Cobalt–Schiff Base Complex Catalyzed Oxidation of Para-Substituted Phenolics. Preparation of Benzoquinones

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Para-substituted phenolics, serving as models for lignin (a renewable source of carbon), are oxidized to the corresponding benzoquinone with oxygen in the presence of catalytic amounts of Co–Schiff base complexes. The reaction products observed depend on the structure of the catalyst. The 5-coordinate catalysts (pyridine)[bis(salicylidene)ethylenediamine)cobalt [(pyr)Co(salen)] and [bis-[(salicylideneamino)ethyl]amine]cobalt [Co(*N*-Me salpr)] convert syringyl alcohol (3,5-dimethoxy-4-hydroxybenzyl alcohol) to 2,6-dimethoxybenzoquinone in high yield. In contrast, syringaldehyde (3,5-dimethoxy-4-hydroxybenzaldehyde) is unreactive toward these catalysts. However, the 4-coordinate Co(salen) converts syringaldehyde to 2,6-dimethoxybenzoquinone in 72% isolated yield. Phenols bearing a single methoxy group on the ring are unreactive toward any catalyst in MeOH. However, vanillyl alcohol (3-methoxy-4-hydroxybenzyl alcohol) is converted to 2-methoxybenzoquinone with Co(*N*-Me salpr) and oxygen in 43% yield in CH_2Cl_2, and 58% yield in CH_2Cl_2 in the presence of 1% $CuCl_2$. The success of the oxidations appears to be related to the ease of removal of the phenolic hydrogen by the Co/O_2 complex. Competitive deactivation of the catalyst occurs with substrates of lower reactivity.

Introduction

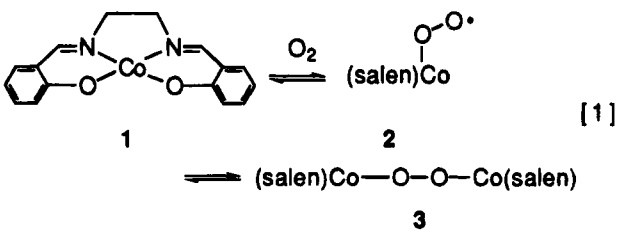
Developing renewable biomass as a raw material for the production of chemicals is an important component of the nation's energy policy to decrease dependence on fossil-derived feedstocks. One of the most underused renewable carbon sources in the biosphere is lignin, the structural material in woody plants, which makes up as much as 30% of the carbon bound in organic matter.[1] However, lignin is largely used in low-value applications; one of its primary uses is as a fuel for chemical recovery operations in the pulp and paper industry. The difficulty in using lignin in a wider range of applications results from its heterogeneous structure. Effective use of lignin as a chemical feedstock requires developing selective transformations that can convert its wide range of substructural features into a *single* material in high yield. Our efforts have focused on the unifying structural feature of lignin, its network of oxygenated aromatic rings. The oxygen substituents render the aromatic rings susceptible to oxidation. Several industrial processes are based on nonselective or low yield oxidation of lignin.[2]

A study of compounds that model major substructural units in lignin could provide useful information for the development of selective, high-yield processes for lignin oxidation. The process investigated in this study was the oxidation of para-substituted phenolics to benzoquinones. Benzoquinones are versatile compounds, widely used as intermediates for dye production and as selective oxidants, and are well known as key structural units in a variety of biologically active materials.[3]

Many oxidative reactions exist for preparing benzoquinones from phenolics.[3] However, the great majority of the reported oxidations are performed on phenolics that have no substituent para to the hydroxyl group of the phenol. In contrast, *every* phenolic unit in lignin contains a substituent para to the hydroxyl group. This para substituent must be selectively cleaved to realize a successful benzoquinone synthesis. We report that certain para-substituted phenolics can be cleanly oxidized to benzoquinones with oxygen in the presence of Co–Schiff base complexes.

Results and Discussion

A wide range of organometallic complexes are known to reversibly bind oxygen.[4] The best examples of such materials are Co–Schiff base complexes, typified by [bis-(salicylidene)ethylenediamine]cobalt [Co(salen), **1**, eq 1).[5]



[1]

1 **2** **3**

The reversible reaction of Co(salen) and related com-

[⊗] Abstract published in *Advance ACS Abstracts,* March 15, 1995.

(1) Fengel, D.; Wegener, G. *Wood: Chemistry, Ultrastructure and Reactions*; Walter DeGruyter: New York, 1984; Chapter 6.

(2) DMSO and vanillin are two products prepared commercially from lignin: see ref 1, Chapter 18.

(3) Patai, S., Rappoport, Z., Eds. *The Chemistry of the Quinonoid Compounds*; Wiley: New York, 1988; Volume 2, parts 1 and 2. The work of Saá should also be consulted; for example, see: Saá, J. M.; Morey, J.; Rubido, C. *J. Org. Chem.* **1986**, *51*, 4471.

(4) (a) Jones, R. D.; Summerville, D. A.; Basolo, F. *Chem. Rev.* **1978**, *78*, 139. (b) Drago, R. S.; Corden, B. B. *Acc. Chem. Res.* **1980**, *13*, 353. (c) Niederhoffer, E. C.; Timmons, J. H.; Martell, A. E. *Chem. Rev.* **1984**, *84*, 137. (d) Busch, D. H. In *Oxygen Complexes and Oxygen Activation by Transition Metals*; Martell, A. E., Sawyer, D. T., Eds.; Plenum: New York, 1988; p 61.

(5) (a) Van Dort, H. M.; Geursen, H. J. *Recl. Trav. Chim.* **1967**, *86*, 520. (b) Vogt, L. H., Jr.; Wirth, J. G.; Finkbeiner, H. L. *J. Org. Chem.* **1969**, *34*, 273. (c) Tomaja, D. J.; Vogt, L. H., Jr.; Wirth, J. G. *J. Org. Chem.* **1970**, *35*, 2029. (d) Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981; Chapters 4 and 12.

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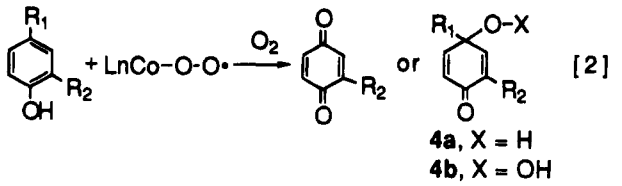
plexes with oxygen gives an equilibrium mixture of Co–superoxo complex **2**, and the dimeric peroxo complex **3**. The relative proportion of complexes similar to **1–3** in solution depends strongly on the nature of the starting Co complex and the reaction conditions.[6]

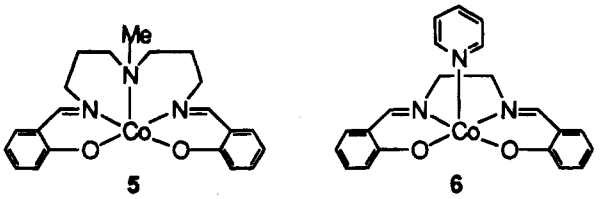
Co(salen)/O_2 adducts have been demonstrated as effective for synthesizing benzoquinones from phenolics unsubstituted in the position para to the hydroxyl group (eq 2, R_1 = H).[5]



[2]

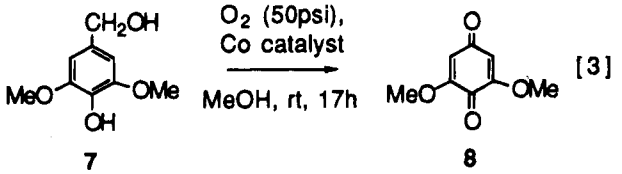
However, few examples are known using Co/O_2 complexes for oxidizing para-substituted phenolics (eq 2, $R_1 \neq$ H). Successful reactions are limited to phenolics substituted with simple alkyl groups, not representative of typical lignin structures.[7] Moreover, reported oxidations generally do not give benzoquinones as the primary products. Instead, quinols **4a** or hydroperoxides **4b** are observed.[7a]

We investigated several Co–Schiff base complexes as oxidation catalysts for para-substituted phenolics, including **1**, the related Co catalyst, [bis[(salicylideneamino)-ethyl]amine]cobalt [Co(*N*-Me salpr), **5**], and complex **6** formed between **1** and pyridine.



The reactivity observed between the Co/O_2 complexes and para-substituted phenolics is strongly affected by the coordination about the cobalt. 4-Coordinate complexes, such as **1**, bind oxygen poorly at room temperature in solution; the amount of superoxo complex **2** present is normally low.[8] In contrast, 5-coordinate complexes, such as **5** or **6**, bind oxygen strongly. The presence of a donor ligand in the axial position of the complex stabilizes the Co–O_2 bond.[9]

Equation 3 shows typical conditions for the oxidations.

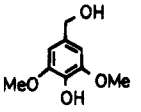
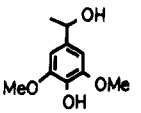
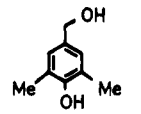
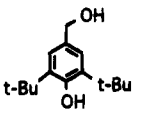
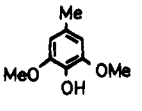
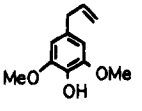
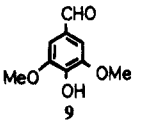
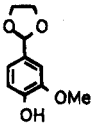
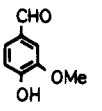
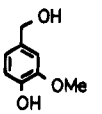


[3]

Treatment of syringyl alcohol (**7**) with O_2 in the presence of 10% of 5-coordinate catalysts **5** or **6** gave 2,6-dimethoxybenzoquinone (**8**) in 71 and 88% yield, respectively. Oxidation of **7** also occurred in 90% yield using 5 mol % of **6**, but lowering the catalyst level to 1%, gave quinone in only 9%. Importantly, the side chain of **7** was cleaved, leading to **8**.

5-Coordinate Co catalysts are also useful for converting other para-substituted phenolics to quinones, as summarized in Table 1. Substitution at the α-position of the side chain did not affect the oxidation (entry 2). Alkyl substituted phenols were also converted in high yield to the corresponding quinone (entries 3 and 4). We observed incomplete oxidation with several of the substrates, as indicated by the presence of the corresponding aldehyde. If the side chain para to the aromatic hydroxyl

Table 1. Summary of Cobalt-Catalyzed Oxidation of Para-Substituted Phenolics in MeOH

Entry	Substrate	Quinone Yield (%)[a]	Aldehyde Yield (%)[b]	Catalyst
1		88	4	6
		90	6	6 (5%)
		9	8	6 (1%)
		71	23[a]	5
		28	50	1
2		82	4% ketone	6
		68	0	5
3		70	trace	5
4		86	0	5
5		11	45	5
6		17	10	5
7	 **9**	72		1
8	 **17**	27	0	1
9	 **19**	trace[b]		all
10	 **21**	12[b]	3	5

[a] Yields are for isolated material. In some cases, NMR analysis of the residue indicated the presence of 3-15% additional quinone. See Experimental Section. [b] Yield estimated from NMR integration.

(6) (a) Floriani, C.; Calderazzo, F. *J. Chem. Soc. A* **1969**, 946. (b) Chen, D.; Martell, A. E. *Inorg. Chem.* **1987**, *26*, 1026. (c) Chen, D.; Martell, A. E.; Sun, Y. *Inorg. Chem.* **1989**, *28*, 2647.

(7) (a) Nishinaga, A.; Watanabe, K.; Matsuura, T. *Tetrahedron Lett.* **1974**, 1291. (b) Frostin-Rio, M.; Pujol, D.; Bied-Charreton, C.; Perree-Fauvet, M.; Gaudemer, A. *J. Chem. Soc., Perkin Trans. 1* **1984**, 1971. (c) Nishinaga, A.; Iwasaki, H.; Shimizu, T.; Toyoda, Y.; Matsuura, T. *J. Org. Chem.* **1986**, *51*, 2257.

Table 2. Oxidation of Substrates under Conditions Favorable for the Oxidation of 9

Compound	7	10	11
Quinone (%)	28	20	17
Aldehyde (%)	50	0	10

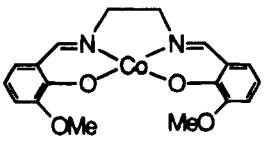
group is alkyl, complete oxidation to quinone is difficult. Oxidation of 2,6-dimethoxy-4-methylphenol gave only 11% quinone but 45% aldehyde (entry 5).

The oxidation of syringaldehyde (**9**) (entry 7) reveals an interesting dependence of the oxidation on catalyst structure. Catalyst **1** and O_2 in MeOH convert syringaldehyde to quinone in 72% yield. However, changing from a 4-coordinate catalyst to a 5-coordinate catalyst, such as **5** or **6**, inhibited the oxidation; only starting material was recovered (>90% yield). Syringaldehyde is unique in undergoing oxidation *only* when 4-coordinate **1** is used as a catalyst.

In contrast, attempted oxidation of compounds **7**, **10**, and **11** using **1** as the catalyst gave poor yields of benzoquinone (Table 2). A 50% yield of syringaldehyde was observed in the oxidation of compound **7** using **1** as the catalyst. The reactions of **10** and **11** were nonselective. On the basis of the observed reactivity of syringaldehyde with Co(salen) and oxygen, we believe that **7** is first oxidized to syringaldehyde, and then to quinone.

The reaction of syringaldehyde with Co/O_2 complexes was also carried out in the presence of increasing amounts of pyridine. In the absence of pyridine, oxidation of **9** with catalyst **1** proceeded in 72% yield. However, adding 10% pyridine to **1** (i.e., catalyst **6**) caused the quinone yield to drop to 54%, the remainder being starting material. When an amount of pyridine equimolar with **9** was added, the oxidation was completely suppressed. We conclude from these observations that **9** coordinates to the metal center prior to oxidation.[10] Only 4-coordinate catalysts can accommodate both a molecule of substrate and oxygen simultaneously. Increasing the amount of pyridine gradually eliminates the availability of an open coordination site and ultimately stops the reaction. The effectiveness of the oxidation of **9** suggests that other factors may be promoting the reaction because of the transient nature of Co/O_2 adducts formed from 4-coordinate Co species. Coordination of **9** to **1** may stabilize the resulting Co/O_2 adduct in a manner similar to pyridine in complex **6**, however, we have no evidence to support that hypothesis.

Further supporting evidence for prior coordination of **9** to the Co center comes from its oxidation using a more electron rich 4-coordinate Co complex, Co(3-methoxysalen) (**12**).



12

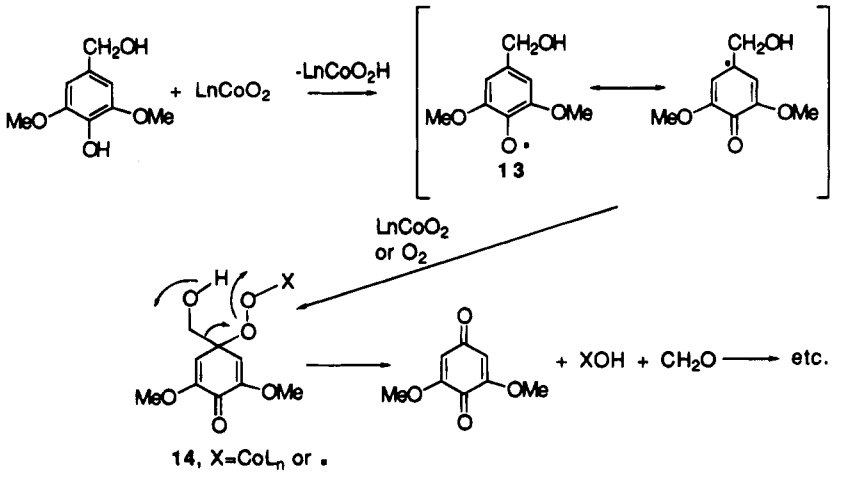
The inductive effect of the electron-donating methoxy groups lowers the Lewis acidity of the Co, and hence, **9** would be expected to coordinate to the Co center more poorly. In accordance with this hypothesis, **9** was oxidized to quinone in 60% yield when **12** is used as the catalyst.

The proposed mechanism for the Co–Schiff base catalyzed oxidation of phenolics is shown in Scheme 1.[11]

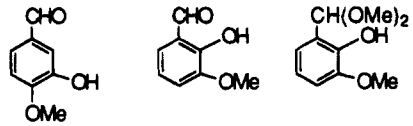
Reaction of the Co complex with oxygen gives a superoxo Co/O_2 adduct (e.g, **2**).[12] This complex abstracts the phenolic hydrogen giving a phenoxy radical **13**. Intermediate **13** is trapped by a second molecule of the Co superoxo complex or oxygen, generating intermediate **14**. Complexes structurally analogous to **14** ($X = CoL_n$) have been isolated and characterized when oxidation of phenols is carried out with stoichiometric amounts of Co/O_2 complexes.[12] Elimination of a molecule of formaldehyde from complex **14** generates quinone and, when $X = CoL_n$, a Co–hydroxy species, known to be catalytically active.[13] Alternatively, L_nCoOOH, formed in the first step of the reaction, breaks down to regenerate the starting catalyst.[11b]

When the substrate is changed from a species bearing two methoxy groups to one bearing a single methoxy group (Table 1, entries 8–10) little or no oxidation to quinone is observed in MeOH using *either* 4- or 5-coordinate Co catalysts. Starting material is the primary product recovered in the reaction of vanillin (**19**) or vanillyl alcohol (Table 1, entries 9 and 10). The failure of these substrates to undergo oxidation is apparently not a function of the presence or absence of a substituent

Scheme 1. Proposed Mechanism for the Oxidation of Para-Substituted Phenolics to Quinones

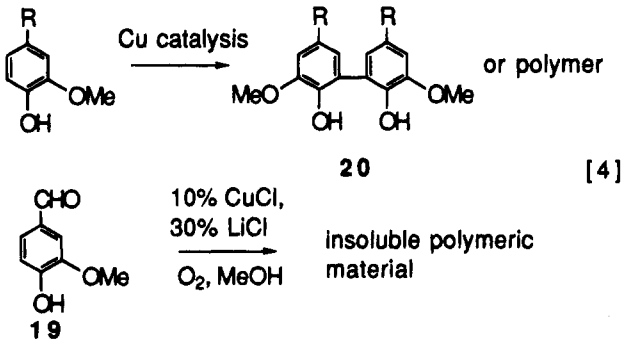


para to the hydroxyl group. Compounds **15** and **16** did not undergo oxidation to quinone under our reaction conditions. However, aldehyde acetals **17** and **18** underwent oxidation to quinone. (Table 1, entry 8 or **18**, oxidized to quinone in 91% yield[14].)



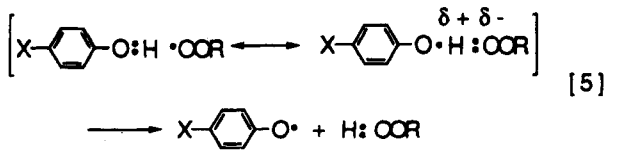
15 **16** **18**

We attribute this observation to an inability of the catalyst mixture to rapidly form a phenoxy radical from the substrate (e.g., **13**, Scheme 1). The reaction of similar monomethoxy substrates with Cu catalysts provides support for this hypothesis. These catalysts readily form phenoxy radicals from compounds similar to vanillin (**19**).[15] Products resulting from radical reactions are observed, for example, the dimer **20** (eq 4), formed by



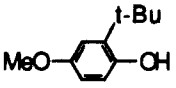
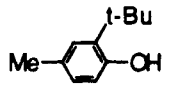
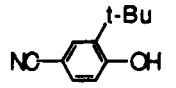
coupling two phenoxy radicals in the position ortho to the hydroxyl group.[16] We have examined the Cu-catalyzed oxidation of vanillin by oxygen in MeOH and observe complete consumption of the starting material to give an insoluble polymer. Polymeric materials or compounds similar to **20** are not formed under Co-catalyzed conditions, implying the absence of phenoxy radicals.

The electronic nature of the aromatic ring may have a significant bearing on the ability of the catalyst system to convert the starting phenol into a phenoxy radical. In general, electron-donating substituents on the ring promote the formation of phenoxy radicals while electron-withdrawing groups slow the reaction.[17] This observation has been attributed to polar character developed in the transition state for hydrogen removal and appears to be independent of the structure of the peroxy radical removing the hydrogen (eq 5).[18]



The OH bond strength is also affected by the substituents present on the aromatic ring. Several studies show that electron-donating groups on the ring lower the bond energy of the OH bond.[19]

Table 3. Selected Relative Rates of Phenolic Hydrogen Abstraction by Styrylperoxy Radical[20]

Compound	$\Sigma\sigma^+$	relative rate of H abstraction
	-1.034	123
	-0.567	28
	+0.403	1

In the absence of unusual steric factors, the promoting effect of methoxy groups on phenoxy radical formation is striking. In studies on the inhibition of styrene autoxidation by different phenols, Ingold reported a good correlation between reaction rates and Hammett σ^+ constants; the more negative the total value of the σ^+, the greater the rate of the reaction (Table 3).[20,21] More recently, Griller reported good correlation between OH bond energies, rate constants for hydrogen removal, and Hammett σ^+ substituent constants.[22] The large negative σ^+ value (−0.78) for the methoxy group suggests that significant differences in the rate of phenoxy radical formation could exist between monomethoxy- and dimethoxy-substituted substrates.[23] More generally, there may be a threshold $\Sigma\sigma^+$ value for certain substrates, above which oxidation in MeOH is favorable (for example, Table 1, entries 3 and 4).

The rate of hydrogen abstraction from the phenolic hydroxyl group is important to the success of a Co-catalyzed oxidation. Irreversible oxidation of the catalyst is a primary deactivation pathway in many processes involving Co−Schiff base complexes.[4d] We observed that treating 4-coordinate Co complexes (**1** or **12**) with oxygen in MeOH in the absence of substrate results in a rapid

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(9) Basolo, F.; Hoffman, B. M.; Ibers, J. A. *Acc. Chem. Res.* **1975**, *8*, 384.
(10) Fujii, T.; Kouno, T. K.; Ono, Y.; Ueda, Y. *Chem. Pharm. Bull.* **1981**, *29*, 1494.
(11) (a) Nishinaga, A.; Tomita, H. *J. Mol. Catal.* **1980**, *7*, 179. (b) Zombeck, A.; Drago, R. S.; Corden, B. B.; Gaul, J. H. *J. Am. Chem. Soc.* **1981**, *103*, 7580. (c) Corden, B. B.; Drago, R. S.; Perito, R. P. *J. Am. Chem. Soc.* **1985**, *107*, 2903.
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(14) Hibino, S.; Weinreb, S. M. *J. Org. Chem.* **1977**, *42*, 232.
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(16) (a) Omura, K. *J. Org. Chem.* **1991**, *56*, 921. (b) Forsskåhl, I. *J. Photochem.* **1984**, *27*, 363.
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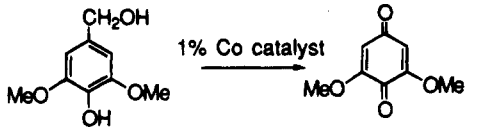
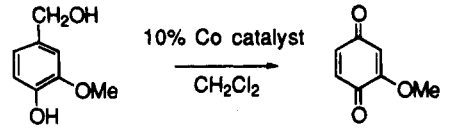
Table 4. Promotion of Oxidation Reactions



Additive	Yield	Solvent
none	9%	MeOH
Fremy's salt	29%	MeOH



21 22

Additive	Yield	Solvent
none	12%	MeOH
none	43%	CH_2Cl_2
1% $CuCl_2$	58%	CH_2Cl_2

reaction to give a new Co complex.[24] This complex has not been completely characterized, but elemental analysis reveals that its oxygen content has increased. More importantly, this complex is inactive as an oxidation catalyst. Thus, if a substrate of low reactivity is used, the rate of hydrogen abstraction is slow and the catalyst can instead undergo rapid deactivation by reaction with oxygen and MeOH. Certain substrates of low reactivity will undergo oxidation to quinone in higher yield when the solvent is changed from MeOH to CH_2Cl_2. Vanillyl alcohol (**21**) is converted to monomethoxybenzoquinone (**22**) in only 12% yield when the reaction is performed in MeOH. The yield increases to 43% when the solvent is changed to CH_2Cl_2 (Table 4).

Because certain substrates appear to form phenoxy radicals more slowly, we have investigated promoting the oxidation of less reactive substrates by performing the reaction in the presence of reagents known to form phenoxy radicals.

Initial experiments were performed with a relatively reactive substrate, syringyl alcohol (**7**). In the presence of oxygen and 1% catalyst **5**, an amount known to be too low to promote effective reaction, oxidation of **7** to quinone occurred in low yield. The remainder of the reaction mixture contained starting material. However, when 1% Fremy's salt was added, the isolated yield of quinone rose to 29%. Fremy's salt readily forms phenoxy radicals and could increase the reactivity by increasing the relative concentration of phenoxy radicals in the reaction mixture.[25]

An even more dramatic change was observed with substrates unreactive in the presence of Co catalysts in MeOH. Adding 1% $CuCl_2$ as a cocatalyst to a mixture of **21** and the 5-coordinate catalyst **5** in CH_2Cl_2 afforded **22** in 58% isolated yield, implying that increased levels of phenoxy radical could be important in the promotion of the oxidation. The mechanism of this promotion effect of $CuCl_2$ is not known. Reaction of **21** with $CuCl_2$ catalyst alone gives only starting material.

The presence of a polar transition state (eq 5) also suggests that a solvent effect on rate should be observed. The rate of hydrogen abstraction from phenols can be correlated with the hydrogen-bonding ability of the solvent.[26] In general, stronger hydrogen bonding solvents slow the rate of the reaction. The increase in yield observed for the oxidation of **21** in CH_2Cl_2 is consistent with this observation. The failure of **21** to undergo reaction in MeOH is surprising, since its $\Sigma\sigma^+$ value is close to that of phenols found to undergo ready oxidation. A steric effect may be involved. The presence of two groups ortho to the hydroxyl group of the phenols may weaken hydrogen bonding interactions and permit oxidation to occur.

At present, the promotion effect of $CuCl_2$ appears to be limited to benzylic alcohols. Attempted application to aldehydes (e.g., **9** and **19**) results in recovery of starting material.

Experimental Section

General. *CAUTION: The reactions are carried out in thick walled glass reactors under oxygen pressure. While we experienced no difficulties in performing these reactions, appropriate precautions should always be used when combining organic materials and oxygen under pressure.* ^1H and ^{13}C nuclear magnetic resonance spectra were measured in $CDCl_3$ solution using a Varian Unity 300 instrument at 300 and 75 MHz respectively. Chemical shifts are reported relative to tetramethylsilane (^1H) or solvent resonance (^{13}C) and are reported in δ. Infrared spectra were measured on KBr pellets (0.5 wt %, 1.5 mg sample per 300 mg KBr) using a Nicolet 5SXC instrument equipped with a deuterated triglycine sulfate (DTGS) detector and are reported in reciprocal centimeters (cm^{-1}). Solvents were reagent grade and used without further purification unless otherwise noted. Routine column chromatography was performed using either Fisher 100–200 mesh silica or Aldrich 200–400 mesh silica. Rotary chromatography was performed on a Harrison Research Chromatotron using silica gel plates.

3,5-Di-*tert*-butyl-4-hydroxybenzyl alcohol, 3,5-dimethyl-4-hydroxybenzyl alcohol, and α-methyl-3,5-dimethoxy-4-hydroxybenzyl alcohol were prepared by reduction of the corresponding aldehyde according to a published procedure for the preparation of apocynol.[27]

3,5-Di-*tert*-butyl-4-hydroxybenzyl Alcohol: Mp 141–142 °C (lit.[28] mp 141–142 °C); ^1H NMR ($CDCl_3$) 1.44, 4.58, 5.22, 7.18.

3,5-Dimethyl-4-hydroxybenzyl Alcohol: Mp 104–105 °C (lit.[29] mp 105 °C); ^1H NMR ($CDCl_3$) 1.48, 2.24, 4.53, 4.85, 6.97.

α-Methyl-3,5-dimethoxy-4-hydroxybenzyl Alcohol: Mp 87–90 °C (lit.[30] 91–93 °C); ^1H NMR ($CDCl_3$) 1.45, 3.86, 4.79, 5.45, 6.58.

Acetal **15** was prepared according to literature methods.[31] All other substrates were purchased from either Aldrich or Lancaster Synthesis and used as received. Co(salen) (**1**), Co(*N*-Me salpr) (**5**), $(KSO_3)_2NO$ (Fremy's salt), and $CuCl_2$ were purchased from Aldrich and used as received. Co(3-methoxysalen) (**12**), was prepared from 3-methoxysalicylaldehyde and ethylenediamine using a published procedure for Co(3-ethoxysalen).[32]

General Method for the Oxidation of Para-Substituted Phenols. The phenolic substrate and the cobalt catalyst were combined in the reaction solvent (5 mL per mmol

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substrate) in a 150 mL Fisher-Porter bottle. The bottle was fitted with a pressure head, flushed three times with oxygen, and pressurized with oxygen to 50 psi. Catalyst **6** was prepared *in situ* by combining Co(salen) (**1**) and pyridine (80 μL per mmol substrate) and stirring at room temperature for 15 min before adding substrate and oxygen. All reactions were stirred at room temperature for 17–24 h. At the completion of the reaction, the products were isolated using one of the following four procedures. Reported yields generally refer to isolated, purified products, homogeneous by spectral analysis and with physical properties identical to literature reports. The analysis of certain product mixtures was estimated from NMR integration as indicated in the text. Percentages reported for analyses of mixtures are chemical yields.

Procedure A. Oxidation of Dimethoxyphenols in Methanol. The precipitate of dimethoxybenzoquinone (**8**) was isolated as a golden powder by gravity filtration: ^{1}H NMR ($CDCl_3$) 3.82, 5.85; ^{13}C NMR ($CDCl_3$) 56.5, 107.4, 157.3, 186.8; IR (KBr) 1697, 1624, 1380, 1323, 1261, 1220, 1006; mp 240–250 °C sublimes (lit.[33] mp 256 °C sublimes). The filtrate was further purified by the removal of solvent by rotary evaporation and separation of the residue by column chromatography (silica gel, 1:1 ether/hexane).

Procedure B. Oxidation of Dimethoxyphenols in Methylene Chloride. The solvent was removed by rotary evaporation. Methanol (5 mL per mmol substrate) was added to the residue and precipitated dimethoxybenzoquinone (**8**) was isolated by gravity filtration. Methanol was removed from the filtrate by rotary evaporation. The residue was purified by column chromatography (silica gel, 1:1 ether/hexane).

Procedure C. Oxidation of Monomethoxyphenols in Methanol. The solvent was removed from the crude reaction mixture by rotary evaporation and the residue was purified by column chromatography. Monomethoxybenzoquinone (**22**) and other products were isolated by elution with ether/hexane (2:1): ^{1}H NMR ($CDCl_3$) 3.76, 5.87, 6.64; ^{13}C NMR ($CDCl_3$) 56.1, 107.6, 134.4, 137.1, 158.5, 181.5, 187.3; IR (KBr) 1678, 1647, 1592, 1240, 1113; mp 141–145 °C (lit.[34] mp 142–146 °C).

Procedure D. Oxidation of Monomethoxyphenols in Methylene Chloride. The crude reaction mixture was transferred directly to a silica gel column. Monomethoxybenzoquinone (**22**) and other products were isolated by elution with ether/hexane (3:1).

Oxidation of Syringyl Alcohol (7) Catalyzed by Co(*N*-Me salpr) (5). Syringyl alcohol (185 mg, 1 mmol) and Co(*N*-Me salpr) (38 mg, 0.1 mmol) were combined in methanol according to the general method. Workup after 18 h (procedure A) gave dimethoxybenzoquinone (118 mg, 71%) and syringaldehyde (43 mg, 23%) as a beige solid.

Oxidation of α-Methyl-3,5-dimethoxy-4-hydroxybenzyl Alcohol (Table 1, Entry 2) Catalyzed by Co(*N*-Me salpr) (5). α-Methyl-3,5-dimethoxy-4-hydroxybenzyl alcohol (199 mg, 1 mmol) and Co(*N*-Me salpr) (39 mg, 0.1 mmol) were combined in methanol according to the general method. Workup after 24 h (procedure A) gave dimethoxybenzoquinone (114 mg, 68%).

Oxidation of 3,5-Dimethyl-4-hydroxybenzyl Alcohol (Table 1, Entry 3) Catalyzed by Co(*N*-Me salpr) (5). 3,5-Dimethyl-4-hydroxybenzyl alcohol (153 mg, 1 mmol) and Co(*N*-Me salpr) (39.5 mg, 0.1 mmol) were combined in methylene chloride according to the general method. Workup after 20 h (procedure D) gave 3,5-dimethylbenzoquinone (95 mg, 70%) as yellow needles and 57 mg of a yellow solid. NMR spectroscopy indicated that the solid contained 3,5-dimethyl-4-hydroxybenzyl alcohol (27%) and a trace of the corresponding dimethylbenzaldehyde.

Oxidation of 3,5-Di-*tert*-butyl-4-hydroxybenzyl Alcohol (Table 1, Entry 4) Catalyzed by Co(*N*-Me salpr) (5). 3,5-Di-*tert*-butyl-4-hydroxybenzyl alcohol (121 mg, 0.5 mmol) and Co(*N*-Me salpr) (21 mg, 0.05 mmol) were combined in methanol according to the general method for 20 h. The solvent was removed from the crude reaction mixture by rotary evaporation and the residue was purified by column chromatography (1:1 ether/hexane) to give 1,3-di-*tert*-butylbenzoquinone (95 mg, 86%) as a golden solid.

Oxidation of 3,5-Dimethoxy-4-hydroxytoluene (Table 1, Entry 5) Catalyzed by Co(*N*-Me salpr) (5). 3,5-Dimethoxy-4-hydroxytoluene (170 mg, 1 mmol) and Co(*N*-Me salpr) (39 mg, 0.1 mmol) were combined in methanol according to the general method. Workup after 24 h (procedure A) gave dimethoxybenzoquinone (19 mg, 11%) and 164 mg of a golden solid. NMR spectroscopy indicated that the solid contained syringaldehyde (44%), syringyl alcohol (44%), and a trace of unreacted starting material.

Oxidation of 4-Allyl-3,5-dimethoxyphenol (11) Catalyzed by Co(*N*-Me salpr) (5). 4-Allyl-3,5-dimethoxyphenol (0.18 mL, 1 mmol) and Co(*N*-Me salpr) (38 mg, 0.1 mmol) were combined in methanol according to the general method. Workup after 24 h (procedure A) gave dimethoxybenzoquinone (28.3 mg, 17%) and 94 mg of a golden solid. NMR spectroscopy indicated that the solid contained syringaldehyde (10%), 4-allyl-3,5-dimethoxyphenol (29%), and dimethoxybenzoquinone (11%).

Oxidation of Vanillyl Alcohol (21) Catalyzed by Co(*N*-Me salpr) (5). Vanillyl alcohol (154 mg, 1 mmol) and Co(*N*-Me salpr) (40 mg, 0.1 mmol) were combined in methanol according to the general method. Workup after 17 h (procedure C) gave 27.4 mg of a golden solid indicated by NMR spectroscopy to contain monomethoxybenzoquinone (12%) and vanillin (3%). A second pale yellow solid was isolated that contained vanillyl alcohol (129.4 mg, 84%).

Oxidation of Syringyl Alcohol (7) Catalyzed by Co(salen)/Pyridine (6). Co(salen) (**1**) (37 mg, 0.1 mmol), pyridine (80 μL) and syringyl alcohol (184 mg, 1 mmol) were combined in methanol according to the general method. Workup after 17 h (procedure A) gave dimethoxybenzoquinone (147 mg, 88%) and 21 mg of a golden solid. NMR spectroscopy indicated that the solid contained syringyl alcohol (2%), syringaldehyde (4%), and dimethoxybenzoquinone (6%).

Oxidation of α-Methyl-3,5-dimethoxy-4-hydroxybenzyl Alcohol (Table 1, Entry 2) Catalyzed by Co(salen)/Pyridine (6). Co(salen) (**1**) (33 mg, 0.1 mmol), pyridine (80 μL), and α-methyl-3,5-dimethoxy-4-hydroxybenzyl alcohol (198 mg, 1 mmol) were combined in methanol according to the general method. Workup after 24 h (procedure A) gave dimethoxybenzoquinone (138 mg, 82%) and 24 mg of a golden solid. NMR spectroscopy indicated that the solid contained dimethoxybenzoquinone (13%) and acetosyringone (3,5-dimethoxy-4-hydroxyacetophenone, 4%).

Oxidation of Vanillyl Alcohol (21) Catalyzed by Co(*N*-Me salpr) (5). Vanillyl alcohol (308 mg, 2 mmol) and Co(*N*-Me salpr) (79 mg, 0.2 mmol) were combined in methylene chloride according to the general method. Workup after 19 h (procedure D) gave monomethoxybenzoquinone (117 mg, 43%) and vanillyl alcohol (145 mg, 47%) as a beige solid.

Oxidation of Syringaldehyde (9) Catalyzed by Co(salen) (1). Syringaldehyde (364 mg, 2 mmol) and Co(salen) (65 mg, 0.2 mmol) were combined in methanol according to the general method. Workup after 20 h (procedure A) gave dimethoxybenzoquinone (242 mg, 72%) as a golden solid. NMR spectroscopy indicated that the residue after chromatography contained dimethoxybenzoquinone (15%).

Oxidation of Vanillin Acetal (17) Catalyzed by Co(salen) (1). Compound **17** and Co(salen) were combined in methanol according to the general method. After 17 h, the solvent was removed by rotary evaporation and the residue purified by rotary chromatography (2:1 hexane/EtOAc) to give monomethoxybenzoquinone (74 mg, 27%) as a yellow powder.

General Method for the Oxidation of Para-Substituted Phenols in the Presence of Radical Promoters. The phenolic substrate, cobalt catalyst, and the radical promoter were combined in the reaction solvent (5 mL per mmol substrate) in a 150 mL Fisher-Porter bottle. The bottle was fitted with a pressure head, flushed three times with oxygen, and pressurized with oxygen to 50 psi. All reactions were stirred at room temperature for 17–19 h. At the completion of the reaction, the products were isolated using procedure A, B, C, or D as previously described.

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Oxidation of Syringyl Alcohol (7) Catalyzed by Co(*N*-Me salpr) (5) and Fremy's Salt. Syringyl alcohol (368 mg, 2 mmol), Co(*N*-Me salpr) (8 mg, 0.02 mmol), and Fremy's salt (5 mg, 0.02 mmol) were combined in methanol according to the general method for promoted reactions. Workup after 17 h (procedure A) gave dimethoxybenzoquinone (98 mg, 29%) and 194 mg of a golden solid. NMR spectroscopy indicated that the solid contained syringyl alcohol (28%), syringaldehyde (20%), and dimethoxybenzoquinone (4%). An additional 66 mg (18%) of syringyl alcohol was recovered as a pale yellow solid.

Oxidation of Vanillyl Alcohol (21) Catalyzed by Co(*N*-Me salpr) (5) and $CuCl_2$. Vanillyl alcohol (154 mg, 1 mmol), Co(*N*-Me salpr) (40 mg, 0.1 mmol), and $CuCl_2$ (2 mg, 0.01 mmol) were combined in methylene chloride according to the general method for promoted reactions. Workup after 18 h (procedure D) gave monomethoxybenzoquinone (79 mg, 58%) as a golden solid and vanillyl alcohol (60 mg, 39%) as a beige solid.

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