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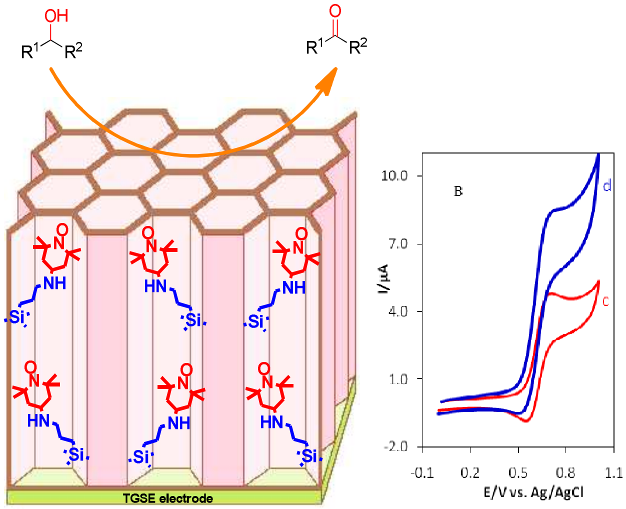
Graphical Abstract



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Eco-friendly Electrocatalytic Oxidation of Alcohols on a Novel Electro-Generated TEMPO- Functionalized MCM-41 Modified Electrode

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The development of highly efficient and waste-free system for selective oxidation of alcohols without using expensive transition-metal catalyst is an extremely important and ground challenging area in organic chemistry and in particular for chemical industry. In this study, a novel procedure for an environmentally friendly electrochemical oxidation of alcohols is introduced, where thin layer of ordered mesoporous silica (MCM-41) with well oriented channels is constructed on the electrode surface and then functionalized with 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) as an electro-active organocatalyst. The electro-catalytic system operates efficiently in mild bicarbonate solution, at room temperature, without the need to any co-catalyst, which provides very fast, simple, selective and waste-free protocol for the oxidation of a wide variety of alcohols. The proposed modified electrodes could be easily employed in 20 mmol scale in one reaction run and shows very good stability and can be successfully re-used in several runs. In term of electro-catalytic activity, this system enables unprecedented turnover frequencies (TOF) up to 3070 h^{-1}, *which is much superior to the entire ever reported nitroxyl radical under chemical, electrochemical, or aerobic oxidation conditions*.

Introduction

The development of efficient catalytic systems for the selective oxidation of alcohols is not only a major concern in basic chemistry research, but it is also a grand challenge for the chemical industry. In this context, heterogeneous compared to homogeneous catalysis offers greater benefits for large-scale operations owing to an easier separation and recycling of the catalysts as well as reduced metal contamination in the final products. As a consequence, a significant effort has been dedicated into the development of new, efficient and metal-based catalysts in recent years by emphasizing the use of molecular oxygen as the most environmentally benign oxidant.[1] In this way, the attentions have been mainly directed toward the designing suitable support to improve the catalyst performance while minimizing the catalyst deactivation arising from metal leaching and/or morphological changes of the catalyst.[2] Although significant advances have been achieved in the field of metal/O_2 heterogeneous catalyst systems, many of them are still environmentally harmful due to the presence of toxic trace of metals in the final products and/or catalyst deactivation. It is therefore highly desirable to replace them with metal-free systems and greener alternatives. Along this line, several seminal metal-free aerobic oxidation protocols have been reported, which centrally employ 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) as catalysts in combination with varied NO_X and or halogen sources as co-catalyst in order to ensure the fast electron transfer from alcohol to molecular oxygen through a catalysis relay mechanism.[3] The essential role of these NO_X and or halogen sources can be simply understood by large oxidation gap between molecular oxygen and TEMPO (Figure 1).

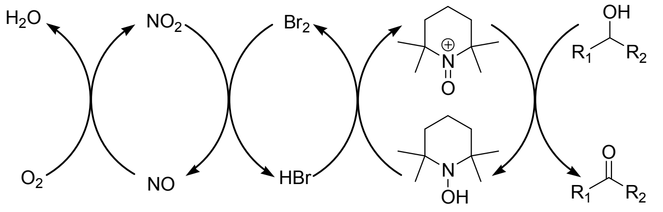

Figure 1. Proposed pathway for the aerobic oxidation of alcohols mediated by TEMPO and non-metallic chemical co-catalysts

However, the use of toxic NO_X sources and/or halogen-based co-oxidants combined with the high cost of the TEMPO in particular as homogeneous form makes these protocols less attractive for industrial applications from both sustainable and green chemistry point of views. Although, the use of expensive homogeneous TEMPO can be avoided to a great extent by employing varied TEMPO supported catalyst systems,[4] the environmental impact of NO_X materials used in these metal-free protocols is still a key

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obstacle that needs to be addressed.[5] Therefore, the development of alternative TEMPO-catalyzed selective oxidation of alcohols by avoiding the use of harmful mediators or co-oxidant while maintaining an adequate reaction kinetic profile is extremely desirable. Considering the fact that TEMPO can be also oxidized electrochemically to its active *N*-oxoammonium (OXO) intermediate without significant kinetic barrier,[6] a waste-free selective electrochemically mediated TEMPO-catalyzed oxidation of alcohols would represent an appealing and highly promising alternative for this type of transformation. Although, a few attempts have been dedicated towards application of homogeneous TEMPO as an electro-catalyst in some oxidative transformations,[7] however, the approaches in designing appropriate and highly effective modified electrodes based on supported TEMPO are very rare at present.[8] In this context, the work of Pagliaro *et al.* on the preparation of a thin layer of amorphous organosilica functionalized TEMPO on the surface of Indium Tin Oxide (ITO) coated glass electrodes for application in selective electrochemical oxidation (selelox) of alcohols foreshadow future opportunities in this transformation in a waste-free pathway.[9] This organosilica modified electrode possesses some desirable properties such as high durability and selectivity in oxidation of alcohols, which are reflected by its suitable surface hydrophobic-hydrophilic balance. Owing to both/either low accessibility of the active sites arising from amorphous nature of the organosilica layer and/or electrodes low surface area, it appears, however, that prolonged reaction times up to 180 h were necessary to ensure satisfactory conversion. In this case a significant numbers of the catalytic groups might be supported within microporous region of organosilica layer, leading to serious diffusion limitations. Another problem regarding ITO-based electrodes is the much higher over-voltage for the electron transfer of TEMPO at the surface of this electrode. The use of ordered mesoporous silica (OMS) are certainly preferred over amorphous silica due to their adjustable and more accessible pores in the range of 2-50 nm that in turn confers them a high specific surface area beside the other important unique properties.[10] However, when using OMS materials to modify the electrode surface, the appropriate pore size as well as channel orientation are challenging issues in order to facilitate the diffusion of substrates into the system pores, where they favorably got reacted at available active sites at the proximity of electrode surface, followed by the departure of the reaction products from the channels which leaves the reaction sites for the next available starting molecules. To address the problem associated with the channel orientation, Walcarius and his co-workers have recently demonstrated that an ordered mesoporous silica film consisting hexagonally packed channels of MCM-41 types perpendicular to the electrode surface could be generated using a technique known as Electro-Assisted Self Assembly (EASA).[11] This approach has thus far been successfully employed for construction of varied high performance modified electrodes in several electrochemical studies.[12] However, despite these unique characteristics, *to the best of our knowledge there is currently no report of preparing and employing EASA-generated (modified) electrodes comprising electro-catalytic moieties in electrochemical functional group transformations.* We envisioned that a properly designed mesoporous film having electro-active TEMPO functionality distributed over the entire the surface of a given electrode might result in an unprecedented and more efficient electrode system for waste-free electrochemical oxidation of alcohols. We predict that high accessibility and uniform nano-sized thickness of this electrochemically derived ordered mesoporous film would not only enable more convenient diffusion of alcohols into the mesochannels where the TEMPO groups are located, but it may also provide a means of faster and easier electron transfer from TEMPO to the electrode surface, thereby enhancing the overall oxidation of alcohols in comparison with the oxidations using conventional modified electrode coated with amorphous organosilica functionalized TEMPO. If this hypothesis could be realized in practice this approach would seem to open a new area in designing high performance modified electrodes for waste-free and environmentally benign oxidation of alcohols.

Experimental Section

Materials: Tetraethylorthosilicate 99% (TEOS), cetyltrimethylammonium bromide 98% (CTAB), potassium nitrate, sodium bicarbonate, sodium acetate, sodium cyanoborohydride95% ($NaBH_3CN$), acetic acid, hydrochloric acid 37% and all of the alcohols were purchased from Merck. (3-aminopropyl)triethoxysilane 99% (APTES) and 4-Oxo-2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPON) were purchased from Sigma-Aldrich. All chemicals were used without further purification.

Typical Procedure for the preparation of 2,2,6,6-tetramethyl-4-(3-(triethoxysilyl)propylamino)piperidin-1-ol (TPTES): The material was synthesis by addition of 2.0 mmol APTES to a solution of 2.0 mmol of TEMPON in dried ethanol (20 mL) in a reaction flask kept closed under a nitrogen atmosphere after 3 h stirring 2.2 mmol of $NaBH_3CN$ was added to the reaction mixture and the resulting mixture was stirred for 24 h, after which the excess of sodium cyanoborohydride was quenched with 1.5 ml of 4.0 M HCl.[13] The ethanolic solution of this precursor was used without further purification.

General procedure for construction EASA-generated (modified) electrodes with TEMPO function (TGSE):

a) Initial sol preparation: various mixtures consist of 3.26 mmol CTAB, (10-X) mmol TEOS, X mmol APS (the percent of functional group containing silica precursor should be less than 10% over TEOS), 15 ml ethanol and 15 ml aqueous solution of 0.1 M $NaNO_3$ and 3.0 mMHCl were used for sol preparation. CTAB and APTS or TPTES should be added under stirring and vigorous stirring respectively.[12] The sol solutions were aged under stirring for 2.5 h at pH 3 prior to electro-deposition.

b) Thin film formation: The graphite or GC electrodes were immersed in the above mentioned precursor solutions and electro-deposition was achieved by applying a suitable cathodic current (-1.9 mA cm^{-2}) for a defined period of time (typically 20 s). The electrodes were rapidly removed from the solution and immediately rinsed with distilled water. The electrodeposited surfactant template film was then dried overnight in an oven at 130^o C. Extraction of the

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surfactant template was carried out in acidic ethanol solutions under moderate stirring for 10 min to give the modified electrodes with aminopropyl functionalized MCM-41 thin film (Figure 2A).[12]

c) Functionalization of mesoporous silica modified electrode: The modified electrodes with aminopropyl functionalized MCM-41 thin film were immersed in 0.15 M acetate solution and the cathodic potential of -.2.2 V (vs. Ag/AgCl for 2 min) were applied for deprotonation of amine groups. The electrodes then rinsed by distilled water and dried in an oven overnight. Thereafter the electrodes were immersed in super dry CH_3OH (150 mL) containing 2.0 mmol TEMPON under nitrogen atmosphere. The electrode immersion followed by the stepwise addition of 2.0 mmol $NaBH_3CN$ (three times addition after 3, 27 and 51 h). The electrodes were then removed after 72 h and rinsed with methanol and distilled water to remove any surface adsorbed TEMPON. The resulting modified electrode was denoted as TGSE.

General procedure for construction EASA-generated (modified) electrodes with TEMPO function (CSTE): The preparation of CSTE was achieved following the step a and b of the above-described protocol for TGSE except the fact that APS has been replace with 2,2,6,6-tetramethyl-4-(3-(triethoxysilyl)-propylamino) piperidine-1-ol (TPTES).

Instrumentation: The film characterizations were performed using the following instruments: Elementar Analysen System GmbH-vario EL Element Analyzer for elemental analysis (CHN), NETZSCH STA 409 PC for Thermal Gravimetric Analysis (TGA), Philips CM20 Microscope an acceleration voltage of 200 kV for Transmission Electron Microscopy (TEM). A Metrohm pH-meter 691 was utilized for measuring the solutions pH. Voltammetric measurements were performed at room temperature using an Autolab PGSTAT-101 monitored by the Electrochemical System Software (Eco Chemie). Voltammetric experiments were carried out in a classical three-electrode undivided cell configuration with a platinum counter electrode and a GC working electrode (surface area=3.14 mm^2). Electrochemical preparative reactions were performed in an undivided home-made three-electrode cell which the working electrodeswere graphite plates, the auxiliary electrodes consisted of a hollow tube and a centralized steel rod. Behpajooh (Isfahan, Iran) coulometer with the maximum current of 300 mA were used for the preparative electrolysis reactions. The working electrodes potentials were measured versus a double junction Ag/AgCl reference electrode in all of electrochemical experiments. All of the electrodes were manufactured by AZAR Electrode Company, Urmia, Iran. The extent of the reaction during the electrolysis experiments was monitored by internal standard method using Varian CP-3800 gas chromatograph equipped with a CP-Sil 8 CB capillary column.

Typical procedure of electro-catalytic oxidation of alcohols: The oxidation of alcohols (1 to 20 mmol) was carried out in 80 to 120 mL of aqueous carbonate buffered ($NaHCO_3$ 0.10 M and Na_2CO_3 0.01 M) using the Modified TGSE or CSTE modified graphite electrodes. In order to attain better solubility for cinnamyl alcohol and 4-nitrobenzyl alcohol mixture of acetonitrile/water solution (20:80 v/v) was employed. The electrolysis reactions were carried under stirring at 1.0 V vs. Ag/AgCl as the optimum potential

Results and Discussion

To prove our hypothesis, we have chosen to employ EASA technique for the construction of two kinds of modified electrodes coated with TEMPO-functionalized MCM-41 thin film as outlined in Figure 2. The surface of either GC or graphite plate electrodes was selected instead of ITO to make the EASA modified electrodes, since it has been well-documented that the former electrodes exhibit much lower overvoltage for the electron transfer of TEMPO.[7a,9a] The present EASA protocol consist of application of a cathodic potential to an electrode immersed in a sol solution containing appropriate silica precursor, tetraethylorthosilicate (TEOS), and cetyltrimethylammonium bromide (CTAB) as structure directing agent.[11a]

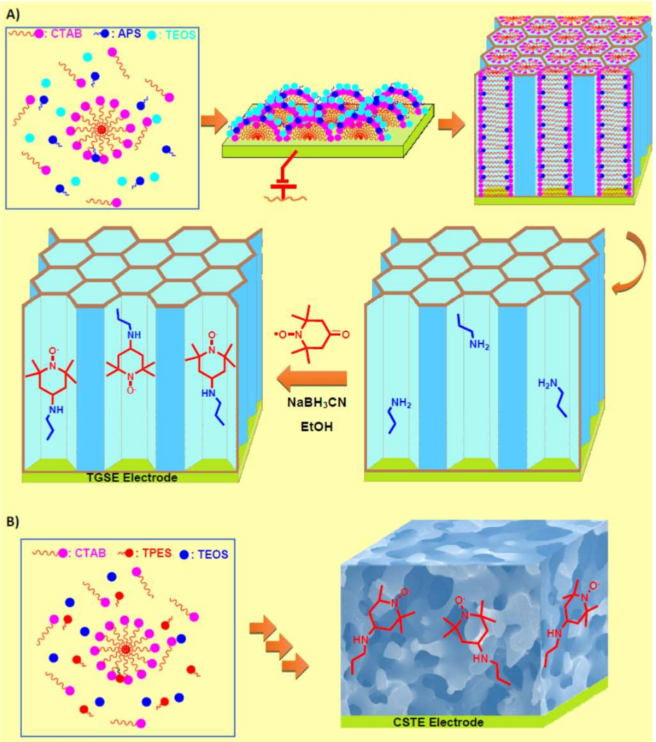

Figure 2. Proposed pathway of electrode modification with thin layer of TEMPO-functionalized ordered mesoporous silica (TGSE electrode, top), and thin layer of TEMPO-functionalized amorphous silica (CSTE electrode, bottom). The functionalized group are demonstrated bigger (exaggerated size) than their actual sizes for clarification

In this regard, electro-generated hydroxyl ions under cathodic conditions are known to function as the catalyst for poly-condensation of the precursors and formation of thin mesoporous silica (MCM-41) film at the electrode surface. The aminopropyl functionalized silica film (APS) with the maximum possible (3-aminopropyl)triethoxysilane (APTS) to TEOS ratio (10% APTS/TEOS in sol solution) was first deposited following the reported EASA procedure on both GC and graphite electrodes.[11a,12a] The accessibility of film deposition was examined by voltammetric study of $Fe(CN)_6^{3-}$ and $Ru(NH_3)_6^{3+}$ as electro-active charged probe and composition of the scratched film after surfactant extraction, have been approved by thermogravimetric (TGA) and elemental

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(CHN) analyses which were in good agreement with the previously reported results.[12a]

The resulted APS was then allowed to react with 4-oxo-2,2,6,6-tetramethylpiperidine-1-oxyh (TEMPON) in the presence of NaBH3CN to afford the corresponding TEMPO-grafted silica modified electrode, which is described as TGSE (Figure 2a). TGA analysis (See Supplementary Figure 1) of the scratched thin film of TGSE exhibited 7% increase in the weight loss between 300-500 °C in comparison with that observed for the initial APS. Although, it is very difficult to quantify the precise amount of incorporated TEMPO moieties alone by TGA, due to the overlapping matrix weight loss, the amount of TEMPO estimated by TGA did show good consistency with the results obtained by elemental analysis (See Supplementary Table 1). High resolution transmission electron microscopy (HRTEM), Electron Tomography (ET) as well as 3D-reconstruction analysis were conducted to get further insight into the structural characteristics of TGSE thin film (Figure 3)

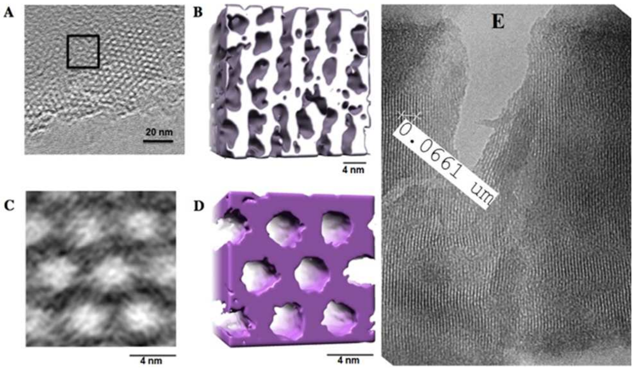

Figure 3. TEM images (A,C and E)and reconstructed images (B, D) of TGSE

As can be clearly seen, the fragment of the separated film from the surface of electrode shows a highly porous well-defined 2D-hexagonal mesostructures perpendicular to the electrode surface. As the 3D reconstruction derived from tomography data obtained from thin film reveals (Figure 3D), the channels are perfectly aligned perpendicular to the surface of electrode. For the purpose of comparison, EASA technique was also employed in hydrolysis combined with co-condensation of 2,2,6,6-tetramethyl-4-(3-(triethoxysilyl)-propylamino) piperidine-1-ol (TPTES, 8%), TEMPO containing silica precursor denoted as TPTES, and TEOS (92%) as silica sources to furnish the respected TEMPO-functionalized which is referred to as CSTE (Figure 2b). The total incorporated TEMPO function was again estimated to be 12 mmolg^{-1} by TGA and CHN analysis (See Supplementary Table 1 and Supplementary Figure 2). However, our attempts in obtaining highly ordered mesoporous thin film by changing the TPTES/TEOS molar ratios in the initial sol solution were unsuccessful as evidenced by TEM analysis (See Supplementary Figure 3).

The electrode accessibility of both TEMPO-functionalized EASA electrodes were then examined and compared by voltammetric study of the dissolved electro-active probes. Figure 4 presents the voltammetric responses of $Fe(CN)_6^{3-}$ on bare, MCM-41 modified electrode, CSTE, and TGSE. As it is evident from the Figure 4, the TGSE showed considerable currents, comparable to the bare electrode and higher than previously reported MCM-41 modified electrodes as well as CSTE electrode after CTAB extraction.[11a] This is a strong evidence for the presence of porous structure of the film and electrode accessibility through TGSE. Moreover, higher voltammetric currents for the TGSE compared with either MCM-41 or surfactant extracted CSTE samples, is an evidence that despite the partial filling of mesopores by pendant TEMPO groups, the presence of positively charged amine groups and electrostatic interaction enhance the electrode accessibility and voltammetric currents of negatively charged $Fe(CN)_6^{3-}$.[12c]

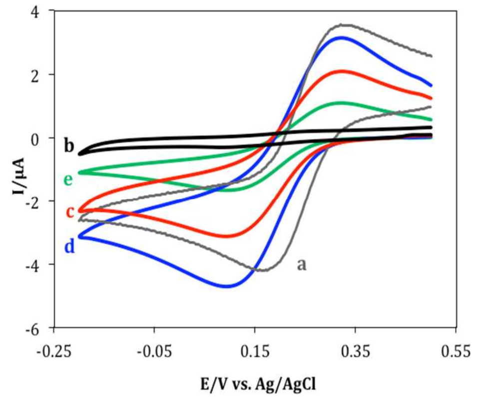

Figure 4. CVs of 1.0 mM $Fe(CN)_6^{3-}$ on bare GC electrode (a), CSTE before (b) and after CTAB extraction (c), TGSE (d) and MCM-41 modified electrode (e); Supporting electrolyte 0.15 M KNO_3, scan rate: 100 mVs^{-1}

The voltammetric analysis of the CSTE was approximately the same but considerably less than TGSE (Figure 4b), which is most likely due to the disordered structure of the film (See also Supplementary Figure 4). It should also be noted that both CSTE and APS modified electrodes did not show any considerable currents before the extraction of CTAB, indicating the appropriate coverage of the electrode surface by the deposited films.[11a,12a]

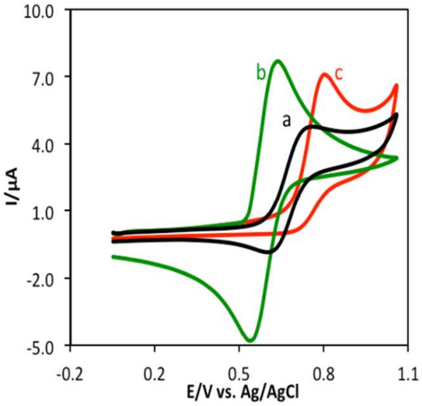

Figure 5. CVs of TGSE in a blank bicarbonate solution (a) 1.0 mM of dissolved TEMPO (b) and TEMPON (c) on GC electrode in bicarbonate solution; scan rates 100 mV s^{-1}

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As mentioned above, TEMPO has a well-defined voltammetric response and thus cyclic voltammetry (CV) was also employed for the investigation of these TEMPO functionalized films.

Figure 5 (curve a) shows the CV of TGSE in a slightly basic blank solution containing only supporting electrolyte (0.15 M sodium bicarbonate). Notably, the constructed TGSE showed one anodic and corresponding cathodic peaks with the mid-peak potential (E_{mid} 0.62 V vs. Ag/AgCl, $\Delta E_p = 0.14$ V) being more positive than TEMPO and less positive than TEMPON moiety (Figure 5, curves b and c respectively). From the considerable faradaic currents in Figure 5, it is apparent that the acceptable loading of electroactive groups has been achieved and the anchored groups have sufficient ability for the electron transfer. Moreover, the supported form of TEMPO exhibited a significantly better reversibility in cyclic voltammogram as compared with that obtained from soluble TEMPON, which is attributed to a great extent to the superior stability of electro-generated oxoammonium salt of supported TEMPO and most likely to the conversion of carbonyl to amine groups during the reductive amination.[4a] In addition, voltammetric studies at various pH values demonstrated that the initial currents of the electrodes at mild acidic solutions were to some extent less than the value measured in basic solutions. Moreover, in contrast to either TEMPO or TEMPON the mid-point potential of anchored TEMPO was dependent on the solution pH, for the first voltammetric cycle only. This may be due to the reduction of *N*-oxyl radicals under reductive amination of TEMPON and electro-inactive nature of the reduced *N*-hydoxy form.[4a] Remarkably, the electrodes showed approximately the same currents in both acidic and basic solution after applying one voltammetric cycle in basic solutions. On the other hand, we found that despite the disordered structure of CSTE, a sample of GC electrode with thin film of CSTE constructed using appropriate concentration of TPTES (less than 8%) in initial sol, exhibited relatively higher voltammetric currents as compared with TGSE) in bicarbonate solution (Figure 6C).

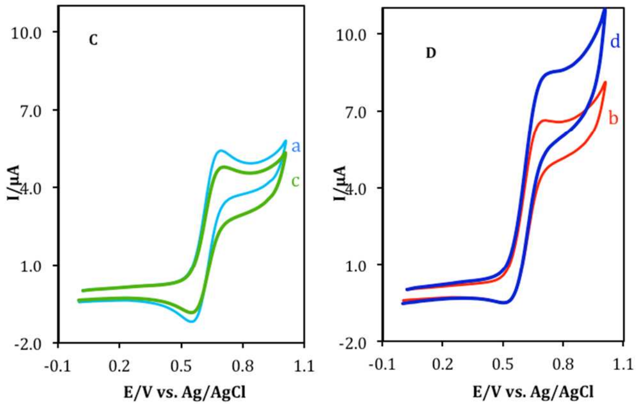

Figure 6. CVs of CSTE in the absence (a) and in the presence of 1.0 mM of BA (b) and CVs of TGSE in the absence (c) and in the presence of 1.0 mM of BA (d) in bicarbonate solution, scan rate 100 mV s^{-1}

These superior voltametric responses of CSTE-based electrodes can be simply understood by considering the fact that the total loading of TEMPO moiety in our prepared CSTE thin film is significantly higher than that measured in TGSE sample as it is evidenced from the elemental analysis (See Supplementary Table 1). In order to make a better comparison and to find the best electrochemical performances and accessibility of CSTE, we attempt to conduct experiments in various sol solution compositions. To do this, the composition of sol solution was changed with respect to TPTES/TEOS ratio to achieve the maximum possible voltammetric currents. The results showed that the optimum ratio of TPTES/TEOS was 7.5/92.5. At the lower ratios; the voltammetric currents of electrodes decreased proportional to TPTES concentrations, whereas at the higher concentration it gradually decreased until 20% of TPTES where voltammetric current completely declined for the constructed films (See Supplementary Figure 5). This observation clearly highlights the notion that the use of higher than 8% concentration of TPTES could indeed strongly block the system pores thus preventing the electro-active species to diffuse into the pores and causing a significant loss of voltammetric current.

A more appealing observation, however, was that in the presence of 1 mM of benzyl alcohol (BA), TGSE displayed a considerably enhanced voltammetric response under mild basic conditions (Figure 6D). The amounts of anodic peak currents, which were proportional to the loading of TEMPO groups is considered as criteria for the leaching stability of the electrode. However, it was found that the decrease in current associated with anodic peak for CSTE was about 13% after 5 h exposed to the buffer solution. The successive potential scans and the peak currents decreased to 80% of the initial values after being exposed for additional 24 hours. In contrast, the current of TGSE anodic peak was decreased to 11% of its initial value only, even being exposed to the mild basic buffer solutions for 3 days. This observation clearly shows that TGSE display much superior leaching stability under the described experimental conditions. The loadings of TEMPO groups incorporated in thin silica film on the electrode surface were estimated by determining the charges under the voltammetric oxidation peak recorded at low scan rate, 10 mV s^{-1}.[13] The charge under the TEMPO peak shows the appropriate loading of 1.5×10^{-8} mol cm^{-2} (geometric area of electrode) for CSTE. The total amount of active TEMPO functionalities in TGSE was also estimated to be 1.1×10^{-8} mol cm^{-1} by charge analysis under the voltammetric oxidation peak, a value that shows a good agreement with those estimated by CHN analysis. The voltammetric studies at various scan rates demonstrated also the presence of diffusion like behavior for the anchored electro-active groups at the electrode surfaces. This behavior may be attributed to the "layer by layer" diffusion of electrons through the anchored electro-active groups inside the channels of silica support.[14] The superior leaching stability and excellent electrochemical performance of TGSE in addition to well-known remarkable catalytic properties of TEMPO makes us ask if the modified electrode having TGSE thin film can function as an effective electro-catalytic system for waste-free oxidation of alcohols.

Figure 7 demonstrates the voltammetric response of TGSE in the absence and presence of benzyl alcohol (BA) under mild basic conditions (aqueous bicarbonate solution). What is appealing in this experiment is that the anodic current of

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electrode was increased 2.5 times in the presence of dissolved BA. Notably, BA didn't show any oxidation current on bare GC and both MCM-41 and APS modified electrodes. Figure 7 also shows a clear trend of increasing the anodic currents by increasing the BA concentration. This finding corroborates the indirect or mediated (by anchored TEMPO) oxidation of BA on TGSE. It is worth of mentioning that the extent of this behavior was indeed inferior in the case of employing CSTE-based modified electrode achieved by increasing the BA concentration. By emphasizing the fact that the loading of TEMPO moieties in TGSE was found to be around 72% of that estimated for CSTE, it is apparent that the modified electrode comprising TGSE thin film demonstrates higher catalytic activity per TEMPO unit as compared with our CSTE-based electrode (See Supplementary Figure 7).

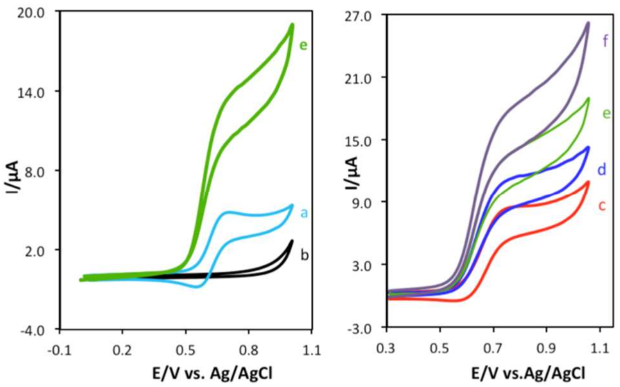

Figure 7. CVs of TGSE in the absence,(a) and in the presence of 9.0mM of BA(e) and CV of BA at bare GC electrode (b); CVs of TGSE in the presence of 1.0 (c), 4.0 (d), 9.0 (e) and 16.0 (f) mM BA, in bicarbonate solution, scan rate 100 mV s^{-1}

Taking into account the consistent higher electro-catalytic behavior of TGSE in the oxidation of BA, it would be reasonable to speculate that the increase in accessibility of ordered mesoporous silica thin film, where TEMPO groups are located in close proximity to the electrode surface might be indeed one of the major reasons for this favorable behavior in comparison with CTSE-based electrode. In a separate experiment, we also found that the voltammetric currents of electrodes increase slightly by increasing the potential scan rates while their normalized currents decreased drastically at high scan rates. Normalized CVs ($I/v^{1/2}$) were obtained by dividing the current by the square root of the scan rate. These voltammetric data very well match with the characteristics of electrocatalytic (EC') mechanism.[14] The amounts of catalytic currents as a criterion for the catalytic activity of the desired electrodes have been studied at different pHs and various alcohol substituents. The best catalytic activities were observed for primary alcohols under mild basic (carbonate solution) condition that are consistent with the results obtained for homogeneous study of the TEMPO.[7a] It was also exciting that TEMPON itself doesn't have a reversible electrochemical behavior and catalytic activity toward the oxidation of BA under the same conditions (See Supplementary Figure 7). It appears however, that conversion of carbonyl to amine group during reductive amination improves the electrochemical reversibility of the TPTES and enhances its catalytic activity.

The ultimate goal of this study was to enable the electrochemical conversion of alcohols to their corresponding carbonyl compounds in preparative scale through a waste-free protocol. In order to attain this objective, an individual homemade electrochemical cell comprising 8 well-separated graphite plates as working electrode in combination with a hollow tube and a centralized rod of steel as an auxiliary electrode were designed and assembled. An array of TEMPO modified graphite plates, which were constructed exactly in a similar way as our previously described TGSE, has been deposited using the essentially the same EASA protocol with uniform distances to both steel anodes (See Supplementary Figure 7). The geometric area of the working electrodes was 124 cm^2 considering the dimensions of electrodes and the height with which the electrodes have been immersed in electrolysis solution.

Figure 8. Images of employed electrochemical cell with 260 cm2 geometric area of working electrode; inner (a) and outer (b) parts

By employing this new setup, complete conversion and selectivity (a 100% BA conversion with >99% selectivity toward benzaldehyde) were obtained by using 1.0 mmol of BA within 10 hours under optimal conditions (slightly 0.1 M bicarbonate solution or buffer pH=9). Remarkably, this method was also equally applicable for the quantitative oxidation of 7.0 mmol of BA in 10 hours. These results indicate that the desired electrodes have no restriction with respect to kinetic and mass transfer throughout the ordered mesoporous thin film. In other words, the limiting factor may occur by mass transfer in solution and the cell design. Therefore, to shed light to this issue we decided to improve the electrochemical cell device by employing additional graphite plates in a hollow tube with greater radius and adding more steel plates between the graphite electrodes (Figure 8). Using this new cell design we were able to increase the electrode functional surface up to 260 cm^2 by maintaining the alternative array of working and auxiliary electrodes. Gratifyingly, by employing this new electrode system, practically quantitative conversions of BA with excellent selectivity toward benzaldehyde were achieved for all the solutions containing 2.0, 7.0 and even 12.0 mmol of BA within only 100 minutes. By employing this new unit, the

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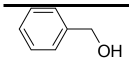
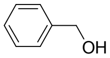
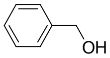
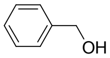
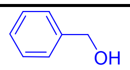
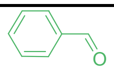
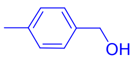
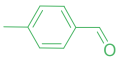
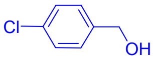
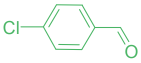
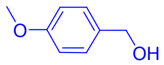
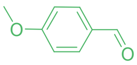
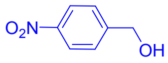
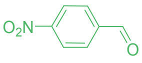
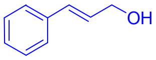
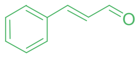
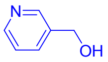
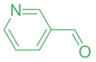
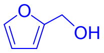
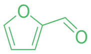
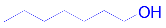
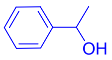
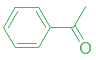
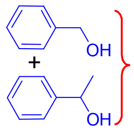
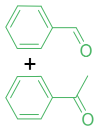
oxidation of 20.0 mmol BA was also achieved within 4 hours, whereby the limiting factor was the maximum current of the employed coulometer (0.3 A was the maximum tolerant of the utilized coulometer). These conversions were obtained under potentiostatic conditions and the potential of working electrodes was 1.0 V versus Ag/AgCl. Based on these results, all of the potentials higher than 0.62 V vs. Ag/AgCl (mid-point potential of the supported TEMPO) should be appropriate for the oxidation of TEMPO and promotion of the reaction. However, in order to find the most efficient electrochemical pathway, the applied potential has been optimized for the electrolysis reactions, which the results were summarized in Table 1. From the data presented in Table 1, it is apparent that the higher over-voltages lead to higher conversions at a fix time. But the non-selective over-oxidation of alcohols was considerable at the positive potentials higher than 1 V. While the control experiments at bare graphite electrodes applying 1.0 V potential resulted in only 4 % conversion of BA at 100 minutes; the same experiments at 1.2 V gave 30% conversion under otherwise identical reaction conditions.

Table 1. Electrochemical oxidation of BA at various applied potential of working electrode, vs. Ag/AgCl, using TGSE

Substrate	Applied potential	Time (min)	Conversion on TGSE	Conversion on Graphite
	0.7	100	28	--
	0.85	100	70	--
	1.0	100	100	4
	1.2	100	100	26

Applying the less positive potentials, however, is more favorable from the economical point of views, in particular for the preparative scale reactions. Therefore, the potential range of 0.9 to 1.0 V was selected as the optimum applied potential for the rest of studies. The other important parameter that should be considered in electrochemical reactions is the current yield. Current yield of a reaction is usually measured by the number of coulomb or electrons consumed for the desired reaction by the total passage of coulomb. The current yield of 95% was calculated for conversion of 7.0 mmol of BA whereas it was 57% for conversion of 1.0 mmol BA. One of the reasons of obtaining these excellent current yields, using an undivided cell, may be the immobilization of the TEMPO as the only electro-active component of reaction and prevention of back reactions. Another explanation for this excellent favorable current yield at higher BA concentrations could be the fact that the side reactions and background currents are insignificant at higher ratio of BA to TEMPO. Having optimized the electro-catalytic system based on TGSE electrode, we next proceeded to employ this system for oxidation of a wide variety of alcohols, which the results are summarized in the Table 2. As can be seen, TGSE equally functioned in highly efficient electrochemical oxidation of substituted benzyl alcohols with excellent selectivity to yield the corresponding aldehyde as the sole products (Entries 1-4, Table 2).

Table 2. Electrochemical oxidation of alcohols using TGSE [a]

Entry	Substrate	Product	Time/min	Product yield
1			100	100
2			100	100
3			100	100
4			200	100
5			50	48§
6			100	100§
7			500	95
8			1000	85
9			300	91
10			500	48
12			100	100 20

[a] Reaction conditions: alcohols (1.0 mmol), water (100 mL), $NaHCO_3$ (10 mmol, 0.84 g), Na_2CO_3 (1 mmol, 0.106 g), E=1.0 V vs. Ag/AgCl unless otherwise stated.

[b] The product yields were determined by GC analysis after the extraction of all aqueous phase contents.

[c] Reaction conditions: alcohols (1.0 mmol) water (80 mL), CH_3CN (20 mL), $NaHCO_3$ (10 mmol, 0.84 g), Na_2CO_3 (1 mmol, 0.106 g), E=1.0 V vs. Ag/AgCl.

The only exception in the case of primary benzylic alcohols was the oxidation of 4-nitrobenzyl alcohol, which furnished 4-nitrobenzaldehyde in moderate yields of 48%, possibly due to some electrochemical side reactions at nitro moieties (Entry 5, Table 2). The present waste-free electrochemical oxidation

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was also suitable for the highly selective oxidation of cinnamyl alcohol to cinnamaldehyde as a model for allyic alcohols within relatively short reaction times (Entry 6, Table 2). This system was also successfully extended to the oxidation of heterocyclic as well as primary aliphatic alcohols with excellent selectivity and good activity (Entries 7-9, Table 2).

For the purpose of comparison, electrochemical oxidation of BA was also performed using CSTE and complete conversion has been achieved in 2 hours. However, the electrocalytic activity of CSTE was declined faster than that observed for TGSE-based electrode. Ease of recovery and recycling that is of great importance and often vital for the economic viability of the described catalytic processes. Recovery of the desired electro-catalytic system has been examined by consecutive addition of BA to the cell.

As demonstrated in Table 3, excellent conversion of approximately 95% was achieved in 5 successive reaction runs. Knowing the loading of the TEMPO and colummetric measurements during the electrolysis or total amount of products could simply provide the possibility to calculate both Turnover Number (TON) and Turnover Frequency (TOF). Considering the 1.1×10^{-8} mol per cm^2 geometric area of the TGSE and the whole geometric area of 260 cm^2 which have been utilized in electrolysis reaction the total amount of anchored catalyst was calculated as 2.8×10^{-3} mmol.

Table 3. Subsequent runs for oxidation of BA on TGSE

Run	Conversion	Time (min)
1	100	100
2	100	125
3	95	158
4	95	200
5	95	240

Conversion of 12.0 mmol of BA has been achieved in 2 hours that present an effective and impressive TON of 5130 and the unique TOF of 3070 h^{-1}. The TOF of 1570 that were obtained using CSTE, was considerably less than the value obtained by TGSE. This decrease in TOF can be certainly attributed to the disordered structure of the film and diffusion problem. Obtaining the TOF for all of the entries embodied in the Table 2S (See Supplementary Table 2) presents a significant trend; the desired electrocatalytic system has higher efficiency toward the oxidation of primary alcohols and among them; the better reactivity was observed for benzylic and allylic substrates rather than the aliphatic ones. The obtained trend is approximately identical to those found in a homogeneous kinetic study.[7a] The obtained trend and superior activity provide solid evidences that the supported TEMPO can be considered as the key and only catalyst appeared inherently and the designed electrochemical system and the support have no considerable restriction for its activity.

Conclusions

In summary, based on the electrocatalytic oxidation results presented in Table 2, TGSE-based electrode could be considered as an efficient electrode system in the electrochemical oxidation of alcohols. In this context, it was found through several compelling electrochemical studies that the voltammetric responses of the CSTE was considerably less than TGSE with ordered mesoporous structure (Figure 4b), which could be most likely due to the disordered (amorphous) structure of the film in CSTE that resulted in less accessibility of the anchored electro-active groups. Since the loading of TEMPO moieties in TGSE was found to be around 72% of the estimated value for CSTE, then the effect of TEMPO loading on the enhanced electro-catalytic activities could be excluded. The higher accessibility of TEMPO units in the modified electrode comprising TGSE thin film combined with its highly organized nano-architecture should be the origin of its prominent performance. This is further supported by the TEM, HRTEM, electron tomography (ET) as well as 3D-reconstraction data of the isolated film of TGSE, which reveals a highly porous well-defined 2D-hexagonal mesostructures perpendicular to the electrode surface. In general the advantages of this new electrode system can be summarized as following:

(1) As indicated by cyclic voltammetric studies, the current of TGSE anodic peak was decreased only by 11% of the initial value even after 3 days remaining in mild basic buffer solutions. This observation clearly shows that TGSE display much superior leaching stability and relatively high durability under the described experimental conditions.
(2) The proposed TGSE-modified electrodes could be easily employed in electrochemical oxidation of benzyl alcohol in 20 mmol scales in one reaction run using our home-made electrochemical cell unit.
(3) In term of electro-catalytic activity, this system affords unprecedented turnover frequencies (TOF) up to 3070 h^{-1}, which is much superior to the entire reported nitroxyl radical under chemical or aerobic oxidation conditions. In addition, this TOF is also far superior than TEMPO@DE reported earlier by Pagliaro and co-workers.[9a]
(4) The use of water as the reaction solvent in most cases and the absence of any expensive and/or toxic transition metal co-catalyst make this protocol as an attractive environmentally benign alternative for this important transformation.
(5) To the best of our knowledge the present protocol could be considered as the first example of employing EASA-generated (modified) electrodes having electro-catalytic moieties such as TEMPO in electrochemical oxidation of alcohols in a preparative pathway.

Considering all of the above-mentioned advantages, we suggest that the present discovery would open a new challenging area in the design of new types of modified electrodes for application in varied functional group transformations.

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Notes and references

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† Electronic Supplementary Information (ESI) available: [including the additional electrochemical studies, optimization data, TGA diagrams, TEM images for CSTE electrode, details of elemental analysis of the modified films, initial prototype electrochemical cell data for the catalyst in the oxidation of BA, and TON as well as TOF number for electrochemical oxidation of all studied alcohols]. See DOI: 10.1039/b000000x/

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