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Electrochemical Aminoxyl-Mediated Oxidation of Primary Alcohols in Lignin to Carboxylic Acids: Polymer Modification and Depolymerization

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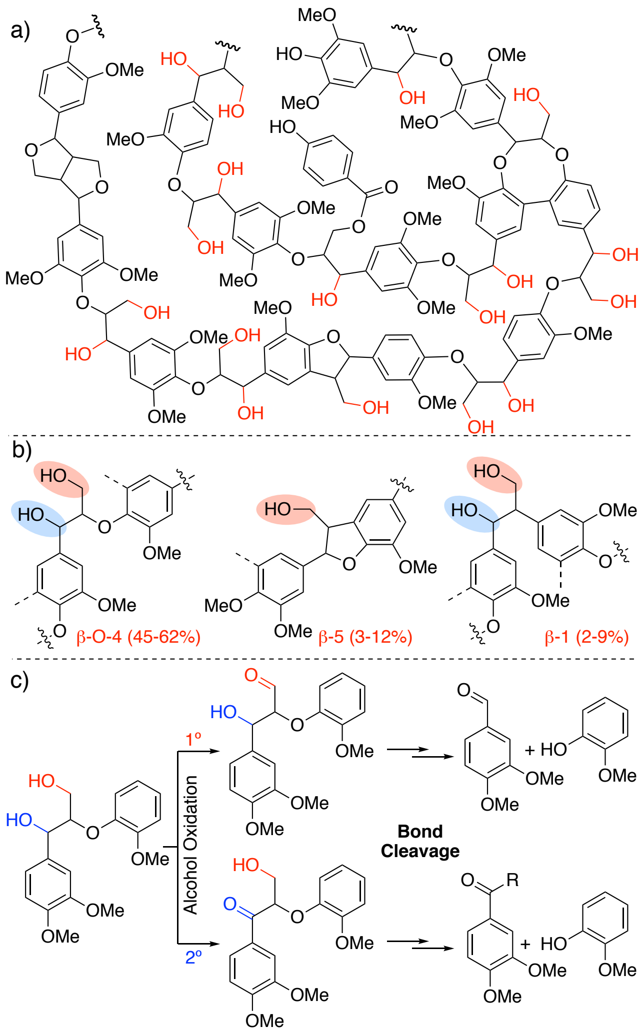
Abstract: An electrochemical process has been developed for chemoselective oxidation of primary alcohols in lignin to the corresponding carboxylic acids. The electrochemical oxidation reactions proceed under mildly basic conditions and employ 2,2,6,6-tetramethyl-1-piperidine N-oxyl (TEMPO) and 4-acetamido-TEMPO (ACT) as catalytic mediators. Lignin model compounds and related alcohols are used to conduct structure-reactivity studies that provide insights into the origin of the reaction selectivity. The method is applied to the oxidation of lignin extracted from poplar wood chips via a mild acidolysis method, and the reaction affords a novel polyelectrolyte material. Gel permeation chromatography data for the oxidized lignin shows that this material has a molecular weight and molecular weight distribution very similar to that of the extracted lignin, but notable differences are also evident. Base titration reveals a significant increase in the acid content, and the oxidized lignin has much higher water solubility relative to the extracted lignin. Treatment of the oxidized lignin under acidic conditions results in depolymerization of the material into characterized aromatic monomers in nearly 30 wt% yield.

Introduction

Lignin is a major constituent of nonedible biomass that is biosynthesized via radical coupling of phenylpropanoid units.[1] The lignin polymer, which features a non-regular pattern of methoxy-substituted aromatic groups linked together via aliphatic ether fragments (Scheme 1a), represents the largest source of naturally occurring aromatic chemicals in nature. The complex structure and composition of the covalent bonds in the polymer backbone, however, complicate selective breakdown of this material, and it is typically treated as a waste product and burned as an energy source in the paper and pulp industry.[2] Marketable applications have been identified for lignin,[3-8] but the installation of cellulosic ethanol plants and preparations for future biorefineries have highlighted the need to gain increased value from lignin and/or lignin-derived materials.[9-12] Major efforts have been directed toward conversion of lignin into low molecular weight chemicals that could potentially serve as fuels or as feedstocks for the chemical industry.[13-20] These efforts have led to a number of effective lignin depolymerization approaches, including pyrolysis, acid or base treatment, catalytic hydrogenolysis or related reductive methods, and oxidation methods. The reduction and oxidation methods have been shown to be capable of converting lignin into a small collection of aromatic monomers in relatively high yields (i.e., ≥ 30 wt% relative to the lignin precursor).

The electron-rich aromatic groups in lignin are susceptible to outer-sphere electron transfer,[21] and oxidative degradation of lignin by laccase and peroxidase enzymes is the primary pathway for lignin breakdown in nature.[22,23] In addition, the aliphatic ethers that connect the aromatic groups in the polymer chain often feature primary or secondary alcohols that are susceptible to oxidation (Scheme 1a). The most prevalent fragment is the β-O-4 unit, which features a benzylic secondary alcohol and a primary aliphatic alcohol (Scheme 1b).[9] In 2013, we evaluated a wide range of stoichiometric and catalytic alcohol oxidation methods in an effort to assess their ability to promote selective oxidation of one of these two alcohols.[24] In fact, a number of oxidation methods and reagents examined led to chemoselective oxidation of a single alcohol in the β-O-4 unit, and both oxidation products undergo facile cleavage of C–C and/or C–O bonds of the aliphatic ether linker to afford monoaromatic products (Scheme 1c).[25,26]

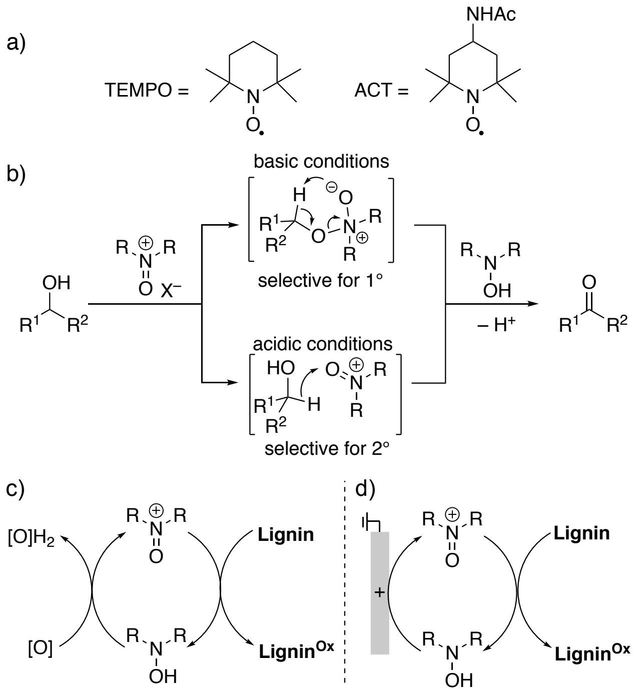
Scheme 1. a) Representative Structure of Lignin, b) Lignin Units Bearing Alcohol Groups, and c) Chemoselective Alcohol Oxidation Strategies for Cleavage of β-O-4 Lignin Model.



Numerous selective alcohol oxidation methods have now been identified for lignin and lignin model compounds by our group and others, and the majority of these examples promote selective oxidation of the secondary benzylic position.[24,27-41] Although partial oxidation of primary alcohols in lignin was observed in the process of oxidative pulp treatment by TEMPO/bleach (TEMPO = 2,2,6,6-tetramethyl-1-piperidine N-oxyl),[42-44] relatively few methods have been identified for selective oxidation of the primary alcohols in lignin, and successful examples typically afford the aldehyde as the product.[24,45-48]

Organic aminoxyls (also called nitroxyls), such as TEMPO and ACT (4-acetamido-TEMPO) (Scheme 2a), are especially effective stoichiometric reagents and catalysts for alcohol oxidation in lignin.[24,28,29,42,45] Aminoxyl-mediated alcohol oxidation has an extensive history,[49] and catalytic methods are widely used in industrial chemical synthesis.[50,51] The methods are initiated by oxidation of the aminoxyl radical (or the corresponding hydroxylamine) to the oxoammonium species. Under acidic conditions, the oxammonium promotes alcohol oxidation via a bimolecular hydride transfer mechanism that strongly favors reaction with the secondary benzylic alcohol in lignin (Scheme 2b). In contrast, under basic conditions, the oxoammonium mediates alcohol oxidation by an inner sphere mechanism that favors reaction with the less sterically hindered primary alcohol (Scheme 2b).[49,52,53] The different conditions pair different terminal oxidants with the aminoxyl catalyst, however. The acidic conditions are capable of using O_2,[24,29,54] while basic conditions typically employ chlorine- or hypervalent iodine-based oxidants.[24,42-45] The NO_x-based co-catalyst that enables aerobic regeneration of the oxoammonium species under acidic conditions[55] is not effective under basic conditions. On the other hand, aminoxyl catalysts have been widely studied in the context of electrochemical alcohol oxidation,[56,57] including oxidation of biomass-derived carbohydrates and sugars,[58-61] and such approaches would provide a sustainable alternative to the use of undesirable stoichiometric oxidants (Schemes 2c and 2d).[62-66]

Scheme 2. a) Structure of TEMPO and ACT; b) Mechanism of Alcohol Oxidation by Oxoammonium Under Basic and Acidic Conditions; c) Chemical and d) Electrochemical Oxidation of Lignin Mediated by Aminoxyl Radicals.



In the present study, we show that electrochemical aminoxyl-mediated oxidation methods enable efficient and selective conversion of primary alcohols in lignin to the corresponding carboxylic acids.[67,68] Studies of model compounds are used to compare reactivity of different alcohols and provide insights into the reaction selectivity. The electron-deficient aminoxyl derivative ACT is shown to be more reactive than TEMPO and a preferred electrocatalyst for these reactions,[69-71] and the optimized conditions are shown to be capable of converting lignin isolated from poplar into a water-soluble polyelectrolyte. This material undergoes cleavage of the lignin backbone under acidic conditions resulting in nearly 30 wt% yield of monomeric aromatic compounds.

Results and Discussion

Electrochemical Study. We initiated our study using cyclic voltammetry (CV) and chronoamperometry[72,73] for the study of TEMPO-mediated electrochemical oxidation of the β-O-4 lignin model **1a** under mild basic conditions (pH 10, Figure 1). In the absence of **1a**, the CV of TEMPO shows an anodic peak corresponding to oxidation of TEMPO to oxoammonium ($TEMPO^+$) (labeled A_1 in Figure 1, trace a) and a cathodic peak for the reduction of electrogenerated $TEMPO^+$ at the electrode surface (labeled C_1 in Figure 1, trace a). Two major changes are observed for the CV of TEMPO in the presence of **1a** (Figure 1 trace b): the cathodic peak is absent and the anodic peak current exhibits a 10-fold increase in magnitude. These changes, which indicate the consumption of $TEMPO^+$ and generation/regeneration of TEMPOH (the reduced form of TEMPO) by the substrate, respectively, provide evidence for an electrocatalytic

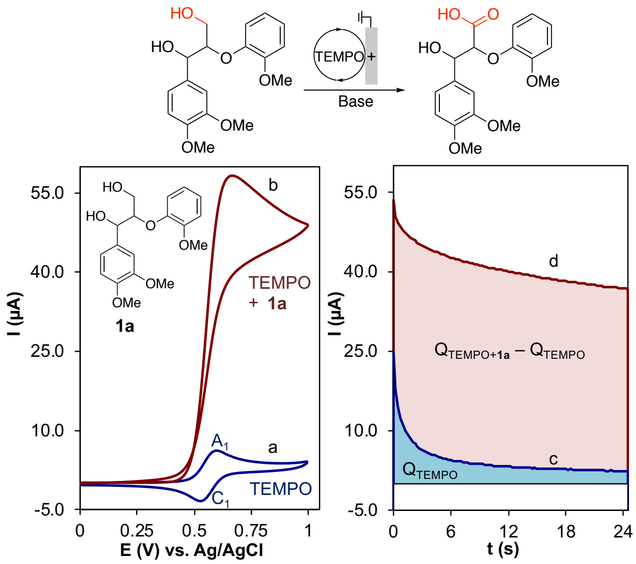


Figure 1. Cyclic voltammograms (left) and chronoamperograms (right) of 1.0 mM TEMPO in the presence (red, b and d) and absence (blue, a and c) of 10 mM **1a**. Solution condition: H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte (0.07/0.07 M, pH 10), scan rate for cyclic voltammetry is 10 mVs^{-1} and applied potential for chronoamperometry is 0.7 V vs. Ag/AgCl, the above scheme represents the possible mechanism for TEMPO catalyzed alcohol oxidation.

reaction. The enhancement of the oxidation peak current in the presence of the lignin model compound is proportional to the catalytic turnovers that occur on the CV time scale. Chronoamperometry was used to obtain quantitative data complementary to the CV data. A chronoamperogram of TEMPO in the absence of **1a** (Figure 1, trace c) shows the diffusion-controlled oxidation current corresponding to the oxidation of TEMPO to $TEMPO^+$ at the electrode surface. Addition of **1a** to the TEMPO solution leads to an increase in the oxidation current (Figure 1, trace d) due to the catalytic turnover of TEMPOH. Integration of the resulting current/time traces, depicted by the shaded regions under the chronoamperogram traces, provides the total consumed charge in the redox reaction. The ratio of the consumed charge in the presence and absence of substrate during the chronoamperometry experiments, together with the reaction stoichiometry, provides the basis for the TOF of the catalytic reactions.[74]

Analogous chronoamperometry experiments were then conducted with a number of different model compounds and subunits bearing lignin-type alcohol groups (**1a** – **7a**, Figure 2). The results clearly demonstrate higher TOFs with primary alcohols (e.g., **2a** > **3a**), in addition to higher reactivity with alcohols bearing an ether oxygen atom in the β position of the alcohol (**1a > 4a**, **2a > 5a** and **6a**/**7a > 3a**). The presence of electron-donating methoxy group on the benzene ring has minimal effect on the reactivity of benzylic alcohol groups toward oxidation by $TEMPO^+$ (**6a** vs **7a**).

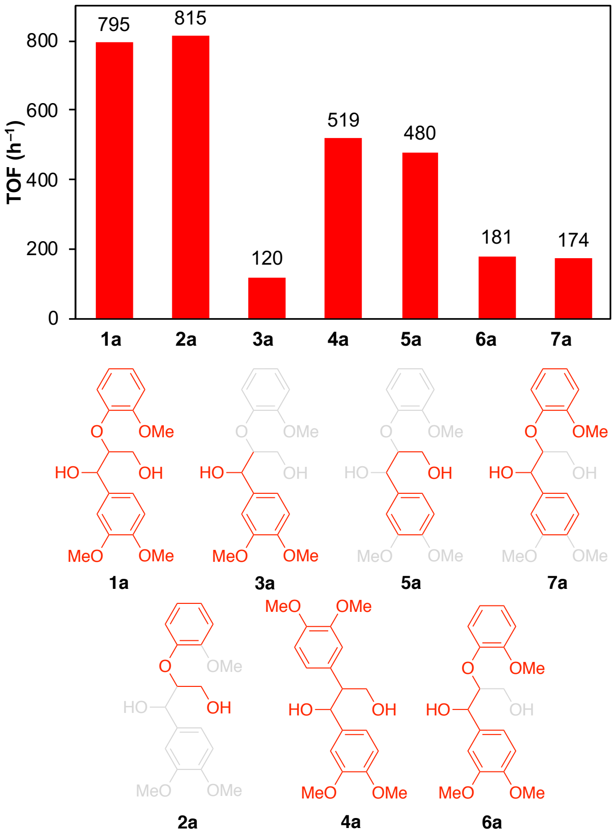


Figure 2. TOFs for TEMPO-catalyzed electrochemical oxidation of various lignin-related alcohols, derived by chronoamperometric experiments. Alcohol structures are shown in red; gray portions of the structures are not part of molecule, but are included to show the relationship to the lignin substructures. Reaction conditions: H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte (pH 10), applied potential for chronoamperometry 0.7 V vs. Ag/AgCl.

In previous studies, we have shown that TEMPO derivatives with higher redox potentials perform better than TEMPO in electrochemical alcohol oxidation, and ACT is one of the most appealing aminoxyls, owing to its low cost, good stability, and excellent catalytic performance.[69-71] Cyclic voltammetry analysis of TEMPO and ACT in the presence of **1a** confirms the improved performance of ACT. Chronoamperometric analysis of ACT-catalyzed electrochemical oxidation **1a**, **2a** and **6a** revealed TOFs of 1045, 1065 and 316 h^{-1}, respectively, all of which represent significant improvements relative to the results obtained with TEMPO (cf. Figure 3, and Figure

S2-S4 in Supporting Information). As a result of these observation, bulk electrolysis experiments were carried out with ACT.

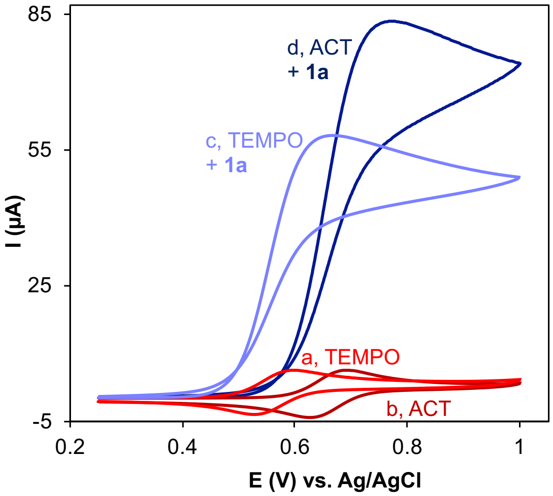
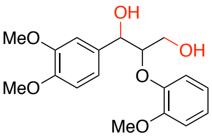
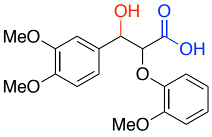
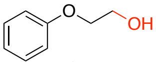
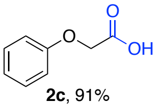
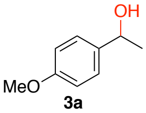
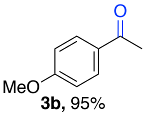
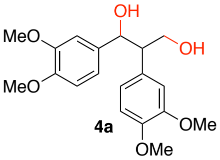
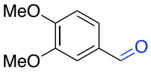
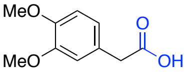
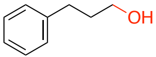
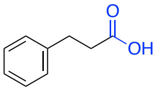
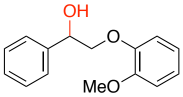
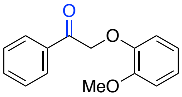
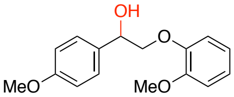
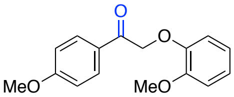
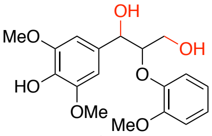
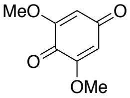
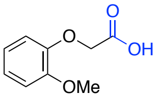
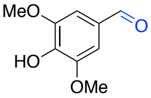
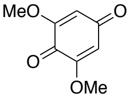


Figure 3. Cyclic voltammograms of 1.0 mM TEMPO and ACT in the absence (a and b) and presence of 10 mM **1a** (c and d), highlighting the increased activity of ACT. Solution condition: H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte (0.07/0.07 M, pH 10), scan rate for cyclic voltammetry is 10 mVs^{-1} and applied potential for chronoamperometry is 0.7 V vs. Ag/AgCl.

Bulk Electrolysis. ACT-mediated bulk electrolysis reactions were performed under constant-potential conditions (0.80 V vs. Ag/AgCl) in order to probe the preparative utility of the reactions described above and to establish the identity of the reaction products. The results of these experiments are presented in Table 1. Oxidation of the guaiacyl-derived β-O-4 model compound **1a** undergoes oxidation to the corresponding β-hydroxy acid (**1c**) in 91% isolated yield, highlighting the selectivity for primary alcohol oxidation. No product derived from oxidation of the secondary alcohol group was observed under these conditions, and attempts to promote further oxidation to the β-ketoacid under more strongly basic conditions (pH 11.2, using Na_2CO_3 as base and sole supporting electrolyte) led to only partial oxidation of the secondary alcohol group (< 30% after 2 h). The substrates bearing lignin-like subunits, with only primary or secondary alcohol groups, undergo clean oxidation in excellent yields to the corresponding

Table 1. ACT mediated electrolysis reactions of various lignin models.

Entry	Substrate	Products, Yield
1	 **1a**	 **1c**, 91%
2	 **2a**	 **2c**, 91%
3	 **3a**	 **3b**, 95%
4	 **4a**	 **4c**, 79%  **4d**, 86%
5	 **5a**	 **5c**, 93%
6	 **7a**	 **7b**, 98%
7	 **8a**	 **8b**, 97%
8	 **9a**	 **9c**, 52%  **9d**, 36%
9	 **9b**	 **9c**, 59%

Conditions: 0.05 mmol of ACT and 1 mmol of each substrate in 8 mL H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte pH 10, electrolysis at 0.80 V vs. Ag/AgCl, the reactions were terminated when the current reached to 5% of the initial current. Yield determined by ^{1}H NMR spectroscopy; int. std. = 1,3,5-trimethoxybenzene.

carboxylic acid (**2c** and **5c**) or ketone (**3b**, **7b** and **8b**) products. Oxidation of compound **4a**, bearing a β-1 linkage (i.e., lacking the ether present in **1a**; see also, Scheme 1b), results in cleavage of the aliphatic ether unit, affording products that arise from the retro-aldol reaction of the initially formed aldehyde intermediate to generate 3,4-dimethoxybenzaldehyde and the homologous aliphatic aldehyde fragment. The aliphatic aldehyde then undergoes oxidation to generate carboxylic acid **4d**, while the benzaldehyde does not undergo oxidation under these reaction conditions due to its lower susceptibility to hydrate formation.[70] Lignin models bearing a free phenol group, **9a** and **9b**, undergo direct electron transfer at the electrode surface at potentials similar to redox potentials of ACT or TEMPO; therefore, subjecting these molecules to the standard electrochemical oxidation conditions affords 2,6-dimethoxyquinone (**9c**) as the major product.[75]

Substrates **1a** and **4a** differ only in the presence or absence of a β-ether group in the aliphatic tether between the two aryl groups; however, these two substrates exhibit substantial differences in reactivity toward oxidative cleavage. To probe the basis for these differences, we analyzed the reaction progress for the simplified substrate analogs **2a** and **5a** (Figure 4a). The data show nearly direct conversion of **2a** into the corresponding carboxylic acid **2c**, with little build-up of the intermediate aldehyde **2b** (Figure 4b). In contrast, the oxidation of **5a** leads to significant build-up of the intermediate aldehyde **5b** (Figure 4c). This difference is again rationalized by the relative preference for formation of the aldehyde hydrate, which is favored for more electron deficient aldehydes (**2b** > **5b**).[76] These results suggest the aldehyde product arising from initial oxidation of **4a** may have sufficient lifetime to undergo retro-aldol cleavage of the C–C bond, while the analogous intermediate derived from oxidation of **1a** has negligible lifetime and undergoes further oxidation to the carboxylic acid product **1c**.

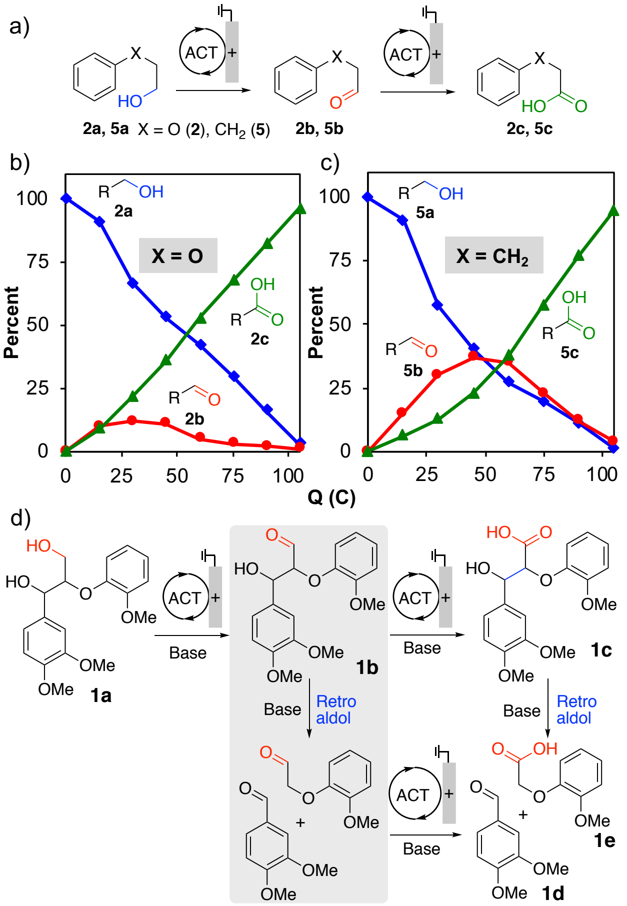
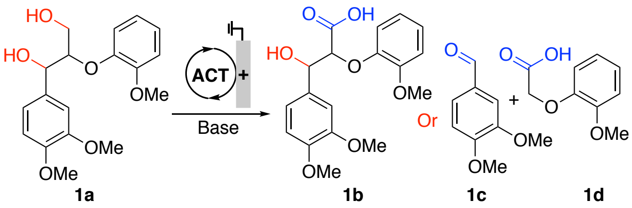


Figure 4. (a) Reaction sequence showing oxidation of alcohols **2a** and **5a** to aldehydes **2b** and **5b** and then to carboxylic acids **2c** and **5c**. (b and c) Reaction progress data showing the concentration profiles of the alcohol, aldehyde and carboxylic acids as a function of charge passed for the oxidation of **2a** and **5a** during the bulk electrolysis reactions. (d) Mechanistic proposal to account for the products obtained from oxidation and oxidative cleavage of the β-O-4 substrate **1a**. Reaction conditions: 0.05 mmol of ACT and 1 mmol of each substrate in 8 mL H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte pH 10, electrolysis at 0.80 V vs. Ag/AgCl.

The observations in Figure 4a-c and mechanistic rationale in Figure 4d prompted us to test whether the branching between retro-aldol cleavage of **1b** vs oxidation to the carboxylic acid **1c** could be influenced by the solution pH. The effect of pH was evaluated by examining ACT-mediated oxidation **1a** from pH 9.2 – 12.5, by varying the composition of the buffering electrolyte (cf. Table 2). At pH 9.2 and 10.1, the carboxylic acid product **1b** was obtained as the major product (94% and 89% yields, respectively; Table 2, entries 1 and 2). At higher pH (11.5 and 12.5), however, increasing quantities of retro-aldol C–C cleavage products **1b** and **1c** were observed (entries 3 and 4).

Table 2. Oxidation and oxidative cleavage of β-O-4 lignin linkage.[a]



Entry	Solvent (ratio)	Base (M)	(pH)	Yields 1b	1c	1d
1	H_2O/MeCN (75/25)	$NaHCO_3$ (0.13) Na_2CO_3 (0.02)	9.2	94	**3**	**0**
2	H_2O/MeCN (75/25)	$NaHCO_3$ (0.07) Na_2CO_3 (0.07)	10.1	89	**9**	**7**
3	H_2O/MeCN (75/25)	Na_2CO_3 (0.15)	11.5	59	**33**	**28**
4	H_2O	Na_3PO_4 (0.15)	12.5	9	**88**	**76**

[a] Reaction conditions: 0.05 mmol of ACT and 1 mmol **1a** in 8 mL solution, electrolysis at 0.80 V, the reactions were terminated when the currents reached to 5% of the initial current. Reported yields obtained by ^{1}H NMR spectroscopy (internal standard = 1,3,5-trimethoxybenzene).

Lignin Oxidation and Characterization of Oxidized Lignin. With these insights from the lignin model studies in hand, we turned our attention to experiments with lignin itself. The lignin sample was obtained from poplar wood chips via a previously reported mild acidolysis extraction method,[39,77] which affords a native-like lignin material (44% yield based on compositional analysis; see Supporting Information for details), with considerable retention of the desired β-O-4 subunits. The CV of ACT in the presence of poplar lignin demonstrates a well-defined oxidative catalytic feature (Figure 5a, red trace), while the lignin in the absence of ACT doesn't show significant redox activity in the potential range of ACT oxidation (Figure 5a, blue trace). Bulk electrolysis of the lignin under constant-potential conditions (0.80 V vs Ag/AgCl, Figure 5b) suggests a removal of somewhat more than 2e$^-$ per monomer unit of lignin (i.e., 2.4 e$^-$ per each 180 AU of lignin). The oxidized lignin exhibits significantly higher solubility in water than the original unoxidized lignin (14 g/L vs < 2 g/L, respectively, at pH 9). This observation is rationalized by the presence of carboxylate functional groups that will enhance the water solubility of the polymer. An acid-base titration of the oxidized lignin with NaOH (Figure 5c) reveals the presence of approximately 2.3 mmol of acid functional groups per gram of the oxidized lignin. This value may be compared to the much lower value of approximately 0.2 mmol of acid per gram of unoxidized lignin.

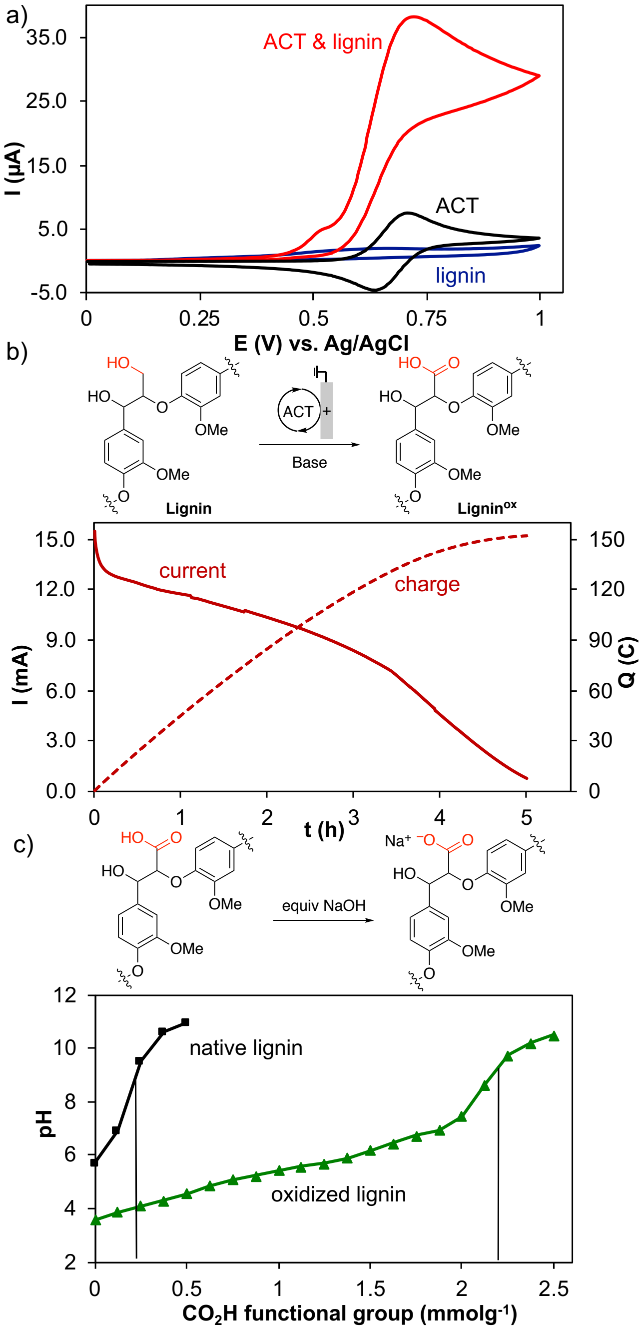


Figure 5. (a) Cyclic voltammograms of poplar lignin (blue), ACT (black) and mixture of ACT and lignin (red); (b) ACT mediated electrochemical oxidation of lignin; the resulting current and consumed charge curves for controlled potential electrolysis (at 0.80 V vs Ag/AgCl). Reaction Conditions: 0.23 mmol of ACT and 100 mg of lignin in 8 mL H_2O/CH_3CN (70/30), $NaHCO_3/Na_2CO_3$ electrolyte pH 10, scan rate for cyclic voltammetry 100 mVs^{-1}, electrolysis at 0.80 V vs. Ag/AgCl. c) Acid-Base of oxidized lignin; and titration curves of lignin before (black trace) and after ACT-mediated oxidation (green trace) in 10 ml mixture of H_2O/CH_3CN (70/30) using 0.01 M aqueous NaOH.

Analysis of the lignin before and after oxidation by gel-permeation chromatography (GPC) revealed an approximately 30% reduction in the molecular weight of the material (Figure 6), as reflected by the M_n and M_w values derived for untreated and oxidized lignin: 1.94 and 7.92 kDa (untreated) and 1.49 and 5.05 kDa (oxidized), respectively. This observation suggests that some depolymerization occurs as a result of the electrochemical oxidation at pH 10; however, the material clearly retains a polymeric structure. Analysis of the 2D ^{1}H-^{13}C HSQC NMR spectra of the lignin samples before and after oxidation provides further evidence for conversion of primary alcohol groups to the corresponding carboxylic acids (Figure 7). The oxidized lignin exhibits a decrease in intensity of the signal corresponding to the γ- and β-hydrogens for the β-O-4 and β-5 lignin residues, together with the appearance of a new signal corresponding to the β-hydrogen of the oxidized β-O-4 residue. Moreover, the signal corresponding to the α-hydrogens of the β-O-4 lignin residues remain comparatively unchanged, supporting preferential oxidation of the primary aliphatic over the secondary benzylic alcohol groups.

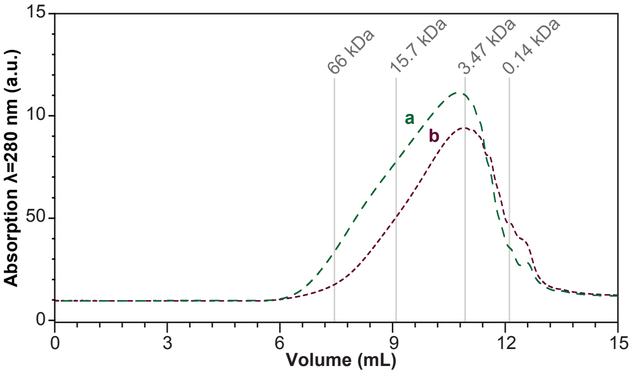


Figure 6. GPC chromatograms of (a) untreated and (b) oxidized poplar lignin. Conditions: PSS PolarSil Linear S column with solution of 0.1 M lithium bromide (LiBr) in dimethyl formamide (DMF) as the mobile phase (flow rate of 0.3 mL/min).

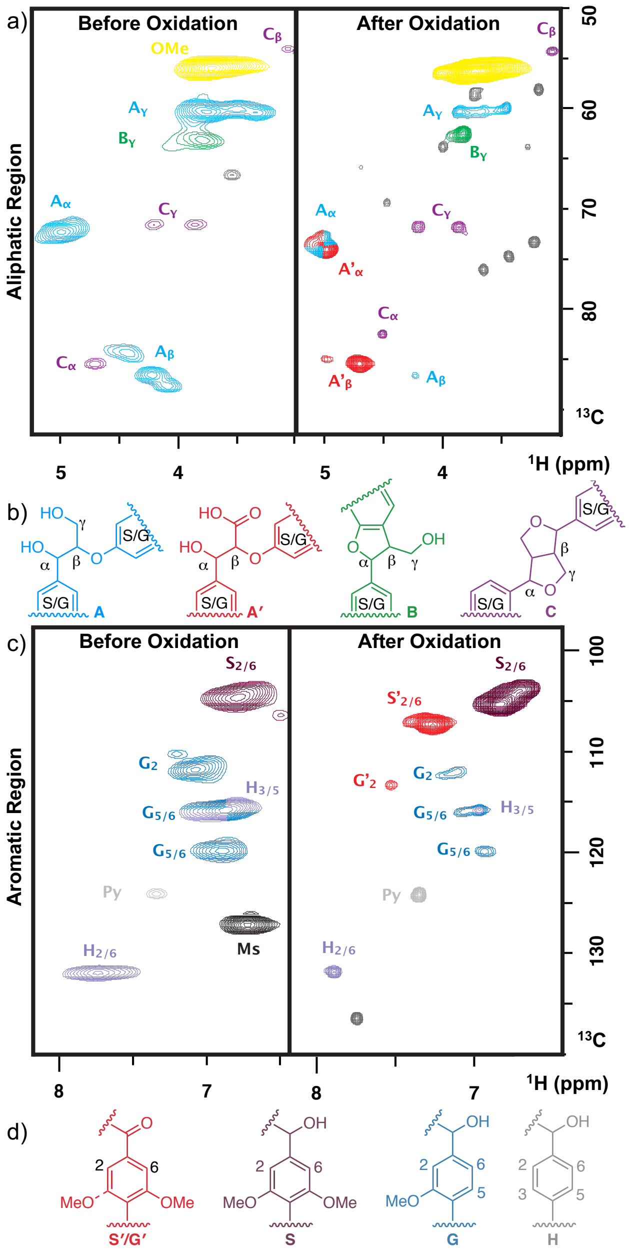


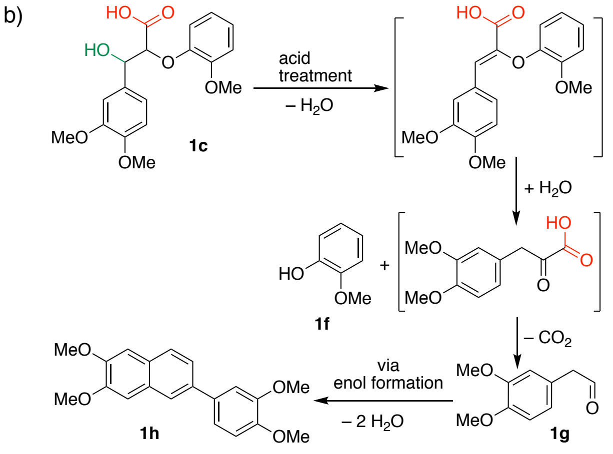
Figure 7. HSQC spectra of lignin before (left) and after (right) ACT-mediated electrochemical oxidation: a) aliphatic region, and c) aromatic region, b) and d) structures of lignin fragments with corresponding NMR signals.

Depolymerization of Carboxylated Lignin. The pH-dependent bulk electrolysis results in Table 2, together with the modest reduction in the molecular weight of the lignin polymer following oxidation at pH 10, suggested that it may be possible to achieve effective one-step oxidative depolymerization of lignin under more basic conditions. Efforts to achieve this goal, however, led to suboptimal results. Bulk electrolysis of the lignin sample at pH 12, for example, afforded ≤ 8 wt% yield of monomeric aromatic products relative to the mass of the initial lignin (see section 5 in the Supporting Information for details). The products derived from lignin depolymerization under these conditions are susceptible to recondensation/oligomerization or oxidative degradation.[78-82]

In order to bypass this complication, we targeted a two-step oxidation/depolymerization sequence in which the lignin polymer could be oxidized and then treated under modified conditions to induce depolymerization. Cleavage of β-hydroxy acids has been reported under basic conditions;[83] however, subjecting the oxidized model compound **1c** or oxidized lignin material to more basic conditions (0.1 M NaOH, see section 9, Supporting Information) afforded less than 5% yield of cleavage products. In contrast, treatment of the oxidized lignin model compound **1c** under various acidic conditions generated a mixture of the monomeric aromatic compounds, **1d-h** (Figure 8a). This distribution of products may be rationalized by the reaction sequence shown in Figure 8b. The process is initiated by acid-induced elimination of the benzylic hydroxyl group from **1a** to afford a vinyl ether that is susceptible to hydrolysis and generation of an α-ketoacid that resembles the Hibbert ketones.[84-86] Subsequent decarboxylation of the ketoacid generates the observed products, guaiacol **1f** and the aliphatic aldehyde **1g**. The aldehyde **1g** is susceptible to acid-catalyzed dimerization, via aldol condensation, electrophilic addition to the arene, and loss of water to form the naphthalene derivative **1h**. Building on a report by Barta and de Vries, the H_2SO_4 conditions from Figure 8a, entry 3 were repeated in the presence of ethylene glycol (eq 1).[87] Under these conditions, **1g** was trapped as the acetal **1i**, which prevented further conversion of **1g** into **1h**. In addition to the products obtained from the sequence in Figure 8b, a small quantity of products arising from retro-aldol cleavage of **1c,** generating **1d** and **1e** (Figure 8c) were also observed under the conditions noted in entries 1, 2, and 5 of Figure 8a.

a)

Entry	Acid Solution	t (h)	**1c**	**1f**	**1g**	**1h**(x2)	**1d**	**1e**	Yield
1	H_2O/Acetone (50/50) **1M HCl**	6	4	66	38	34	11	9	84
2	H_2O/CH_3CN (50/50) **1M HCl**	4	–	69	41	44	5	–	90
3	H_2O/CH_3CN (50/50) **1M H_2SO_4**	3	–	73	66	29	–	–	95
4	H_2O/**HCO_2H** (10/90)	3	–	68	50	36	–	–	86
5	H_2O/**CH_3CO_2H** (10/90)	12	52	15	21	5	16	11	42



c) Minor Pathway

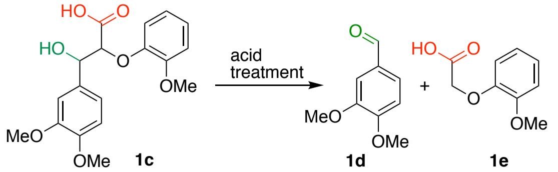


Figure 8. Acid-induced cleavage data with **1c** (a) together with major and b) minor cleavage pathways that explain the origin of the observed depolymerization products. Reaction conditions for (a): 70 mg **1c**, 5 mL solvent, 110 °C (100 °C for entry 3), yields of **1d-h** determined by ^{1}H NMR spectroscopy (int. std. = trimethoxybenzene). Note: yield obtained for **1h** is multiplied by two to account for the dimeric nature of this product.

The oxidized lignin sample described above was then subjected to the H_2SO_4 conditions (Figure 8a, entry 3), which afforded the highest yield of cleavage products, and the H_2O/HCO_2H conditions (Figure 8a, entry 4), which were used previously in the cleavage of lignin oxidized at the benzylic position.[26] Both conditions induced depolymerization of the resulting lignin, as revealed by GPC analysis of the material (cf. Figure S8). HPLC analysis of the product mixtures revealed significant quantities of aromatic products (Figure 9), with higher depolymerization yields from treatment with formic acid relative to those obtained when using sulfuric acid: 29 wt% (H_2O/HCO_2H) and 24 wt% (H_2SO_4; yields reported vs the original mass of untreated lignin). The significant yield of syringyl (S)- and guaiacyl (G)-derived aldehydes is consistent with the reactivity observed with the model compound **1c** in Figure 8b and 8c. On the other hand, the significant yield of S- and G-derived α-diketones and carboxylic acids suggests that other cleavage pathways are occurring within the oxidized lignin that are not evident from the oxidized model compound **1c**. We note that the HSQC NMR data in Figure 7 indicates the electrochemical oxidation leads to some oxidation of the benzylic alcohol groups, in addition to oxidation of the primary alcohols that produce the carboxylated lignin. Acid treatment of lignin oxidized at the benzylic position has been shown to generate α-diketones.[26]

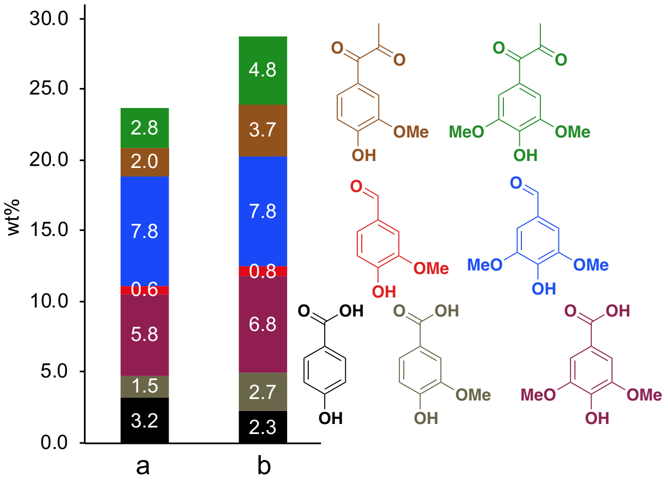


Figure 9. Aromatic monomers (weight percent) obtained from treatment of oxidized lignin with (a) sulfuric acid and (b) formic acid. Reaction conditions: 50 mg oxidized lignin, 6 mL 1 M H_2SO_4 in CH_3CN for (a) and 5 mL H_2O/HCO_2H 1:9 for (b), 100 °C for 12 h for (a) and 110 °C for 24 h, product yields determined by HPLC (see Supporting Information for details).

Overall, the results show that oxidation of the primary alcohols within lignin provides the basis for effective depolymerization of lignin into low molecular weight aromatic compounds. The yields of aromatic monomers are somewhat lower than those obtained from oxidation methods that favor reaction with the benzylic position;[26,39] however, optimal results can vary as a function of the biomass source material, lignin extraction method, among other variables. In this context, the present methods offer a useful complement for future consideration.

Conclusion.

The aminoxyl-mediated electrochemical oxidation method described here exhibits high selectivity for oxidation of primary alcohols groups within lignin model compounds, and the method has been shown to be effective for the oxidation of lignin extracted from poplar. Structure-reactivity correlations of small molecules has provided valuable insights into the reaction selectivity, including the synergistic role of other functional groups within the lignin structure on the oxidative reactivity of the alcohols. Conversion of the primary alcohols in lignin to carboxylic acids results in formation of a polyelectrolyte that is complementary to established lignosulfonate materials[88] and that warrants further investigation among the growing number of other lignin-derived polymer applications.[89-91] In addition, the electrocatalytic oxidation method renders the modified lignin susceptible to depolymerization, allowing for conversion of lignin into monomeric aromatic chemicals in good yields.

ASSOCIATED CONTENT

Supporting Information. Experimental procedures and compound characterization data (PDF).

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Notes

A patent application describing some of the content described in this study has been submitted.[67]

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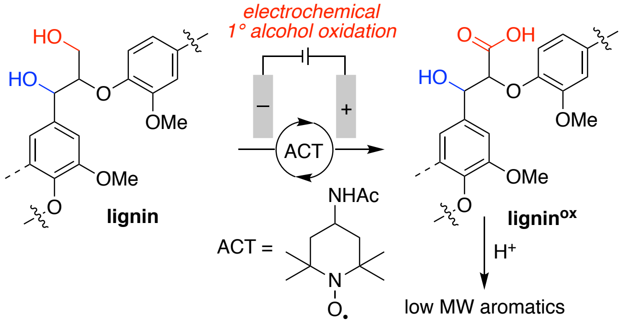
TOC Graphic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