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Synthesis of Fibrous Nano-silica-supported TEMPO and Its Application in Selective Oxidation of Alcohols

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A fibrous nanosized catalyst with TEMPO supported on silica nanospheres was synthesized and used in the selective oxidation of alcohols into the corresponding aldehydes or ketones. The fibrous morphologies of the catalyst allowed easy accessibility between the substrate and the catalyst, and thus, improved reaction efficiency was obtained. A pseudo-homogeneous system was formed during the reaction process, with easy recovery of the catalyst through filtration.

Selective oxidation of primary and secondary alcohols into the corresponding aldehydes or ketones is undoubtedly one of the most important and challenging transformations in organic chemistry.[1] Many oxidation reagents such as Ru-, Se-, Cr-, and Mn-based oxides[2] and hypervalent iodine[3] have been traditionally used to accomplish this transformation. These oxidants, however, tend to be expensive and generate large amounts of toxic heavy metal waste, which inhibit their application. Recently, utilization of the stable nitroxyl radical 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) for the oxidation of alcohols, employing a cooxidant such as NaOCl,[4] trichloroisocyanuric acid,[5] *m*-chloroperbenzoic acid,[6] oxone,[7] or a hypervalent iodine compound[8] appears very appealing in view of catalytic efficiency and green chemistry concerns. Irrespective of the cooxidant is used, however, product isolation and TEMPO recovery remain key issues.

To address these problems, several supported TEMPO catalytic systems have been developed, including silica-supported TEMPO,[9] MCM-41-supported TEMPO,[10] sol–gel-entrapped TEMPO,[11] and polyamine-immobilized piperidinyloxyl (PIPO),[12] poly(vinyl alcohol)-*graft*-poly(ethylene glycol) resin-supported TEMPO,[13] to afford heterogeneous catalysts, are readily separated from the reaction mixtures but are usually far less versatile than the homogeneous TEMPO. Immobilization of TEMPO onto ionic liquids to realize a homogeneous process has also been reported. However, the disadvantages are also obvious, including the complexity of preparation and storage, difficulty in separation, and loss of activity during recycles.

The past decade has seen significant advances in the fabrication of new porous solids with ordered structures from a wide range of different materials, with silica being the most common one. In particular, Polshettiwar reported a silica nanosphere with fibrous morphologies, KCC-1, with the high surface area attributed to the fibers but not to the pores, which dramatically increases its accessibility.[14] The unique property should be useful in the design of silica-supported catalyst, but only limited research has been carried out in this area.[15]

Herein, in this paper, a nanosized catalyst with TEMPO supported on silica nanospheres was synthesized, KCC-1/TEMPO. The nanosized catalyst with a fibrous morphology offered a large surface area and was proved to be effective in the selective oxidation of various alcohols into their corresponding carbonyl compounds. Thanks to the combination of TEMPO and the fibrous silica nanospheres, a pseudo-homogeneous system was formed during the reaction process, and both improved reaction efficiency and simple separation of the catalyst were achieved.

The nanosize and large surface area of KCC-1 make it an excellent choice for TEMPO grafting. As opposed to normal nanoparticles with pores to maintain the large surface area, the fibrous KCC-1 ensured that TEMPO was grafted on the external surface, which could dramatically increase the accessibility between the substrate and the catalyst. The nanosized catalyst provided a pseudo-homogeneous system rather than a heterogeneous one, which also greatly facilitated the reaction process. The first step in synthesizing this catalyst was to functionalize KCC-1 with amino groups, which was achieved with 3-aminopropyltriethoxysilane to generate amino-functionalized KCC-1, denoted as KCC-1-NH_2. Then, the obtained aminopropyl-functionalized nanoparticles were subjected to reductive amination with 1-hydroxy-4-oxo-2,2,6,6,-tetramethylpiperidine in the presence of $NaBH_3CN$ to prepare the corresponding KCC-1-supported TEMPO (KCC-1/TEMPO).

The IR spectrum (Figure S1)[16] of KCC-1-NH_2 showed detectable changes that were characteristic of the –NH_2 group, between 3000 and 3500 cm^{-1}, C–H stretching vibrations in APTS around 1500 cm^{-1}, which clearly differed from that of the bare KCC-1 nanoparticles. Some characteristic peaks due to TEMPO at around 1300 cm^{-1} were also exhibited when comparing the IR spectrum of the 4-hydroxy-2,2,6,6-tetramethylpiperdine-1-oxyl raw material (4-oxo-TEMPO) and the catalyst KCC-1/TEMPO. A minor difference could be detected when comparing the IR spectrum of catalyst KCC-1/TEMPO with that of KCC-1-NH_2. However, the characteristic peaks belonging to TEMPO were not too obvious. There are probably two main reasons for this observation. First is the overlap of characteristic bands for the amino group and TEMPO. Second, is the lower amount of TEMPO compared with the bulk silica, and the fibrous morphologies hindered its detection.

Hence, to further confirm the immobilization of TEMPO, thermogravimetric (TG) studies for KCC-1, KCC-1-NH_2, and KCC-1/TEMPO were also carried out, as shown in Figure S2.[16] KCC-1 showed only negligible (about 1.2%) weight loss from 50 to 800 °C. As for KCC-1-NH_2, after an initial weight loss of absorbed moisture up to 110 °C, the nanocomposite was stable until 450 °C, after which a weight loss of 12% was observed up to 650 °C, which can be attributed to the loss of the covalently bound aminopropyl groups. For KCC-1/TEMPO, two-step weight losses could be observed. 4-Oxo-TEMPO decomposed completely before 200 °C, as shown in curve d (Figure S2). Hence, the weight loss of KCC-1/TEMPO in the same range of temperature was proposed to be the loss of TEMPO. A loading of TEMPO at approximately 0.3 mmol g^{-1} was confirmed. There was still some weight loss around 650 °C for KCC-1/TEMPO, which was attributed to the remained aminopropyl groups.

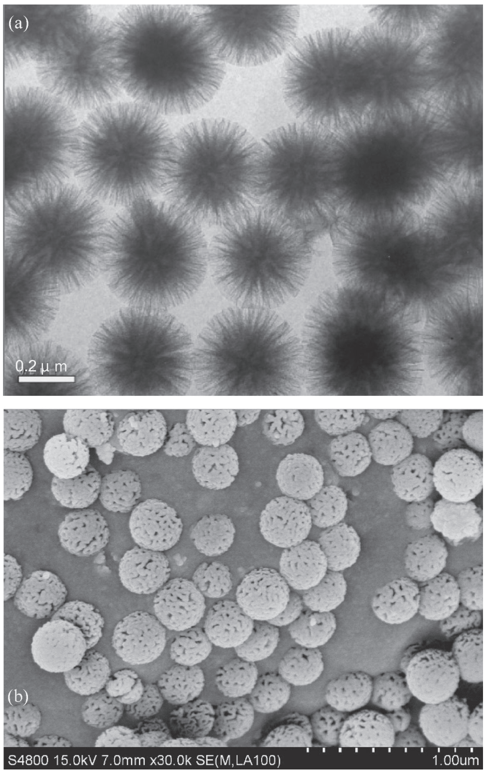


Figure 1. (a) TEM images of KCC-1/TEMPO; (b) SEM images of KCC-1/TEMPO.

Transmission electron microscope (TEM) and scanning electron microscope (SEM) images (Figure 1) indicated that the material consisted of colloidal spheres of uniform size, with diameters that range from 200 to 300 nm (the length of fibers was not included). The catalyst also exhibited excellent dispersivity without assembly or scattered SiO_2. It confirmed that the coating of amino groups and grafting of TEMPO did not destroy the morphologies and that KCC-1/TEMPO retained the fibrous structure of the original KCC-1. The dendrimeric fibers could be observed clearly on these materials to form spheres, which allowed easy access to the available large surface area.

The size of KCC-1/TEMPO could tend to the nanoscale, as also reflected in Figure 1. During the oxidation process, nanosized KCC-1, carrying TEMPO, was well distributed in the solvent to form a pseudo-homogeneous system rather than a heterogeneous one, which alleviated the disadvantage of heterogeneous immobilization. Furthermore, as opposed to the homogeneous catalytic system of TEMPO, there was an advantage of recycling since the catalyst was on the order of hundreds of nanometers and could easily be recovered through filtration.

The performance of the fibrous catalyst was first tested in the oxidation of benzyl alcohol with O_2 as the oxidant and $NaNO_2$ as the cooxidant; the comparable results are summarized in Table S1.[16] It was found that almost no product was obtained in pure acetonitrile without any catalyst or with KCC-1, KCC-1/NH_2 only without TEMPO. As the oxidant and cooxidant, both O_2 and $NaNO_2$ were essential to the oxidation process. KCC-1/TEMPO (nitrosonium) oxidized alcohols into their corresponding aldehydes or ketones and was itself converted into hydroxylamine (KCC-1/TEMPOH). NO and NO_2 were released from NO_2^- under acidic conditions and the oxidation of NO into NO_2 could proceed smoothly with the help of O_2. The reaction between NO_2 and hydroxylamine led to the completion of the recycling of KCC-1/TEMPO. The reaction efficiency increased directly along with the amount of catalyst and was almost free from the effect of the silica support. A catalytic amount of KCC-1/TEMPO (as less as 5 mol % that of substrate) was enough to obtain a good yield, and further increase in the catalyst amount would be meaningless. Reaction termination could be observed with the removal of it.

In the view of TOF (turnover frequency), 4-oxo-TEMPO performed much better compared with the supported ones, probably because of the nature of the homogeneous process. The TOF of the pseudo-homogeneous TEMPO-catalyzed process would be similar under the same reaction conditions. With temperature being the most important influence factor on TOF, high temperatures were favorable for the reaction, and excellent catalytic performance was achieved at 80 °C. After the supporting process, the activity (reflected as TOF) decreased from 13.8 to 9.1, probably because of the transformation from the homogeneous to the pseudo-homogeneous system. TEMPO with KCC-1 support (with a surface area of $641\,\mathrm{m^2\,g^{-1}}$[15]) showed both a higher TOF and yield compared with nano-SiO_2 and Al_2O_3 (with a surface area of 500 and $150\,\mathrm{m^2\,g^{-1}}$, respectively). This was attributed to the larger surface area and greater accessibility of fibrous KCC-1 compared with both nano-SiO_2 and Al_2O_3. The bad dispersion of TEMPO on support with smaller surface area would lead to less active site than that in theory.

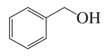
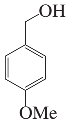
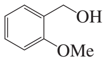
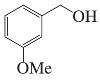
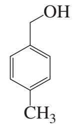
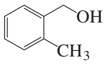
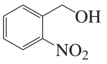
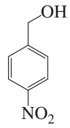
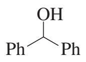
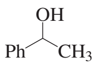
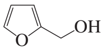
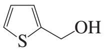
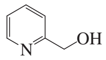
All these facts indicated that it was still TEMPO that served as the active species of oxidation reactions. The immobilization process would not change the reaction mechanism and the activity decrease was not obvious either, probably because of the pseudo-homogeneous process and fibrous morphologies, which provide the large surface area and ready access to the substrate molecules. The merits of introducing KCC-1 nanoparticles contribute to both good catalytic performance and easy recycling.

To examine the utility and generality of this methodology for the oxidation of alcohols, we applied the present catalyst system to various alcohols. The substrate scope was extended to benzylic, allylic, heterocyclic, alicyclic, and aliphatic alcohols. In all cases, ketones or aldehydes were the only detected reaction products. The oxidation results of aromatic alcohols are shown in Table 1. Obviously, all the primary benzylic alcohols were converted into their corresponding aldehydes in high yields. Secondary alcohols such as benzhydrol and 2-phenylethanol also gave a yield of 53% and 58%, respectively. It is noteworthy that a type of heterocyclic alcohol, which was less active in many reported systems, worked well in this system.

Furthermore, oxidations of some aliphatic alcohols were tested, as listed in Table 2. With 2 mol % of the catalyst, the activities exhibited by secondary alcohols were not too low in the system. It was found that the oxidative efficiency was not affected by the existence of the double bond and that the double bond remained stable during the oxidation process. Unfortunately, in case of aliphatic alcohols such as 1-$C_8H_{17}OH$ and isooctyl alcohol, the results were unsatisfactory even after increasing the reaction time.

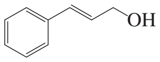
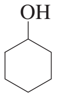
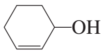
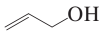
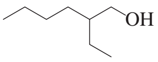
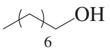
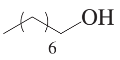
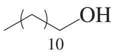
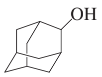
Usually, leaching is a major problem hindering the recycling process. In order to further investigate the stability of the catalyst during our catalytic process, TG and IR measurements for freshly prepared KCC-1/TEMPO and the catalyst reused 5 times with the same mass were carried out, as shown in Figure S3.[16] The TG curve for the reused catalyst revealed a weight loss process similar

Table 1. Oxidation of aromatic alcohols[a]

 3 h 99% (98%)	 3 h 96% (95%)	 4 h 96% (94%)	 4 h 94% (92%)	 2 h 98% (98%)
 3 h 99% (98%)	 6 h 83% (81%)	 7 h 85% (82%)	 10 h 54% (53%)	 10 h 59% (58%)
 4 h 93% (91%)	 5 h 84% (83%)	 5 h 74% (72%)		

[a]Reaction conditions: alcohol 2 mmol, CH_3CN 15 mL, catalyst 0.02 mmol, $NaNO_2$ 0.1 mol, 10% H_2SO_4 0.1 mL, O_2 was imputed of 0.004 $m^3 h^{-1}$, 80 °C. Conversion was in parenthesis and GC-yield out of parenthesis.

Table 2. Oxidation of aliphatic alcohols[a]

 10 h 80% (79%)	 12 h 65% (63%)	 6 h 88% (87%)
 3 h 97% (96%)	 24 h 7% (7%)	 24 h 7% (6%)
 24 h 7% (6%)	 24 h 28% (27%)	 48 h 89% (89%)

[a]Reaction conditions: alcohol 2 mmol, CH_3CN 10 mL, catalyst 0.04 mmol, $NaNO_2$ 0.1 mol, 10% H_2SO_4 0.1 mL, O_2 was imputed of 0.004 $m^3 h^{-1}$, 80 °C. Conversion was in parenthesis and GC-yield out of parenthesis.

to that of fresh KCC-1/TEMPO, demonstrating the stability of the catalyst even after 5 times of recycling. However, a slight decrease in weight loss at both periods of the TEMPO and –NH_2 group were observed, which is attributed to the leaching process. The leaching of a small amount of TEMPO or –NH_2 group during the reaction process led to an increased ratio of silica, so as to reduce the weight loss in TG. The IR spectrum of the catalyst reused 5 times also confirmed the conclusion.

The advantage of the catalyst KCC-1/TEMPO lies in not only the high catalytic activity attributed to TEMPO, but also the pseudo-homogeneous process and ease of separation and recyclability provided by the KCC-1 support. As proved by TEM images, the size of the catalyst reached the nanoscale and a pseudo-homogeneous process could be achieved when mixing the catalyst and the solvent, as shown in Figure S4.[16] Further, with hundreds of nanometers, the catalyst could be separated simply by filtration. More than 90% of the catalyst could be recovered from the reaction system, with only a trace amount remaining in CH_3CN, which was also proved by comparing the solution state before and after separation, as shown in Figure S4. This also ensured the possibility of reuse of the catalyst.

With benzyl alcohol as the substrate, the reusability of the catalyst was further studied. As shown in Figure S4, the recovered KCC-1/TEMPO can be reused at least 5 times without any notable loss of activity. High selectivity was maintained as well during the recycling, without any apparent decline. The leaching process was not obvious, as mentioned above, and the recovered catalyst was sufficient to achieve 5 rounds of recycling.

In conclusion, a novel catalyst that was efficient for selective alcohol oxidation was prepared with TEMPO supported on silica nanospheres. The catalyst maintained the fibrous morphology of the KCC-1 support, which dramatically increased the accessibility between the substrate and the catalyst. A wide set of aliphatic, allylic, heterocyclic, and benzylic alcohols could be oxidized into the corresponding carbonyl compounds with good-to-excellent yields. As the catalyst was on the order of hundreds of nanometers, a pseudo-homogeneous system was realized during the reaction, and both improved reaction efficiency and simple separation of the catalyst could be achieved.

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