Supporting Information

TEMPO-Modified Linear Poly(ethylenimine) for Immobilization-Enhanced Electrocatalytic Oxidation of Alcohols

David P. Hickey, Ross D. Milton, Dayi Chen, Matthew S. Sigman, Shelley D. Minteer**

Department of Chemistry, University of Utah, 315 South 1400 East, Salt Lake City, Utah 84112, United States

* E-mail: minteer@chem.utah.edu sigman@chem.utah.edu

1. Experimental Procedures & Results

1.1 Synthesis of 4-glycidyl-TEMPO

Glycidyl-TEMPO was prepared using a procedure originally published by Song et al.[1] Tetrabutylammonium hydrogen sulfate (0.09 g, 4 mol%) and (±)-epichlorohydrin (2.69 g, 0.032 mol) were dissolved into a solution of 50% wt/wt aqueous NaOH (10 mL). To the stirring mixture was added 4-hydroxy-TEMPO (1.00 g, 0.006 mol), and the reaction solution was stirred for 24 h at 25 ºC. The solution was then poured into water and extracted with ethyl acetate. The organic portion was washed with brine, filtered through $MgSO_4$ and the solvent was removed under reduced pressure. The product was purified by silica column chromatography (CH_2Cl_2 then MeOH); the first fraction off the column was determined to be 4-glycidyl-TEMPO, which was obtained as a red viscous liquid (1.01 g, 83% yield by mass balance). ^{1}H-NMR (400 MHz,

CD_3OD): δ 3.77 (dd, 1H), 3.69 (m, 1H), 3.53 (dd, 1H), 3.08 (m, 1H), 2.75 (t, 1H), 2.58 (m, 1H), 1.92 (dd, 2H), 1.38 (td, 2H), 1.16 (s, 6H), 1.13 (s, 6H).

1.2 Synthesis of 1-TEMPOoxypropan-2-ol-3-LPEI (TEMPO-LPEI)

4-Glycidyl-TEMPO (0.032 g, 0.3 mol equivalents) was added to a stirring solution of LPEI (0.02 g) in methanol. The solution was stirred at room temperature for 24 hours and the solvent was removed under reduced pressure. The product was washed with dichloromethane to remove any remaining staring material. The purified product was obtained as an amber amorphous solid, and was determined by ^{1}H-NMR to be 27% substituted. ^{1}H-NMR (400 MHz, CD_3OD): δ 3.87 (m, 1H), 3.63 (m, 1H), 3.42 (m, 1H), 2.91 (br m, 1H), 2.70-2.87* (br m), 2.58 (br m, 1H), 1.92 (br m, 2H), 1.39 (br m, 2H), 1.17 (s, 6H), 1.13 (s, 6H).

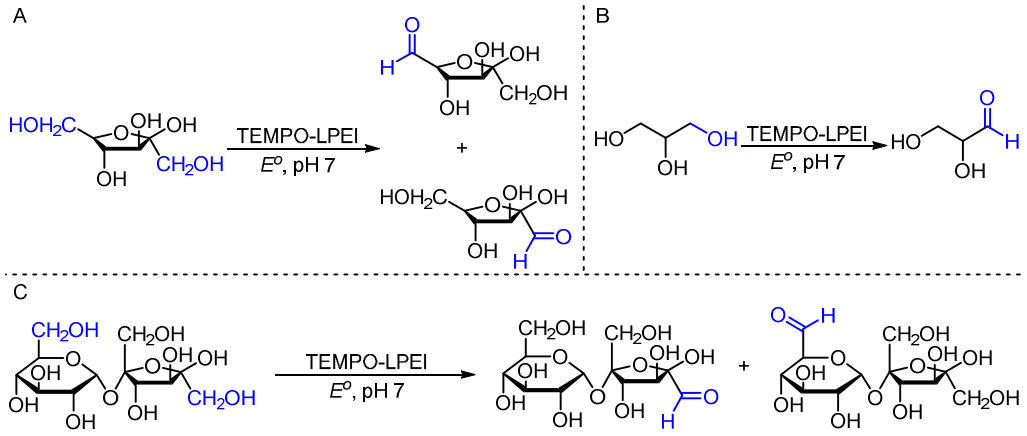
* The substitution ratio of the polymer was determined by normalizing integrations to the TEMPO substituent and dividing the number of protons on the substituted repeat unit (4) by the total number of normalized backbone protons;

Substitution % = [4 / (integration of LPEI backbone Hs, δ 2.70-2.87)] × 100%

1.3 Product Analysis

Preliminary product analysis was performed using a combination of HPLC and ^{1}H-NMR to determine the initial major product in the oxidation of sucrose and fructose. Analysis was performed on solutions of 10 mM fructose or 10 mM sucrose with 50 mM phosphate (pH 7.5) in D_2O after 2 hours of constant potential amperometric oxidation by the immobilized TEMPO-

LPEI catalyst film. HPLC of both solutions indicated the presence of a single major product with no indication of carboxylic acid formation. Additionally, ^{1}H-NMR analysis shows the appearance of an aldehyde peak at ca. 10 ppm. Combined, these results indicate that the initial site of oxidation for both fructose and sucrose is at one of the primary alcohol functional groups. This is in agreement with previous studies on the aqueous oxidation of saccharides by TEMPO.[2] Additionally, we previously reported the electrochemical oxidation cascade for glycerol by 4-amino-TEMPO, for which the initial product was glyceraldehyde.[3] A similar reaction pathway is assumed for the oxidation of glycerol by immobilized TEMPO-LPEI films.



Scheme S1. Initial products of (A) fructose oxidation, (B) glycerol oxidation, and (C) sucrose oxidation by TEMPO-LPEI using 50 mM phosphate buffer at pH 7 and 25 °C.

HPLC separations of glycerol oxidation products were performed with an HP series 1100 chromatograph with a UV-Vis detector at 230 nm. A 300 mm x 7.8 mm Aminex HPX-87H ion-exclusion column was used with 0.008 N H_2SO_4 (aq) as the mobile phase. A flow rate of 0.6 mL min^{-1} was used with a sample injection volume of 10 μL and a column temperature of 25 ^{0}C. The composition of chromatograms obtained from samples was determined by comparison of retention times of sample peaks with that of commercially available glyceraldehyde, glyceric acid, dihydroxyacetone, tartronic acid, and mesoxalic acid for the glycerol cascade. No such

intermediates were available for the fructose nor sucrose cascade; for these reactions, the HPLC was used to determine the number of reaction products. Only one product was observed for each reaction.

1.4 TEMPO-LPEI Self-Reactivity and Film Stability

Electrocatalytic stability of TEMPO-LPEI films was studied amperometrically by measuring the current density in the presence of 2 M methanol over a 24 hour period at a constant potential of 0.8 V vs SCE at 25 °C. A stability comparison of a cross-linked TEMPO-LPEI film with homogeneous TEMPO-OMe is shown in Figure S1. The overall rate of degradation for TEMPO-LPEI films is considerably greater than that of the homogeneous catalyst as is generally expected for immobilized catalysts. However, the dramatically improved catalytic activity of the immobilized TEMPO species allows for catalytic current densities that are nearly 3x higher than homogeneous TEMPO-OMe even after 24 hours of continuous electrochemical use.

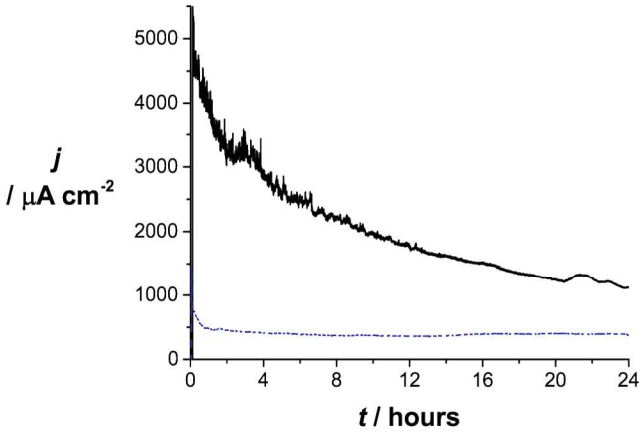


Figure S1. Amperometric stability comparison of an immobilized TEMPO-LPEI film (—) and homogeneous TEMPO-OMe (●●●) in the presence of 2 M methanol. Experiments were performed at a constant potential of 0.8 V vs SCE using 150 mM phosphate buffer at pH 7 and 25 ºC on a 1 cm^2 Toray paper working electrode.

TEMPO has previously been reported to react with secondary amines to generate the corresponding imine.[4] Constant potential amperometry was performed on TEMPO-LPEI films with N-ethylmethylamine as a substrate to simulate the injection of additional polymer backbone into a pre-equilibrated film and thus determine whether the TEMPO-modified polymers were capable of self-reactivity. The resulting reaction profile (shown in Figure S2) shows that TEMPO-LPEI films are capable of oxidizing the small secondary amine with j_{max} of 11.9 mA cm^{-2}. This result suggests that the primary means of catalyst degradation is through oxidation of the polyamine backbone. However, the rate of catalytic amine oxidation is not consistent with the rate of electrode film degradation; this inconsistency is most likely due to the high degree of protonation of the polymer backbone. Previous studies have shown that the majority of amine sites on LPEI are protonated at pH 7, therefore preventing rapid oxidation by the immobilized TEMPO catalyst.[5,6] In this way, the self-buffering nature of LPEI protects the polymer from rapid degradation through self-reactivity.

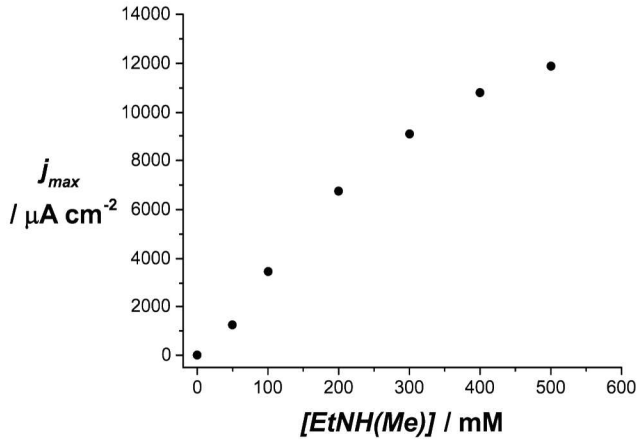


Figure S2. Amperometric response of TEMPO-LPEI film to various concentrations of N-ethylmethylamine. Experiments were performed at a constant potential of 0.8 V vs SCE using 150 mM phosphate buffer at pH 7 and 25 ºC with a 3 mm glassy carbon working electrode.

1.5 Laccase Biocathode Preparation

Anthracene-modified multi-walled carbon nanotubes (Ac-MWCNTs), tetrabutylammonium bromide-modified Nafion (TBAB-Nafion) and subsequent laccase direct electron transfer-type biocathodes were prepared, as previously reported.[7] Briefly, Ac-MWCNTs (7.5 mg) were added to laccase (75 μL, 20 mg mL^{-1}) prepared in buffer (citrate/phosphate, 0.2 M, pH 5.5) and mixed by successive vortex mixing/sonication steps. TBAB-Nafion (25 μL) was added and an additional vortex/sonication mixing step was performed. This mixture was divided evenly between three carbon paper electrodes (Toray) that were previously cut and treated to yield a geometric surface area of 1 cm^2. The resulting laccase biocathodes were dried under positive airflow, until use.

1.6 Methanol Cascade Reaction Profiles

Electrocatalytic reaction profiles were generated using constant potential amperometry in which aliquots of either an 80% solution of formaldehyde or a 4 M solution of sodium formate were added to a stirring solution containing the TEMPO-LPEI film at a fixed potential of 0.8 V vs SCE.

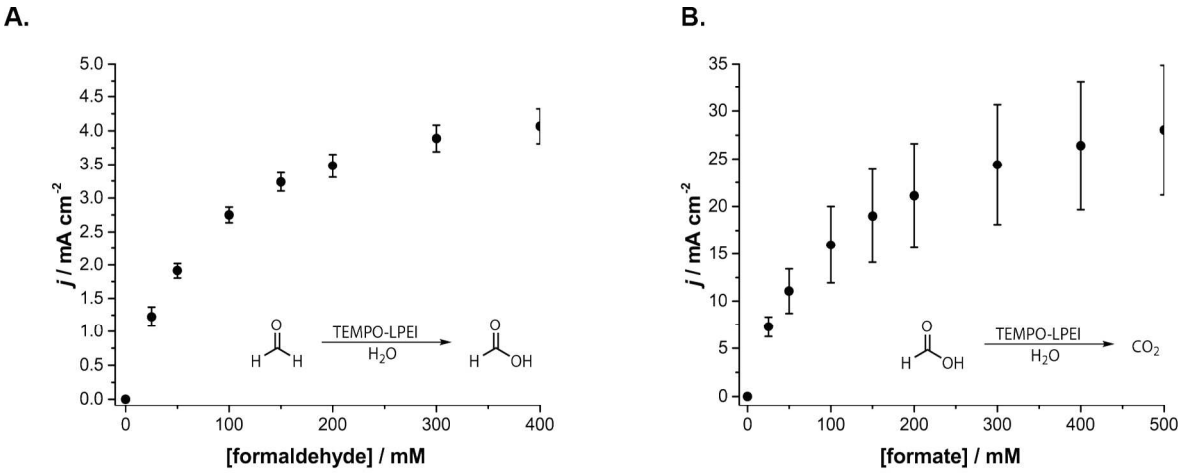


Figure S3. Reaction profiles of MWCNT-infused TEMPO-LPEI films with formaldehyde (A) and sodium formate (B). Experiments were performed using 150 mM phosphate buffer at pH 7.0 and 25 °C. Error bars represent one standard deviation from the mean (n=3).

1.7 Variable Substrate Kinetic Parameters

Kinetic parameters for TEMPO-LPEI films were determined using constant potential amperometry in which the current density was monitored during the injection of various aliquots of substrate. A representative amperometric curve is shown in Figure S4 for multiple additions of ethanol.

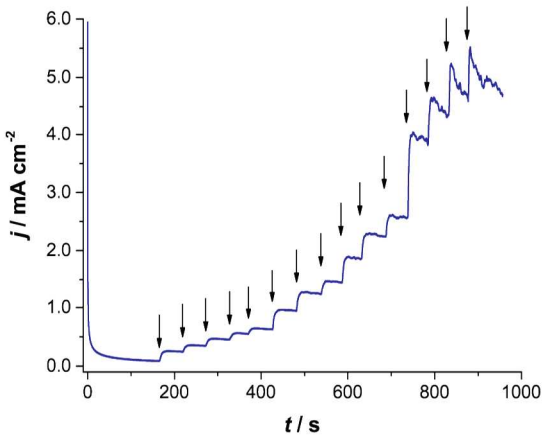


Figure S4. Amperometric *i* vs *t* curve for TEMPO-LPEI films during injections various concentrations of ethanol (indicated by the arrows). Experiments were carried out at a constant potential of 0.8 V vs SCE using a 150 mM phosphate buffer solution at pH 7 and 25 ºC.

Control experiments were performed in the absence of TEMPO catalysts for all substrates. These experiments showed that there was no catalytic oxidation in the absence of a TEMPO catalyst.

Table S1. Comparative kinetic parameters for TEMPO-LPEI (immobilized) and 4-methoxy-TEMPO (homogeneous) for variable substrates. Values of j_{max} were extrapolated from fitted curves. The uncertainty represents one standard deviation from the mean (n=3).

Substrate	j_{max} / mA cm^{-2}		K_m* / M	
	Homogeneous	Immobilized	Homogeneous	Immobilized
methanol	0.72 +/- 0.06	8.20 +/- 0.04	0.25 +/- 0.05	0.9 +/- 0.2
ethanol	0.50 +/- 0.12	7.6 +/- 1.2	0.9 +/- 0.1	1.9 +/- 0.5
isopropanol	0.03 +/- 0.01	3.5 +/- 0.9	3 +/- 1	10 +/- 3
glycerol	0.57 +/- 0.06	1.8 +/- 0.2	0.28 +/- 0.09	0.6 +/- 0.1
fructose	0.21 +/- 0.02	0.57 +/- 0.05	0.08 +/- 0.04	0.30 +/- 0.05
sucrose	0.25 +/- 0.01	0.41 +/- 0.06	0.06 +/- 0.01	0.16 +/- 0.02

References

(1) Song, C.; Hu, K.-N.; Joo, C.-G.; Swager, T. M.; Griffin, R. G. *J. Am. Chem. Soc.* **2006**, *128*, 11385-11390.

(2) de Nooy, A. E. J.; Besemer, A. C.; van Bekkum, H. *Tetrahedron* **1995**, *51*, 8023-8032.

(3) Hickey, D. P.; McCammant, M. S.; Giroud, F.; Sigman, M. S.; Minteer, S. D. *J. Am. Chem. Soc.* **2014**, *136*, 15917-15920.

(4) Huang, B.; Tian, H.; Lin, S.; Xie, M.; Yu, X.; Xu, Q. *Tetrahedron Lett.* **2013**, *54*, 2861-2864.

(5) Kobayashi, S.; Hiroishi, K.; Tokunoh, M.; Saegusa, T. *Macromolecules* **1987**, *20*, 1496-1500.

(6) Pelton, R. *Langmuir* **2014**, *30*, 15373-15382.

(7) Meredith, M. T.; Minson, M.; Hickey, D.; Artyushkova, K.; Glatzhofer, D. T.; Minteer, S. D. *ACS Cat.* **2011**, *1*, 1683-1690.