatively.[63]

Further information about the reaction mechanism can be obtained from the evolution of the reaction with time (Figure 3). In an attempt to slow down the reaction to better observe the evolution at short reaction time, the experiments were conducted with a lower amount of catalyst (35 mg). Under these conditions and in trifluorotoluene, the epoxide (**3**) was barely detected along the reaction, indicating that epoxidation step is slower than the subsequent rearrangement. At the same

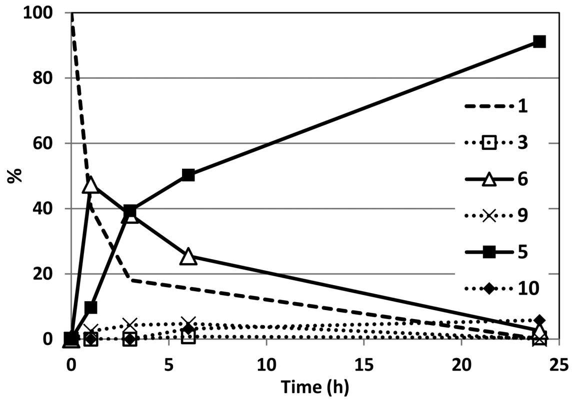


Figure 3. Reaction of *trans*-stilbene (**1**) with TBHP (6 equiv) catalyzed by Ti-MCM41 (35 mg), in PhCF$_3$ at 102 °C. The numbers correspond to the different reaction products (see Scheme 2).

time, as aldehyde **6** was the major product at short reaction times, the subsequent oxidation steps were not faster than rearrangement, but not much slower either considering that the production of benzophenone (**5**) was remarkable, even at relatively low stilbene conversions.

Then, we tested the influence of the support by using Ti-SiO$_2$ and Ti-SBA15 prepared following the same grafting procedure (Table 2 and Figure 4). The main differences with Ti-MCM41 are related to catalyst deactivation. Ti-SiO$_2$ was fairly active in the first hours of reaction, but then it suffered from a faster deactivation, as the reaction did not proceed further after 5−6 h. Conversely, on Ti-SBA15 the alkene conversion remained constant after 10 h. The catalyst was then only active for the subsequent oxidation steps, indicating that these steps take place through a different mechanism, and then it underwent deactivation only after 24 h. It is difficult to propose an explanation for differences in catalyst deactivation, given that, in this case, the reaction steps are influenced by a large number of factors, whose fine counterbalance addresses the global reaction trend toward the final desired product. Those factors are very difficult to evaluate, even in much simpler reaction systems, as the single epoxidation of alkenes, in which the structure of the support material has shown little[64] or very high influence,[65] depending on the substrate and the reaction conditions. Nonetheless, the catalyst stability increases with the surface area and, consequently, with the dispersion of the Ti-sites.

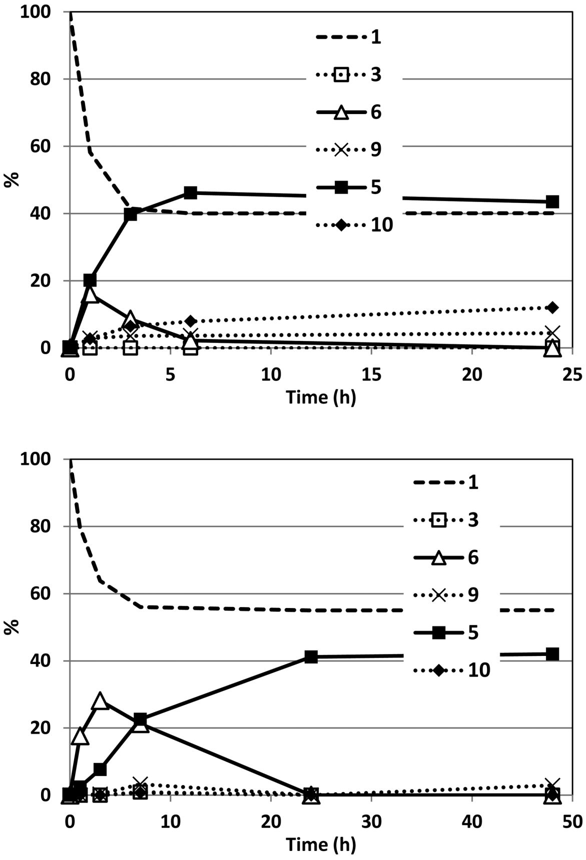


Figure 4. Reaction of *trans*-stilbene (**1**) with TBHP (6 equiv) catalyzed by 35 mg of Ti-SiO$_2$ (top) and Ti-SBA15 (bottom), in PhCF$_3$ at 102 °C. The numbers correspond to the different reaction products (see Scheme 2).

The evolution of the intermediates parallels the one observed in Ti-MCM41, with the epoxide that is hardly detectable. However, at short reaction times, Ti-SiO$_2$ led to a higher proportion of benzophenone (**5**). From DRS-UV−vis, this catalyst contains either a lower amount of isolated Ti-sites or a higher proportion of monopodal species; as in any of the two cases the sites should be less acidic than isolated bipodal or tripodal ones,[66] rearrangement to aldehyde (**6**) is comparatively slower and the amount of aldehyde present in the reaction medium is lower as it is more efficiently oxidized. As the nature of the support did not affect the final selectivity, these tests confirmed that Ti(IV) is the site where not only the oxidation step but also the rearrangement occurs, and hence, they behave as multifunctional sites.

Trying to confirm the hypotheses depicted in Scheme 2 by identifying some of the intermediates, the reaction was carried out using the exact stoichiometric amount of oxidant needed in the reaction from **1** to **5**, namely 3:1 TBHP/stilbene molar ratio. The most striking result was the detection of a rather high amount of benzil (**10**) (around 18 mol %) at the end of the reaction (Figure 5). This product might come from the oxidation of phenyl acetophenone (**9**), so the less favored rearrangement is more important in the presence of a lower amount of oxidant. In view of this, the epoxide (**3**) was made to rearrange in the absence of oxidant (Figure 6). As it can be seen, the amount of ketone (**9**) was very small and it did not

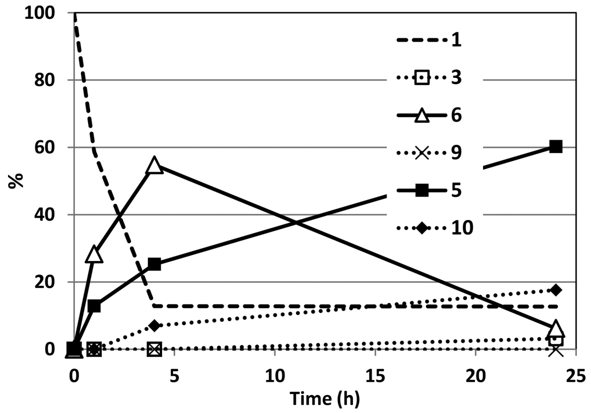


Figure 5. Reaction of *trans*-stilbene (**1**) with TBHP (3 equiv) catalyzed by Ti-MCM41 (35 mg), in PhCF$_3$ at 102 °C. The numbers correspond to the different reaction products (see Scheme 2).

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justify the formation of 18 mol % of benzil, which should be explained by an alternative mechanism.

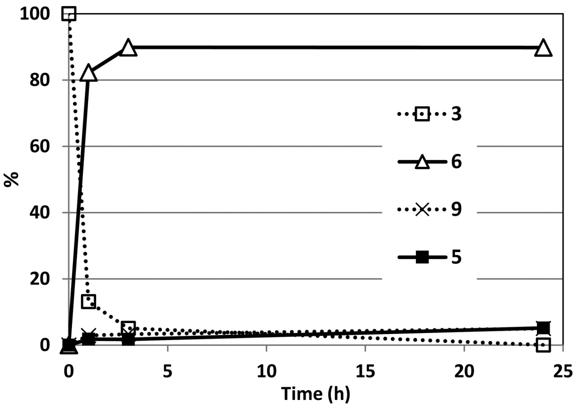


Figure 6. Rearrangement of *trans*-stilbene oxide (3) catalyzed by Ti-MCM41 (35 mg), in $PhCF_3$ at 102 °C (in the absence of oxidant). The numbers correspond to the different reaction products (see Scheme 2).

In order to shed light on this route, the oxidation of the aldehyde **6** was performed with a substoichiometric amount of TBHP (2 equiv) (Figure 7). More than 40 mol % of benzil (**10**) was thus obtained, indicating than the precursor ketone (**9**) is produced by migration of a phenyl group onto the coordinated aldehyde through a unexpected reaction pathway (dashed arrow from **6** to **9** in Scheme 2) and that, in the presence of a low amount of oxidant, this reaction efficiently competes with the oxidation pathway.

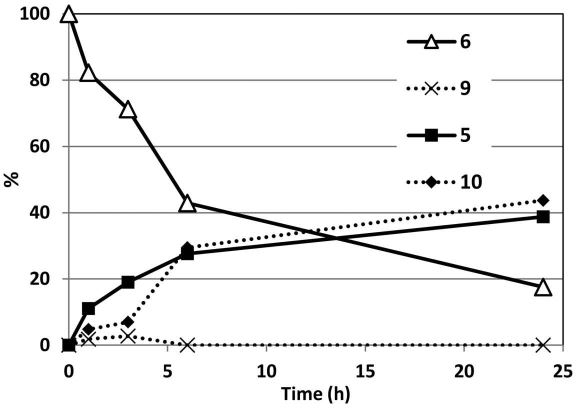


Figure 7. Reaction of diphenylacetaldehyde (6) with TBHP (2 equiv) catalyzed by Ti-MCM41 (35 mg), in $PhCF_3$ at 102 °C. The numbers correspond to the different reaction products (see Scheme 2).

The rearrangement of epoxides to carbonyl compounds (Meinwald rearrangement) is a reaction promoted by Brønsted and Lewis acids. Several aspects of this reaction, including its mechanism, have been recently studied.[67,68] Starting from stilbene oxide, the reaction leads to diphenylacetaldehyde (**6**) as the kinetically favored product through the migration of a phenyl group from the intermediate zwitterion. No traces of deoxybenzoin (**9**) are detected, because of the higher activation energy of the hydrogen migration.[68] Our results agree with the kinetic preference of the aldehyde. However, they show the reversibility of this rearrangement, leading to the ketone from the aldehyde under suitable conditions, a possibility disregarded in most of mechanistic studies of this reaction.

The direct breakdown of diphenylacetaldehyde to benzophenone has been recently described with iodosylbenzene combined with HBF_4 or BF_3,[69] but the proposed mechanism through a five-membered cyclic intermediate including the hypervalent iodine, does not seem to be compatible with our system. As shown in Scheme 2, benzophenone (**5**) could be obtained by two alternative routes: through diphenylacetic acid (**7**) or benzhydryl formate (**8**) as intermediates. The broad peak attributed to **7** was always detected in the intermediate samples of the reaction medium (even though gas-chromatography is not the optimal technique to reveal it). Conversely, the sharp peak of **8** has never been detected. In order to get additional information on this point, both **7** and **8** were used as starting reactants under the typical reaction conditions in the presence of TBHP and both compounds led to the formation of benzophenone **5**, the formate **8** being far less reactive and prone to rearrangement than the acid **7**. So, both pathways are, in principle, possible (via oxidation and decarboxylation or via Baeyer–Villiger and oxidative decarboxylation), but the route via **7** is more likely, since the formate **8** has never been detected as an intermediate compound in the reaction mixture (although it is poorly reactive). Finally, the mechanism leading from **7** to **5** is not fully clear, but it is probable that an oxidative decarboxylation of the carboxylic acid occurs in the presence of a Lewis acid (here Ti(IV)), comparable to the Ruff–Fenton oxidative degradation of aldonic acids with H_2O_2,[70] usually carried out with Cu or Fe catalysts in solution, although one case with Ti-zeolites has been also described.[71]

Several additional tests were performed in order to ascertain the role of Ti(IV) centers in the reaction. First, titanium(IV) isopropoxide, $Ti(O^iPr)_4$, (a common Ti precursor for enantioselective epoxidation reactions in solution) was used as a homogeneous catalyst in the presence of *trans*-stilbene and tested in α,α,α-trifluorotoluene, acetonitrile, and toluene. No detectable reactant conversion was recorded both in the presence and in the absence of 3A drying molecular sieves, as, in principle, $Ti(O^iPr)_4$ might be degraded or deactivated by traces of moisture in the reaction mixture.

In the same way, the Ti-free siliceous MCM41 support was unable to epoxidize *trans*-stilbene. An average stilbene conversion of 10% was obtained, but with a negligible formation of stilbene epoxide (**3**) and no detectable formation of benzophenone (**5**). On the contrary, its intrinsic very weak Lewis acidity conferred some activity in the epoxide rearrangement (5% conversion to aldehyde **6** from epoxide **3** after 1 h) in the absence of oxidant, although much lower than the one recorded over Ti-MCM41 under the same conditions (89% conversion after 1 h). These results show the very low activity of the support in both reactions and confirm the multifunctional role of Ti sites.

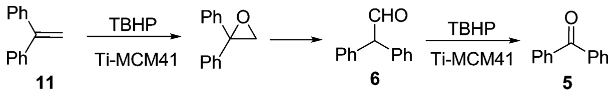
Finally, the heterogeneous nature of the catalysts in this multistep transformation was confirmed by a series of tests, in which the solid catalysts were thoroughly removed from the hot liquid mixture by high-speed centrifugation. These tests proved that no leaching of homogeneous and catalytically active titanium species took place under the reaction conditions tested (see the Supporting Information).

Thus, the observed reactivity is attributed to the peculiar chemical environment of evenly dispersed Ti(IV) sites deposited onto a silica matrix rather than to the presence of

Ti(IV) itself in the reaction mixture and the contribution of the purely siliceous supports to reactivity is negligible.

Reaction with Other Substituted Styrenes. In the case of α-phenylstyrene (**11**), the higher stability of the carbocation makes easier the rearrangement to the aldehyde through hydrogen migration. Under the same conditions, 100% yield of benzophenone was again obtained in 24 h (Scheme 3).

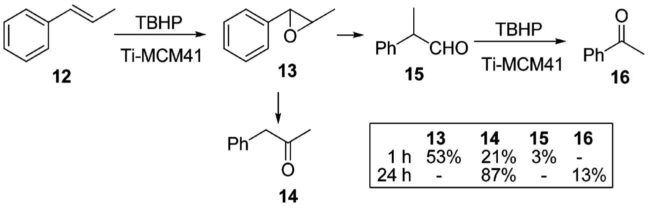
Scheme 3. Ti-Catalyzed Reaction of α-Phenylstyrene with *tert*-Butyl Hydroperoxide



	6	5
yields at 6h	80	0
yields at 24h	0	100

We have also explored the oxidation of *trans*-*β*-methylstyrene (**12**) (Scheme 4) and, from it, phenylacetone (**14**) was obtained as the major product, indicating that migration of hydrogen is favored over methyl migration from the intermediate epoxide (**13**). 2-Phenylpropanal (**15**) and the final decarboxylated product, acetophenone (**16**), were also detected in minor amounts, as side products.

Scheme 4. Ti-Catalyzed Reaction of *trans*-*β*-Methylstyrene with *tert*-Butyl Hydroperoxide

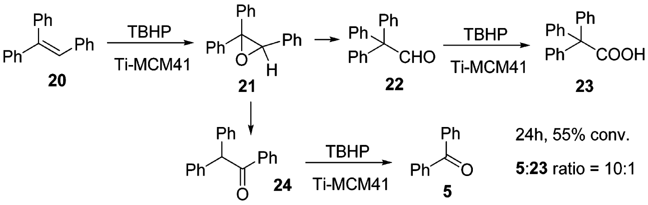


	13	14	15	16
1 h	53%	21%	3%	-
24 h	-	87%	-	13%

Starting from α-methylstyrene (**17**) the reaction was slower, although total conversion was reached at the end of the test. Acetophenone (**16**), with one carbon atom less than the starting reactant, was the major product with 72% selectivity, and 2-phenylpropionic acid (**19**) accounted for the rest of 28% selectivity (Scheme 5).

Lastly, starting from triphenylethylene (**20**) the reaction proceeded with a slower rate too, probably because of steric hindrance. It should be noted that hydrogen migration is indeed favored and, after 24 h, a 55% conversion was reached with a benzophenone (**5**) to triphenylacetic acid (**23**) ratio of 10:1 (Scheme 6). It is worth highlighting that the result of this reaction is similar to an ozonolysis, as in the case of α-methylstyrene. However, following the present experimental protocol, C=C bond cleavage can be obtained under far milder and simpler conditions.

Scheme 6. Ti-Catalyzed Reaction of Triphenylethylene with *tert*-Butyl Hydroperoxide



CONCLUSIONS

Titanium sites on Ti(IV)-silica catalysts, prepared by grafting technique, may act as multifunctional catalytic centers, with both oxidant and acid characteristics. In the present case, titanium centers on the mesoporous silica support were, at the same time, efficient oxidation sites that activate *tert*-butyl hydroperoxide and good Lewis acids that trigger epoxide rearrangement (Meinwald reaction). In this way, the catalyst promotes a tandem one-pot, four-step sequence of reactions, namely alkene epoxidation, epoxide rearrangement, oxidation of the obtained aldehyde, and finally oxidative decarboxylation of the carboxylic acid. This behavior can be optimized by the use of a suitable solvent with polar aprotic character, under anhydrous conditions, to favor the oxidation reactions, and with a poor coordinating ability, to prevent any deactivation of the Lewis acid character of the Ti(IV) sites. Moreover, high temperatures above 100 °C are an additional requirement to run the tandem reaction efficiently in reasonable times.

The number of solvents that fulfill all those requirements is limited, and fluorinated aprotic solvents are a good choice in this regard. In particular, *α,α,α*-trifluorotoluene has been selected as the optimal solvent in this work to perform the tandem oxidation−rearrangement sequence on stilbenes (*cis* and *trans*), substituted styrenes (α-phenylstyrene, *trans*-*β*-methylstyrene, α-methylstyrene), and triphenylethylene. Such solvent is easily commercially available and is being considered as a more sustainable and less hazardous alternative to chlorinated solvents.

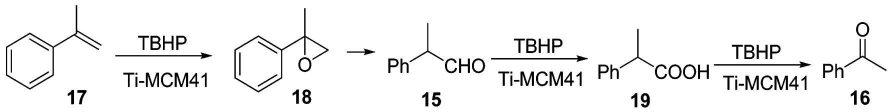
In the best case, *trans*- or *cis*-stilbene was completely (conversions >98%) and selectively (selectivity >96%) transformed into benzophenone in 24 h, as the unique product. Furthermore, in the cases of α-phenylstyrene, α-methylstyrene, and triphenylethylene, the result is the same as that of an ozonolysis, but under far safer and milder conditions.

EXPERIMENTAL DETAILS

Materials. Reagents were purchased from Sigma-Aldrich and used as received without further purification. The solvents were thoroughly dried over activated drying 3A molecular sieves (Sigma-Aldrich). Anhydrous *tert*-butylhydroperoxide (TBHP; Aldrich, 5.5 M solution in decane) was used as oxidant.

Ti-MCM41, Ti-HMS, and Ti-SBA15 were prepared by grafting $Ti(Cp)_2Cl_2$ on the corresponding support following the method reported in the literature.[32] $Ti\text{-}SiO_2$ was prepared by grafting $Ti(OiPr)_4$ on Merck silica following a described procedure.[28]

Scheme 5. Ti-Catalyzed Reaction of α-Methylstyrene with *tert*-Butyl Hydroperoxide



Catalyst Characterization. Titanium content of the prepared catalysts was determined by inductively coupled plasma-optical emission spectroscopy on a ICAP 6300 Duo (Thermo Fisher Scientific) instrument after mineralization of the samples with a mixture of hydrofluoric (aq 40%) and fuming nitric acid.

Thermogravimetric analysis (TGA) was performed on a high-temperature thermal balance (PerkinElmer; 7HT−Pyris Manager) in the temperature range between 50 and 1000 °C, under dry air with a temperature rate of 5 °C min^{-1}.

The textural characterization of the mesoporous materials was performed on a Micromeritics ASAP 2010 instrument. The calcined samples were outgassed at 250 °C, until a stable static vacuum of 3×10^{-3} Torr was reached. Mesopore diameters were calculated from the desorption branch of the nitrogen isotherms by the Broekhoff and de Boer (BdB) method.

Catalytic Tests. The solid catalysts (50.0 mg or 35 mg in the case of the studies of products evolution with time) were pretreated prior to use in the catalytic reactions. Ti-MCM41, Ti-HMS, and Ti-SBA15 were activated under argon flow, raising the temperature from room temperature to 300 °C at a rate of 10 °C min^{-1}, 1 h at 300 °C, and then cooling under vacuum. In the case of Ti-SiO_2, the catalyst was activated at 140 °C under vacuum for 12 h.

The pretreated catalyst was added to a solution of alkene (0.488 mmol) and mesitylene (0.323 mmol, 45 μL, as internal standard) in 10 mL of dry solvent. The suspension was stirred for 3 min and the zero-point sample was withdrawn. After that, *tert*-butyl hydroperoxide (2.93 mmol, 532 μL) was added and the reaction was stirred at the required temperature. The reaction was monitored by GC (FID detector), using a cross-linked methyl silicone column (HP1; 30 m × 0.25 mm × 0.35 μm), oven temperature program: 80 °C (0 min), 20 °C min^{-1} to 180 °C (0 min), and 5 °C min^{-1} to 250 °C (2 min). Products were identified by GC-MS and in some cases by comparison with commercial samples. In order to determine the isolated yield of benzophenone, 2.0 mmol of *trans*-stilbene were reacted over 200 mg of Ti-MCM41 catalyst, in *α,α,α*-trifluorotoluene, at solvent reflux, for 24 h, with 6.0 mmol of TBHP, in the absence of the internal standard. The solvent was removed from the raw reaction mixture at the rotary evaporator, whereas *tert*-butanol and the traces of unreacted TBHP were eliminated by conventional liquid chromatography on a short silica-gel column.

The solid catalysts were recovered and reused in two new catalytic cycles. After each recovery, the materials were carefully filtered, washed with fresh methanol and calcined under air flow at 300 or 500 °C. Then, they underwent a new catalytic run as described above.

In order to check the leaching of catalytically active titanium species, in a series of tests, after 1 h of reaction (at ca. 50% of substrate conversion), the solid catalysts were removed from the hot liquid mixture by high-speed centrifugation and the resulting solutions were tested for further reaction (see also the Supporting Information).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/cs501671a.

Description of the heterogeneity tests and characterization data (XRD patterns and DRS-UV−vis spectra) of supports and catalysts (PDF)

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Notes

The authors declare no competing financial interest.

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(53) Solvent polarity is a commonly used term that refers to the ability of a solvent for solvating charged or dipolar species. This concept involves several properties of the solvent, such as dipolar moment, but also specific molecular interactions, such as hydrogen bonds. $E_{\mathrm{T}}^{\mathrm{N}}$ is the normalized form of $E_{\mathrm{T}}(30)$, a solvent polarity parameter, proposed by Dimroth and Reichardt, based on the solvatochromic shift of a betaine dye in solution (Reichardt, C. *Solvents and Solvent Effects in Organic Chemistry*; VCH: Weinheim, 1988). From IUPAC, this parameter reflects the ionizing power of the solvent, that is the tendency of a particular solvent to promote ionization of an uncharged or, less often, charged solute. In fact, for protic (hydrogen bond donor, HBD) solvents the value of $E_{\mathrm{T}}^{\mathrm{N}}$ increases because this parameter reflects a mixture of polarity and HBD character of the solvent.

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