Polymer Incarcerated Gold Catalyzed Aerobic Oxidation of Hydroquinones and Their Derivatives

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Polymer-incarcerated gold (PI Au) cluster catalysts mediated aerobic oxidation of hydroquinones and catechols to quinones very efficiently under mild conditions. The characteristic role of water in the reaction system was also observed.

Quinones and their derivatives are an important class of compounds not only in organic synthesis but also in biochemistry.[1] In organic chemistry, they are useful as oxidizing reagents[1,2] and starting materials for synthesis of polycyclic compounds[1,3,8c,9] Moreover, the redox properties of quinones are important for living cells, where ubiquinones (coenzymes Q) act as biochemical oxidizing agents to mediate the electron-transfer processes involved in energy production.[1] In plant tissues the plastquinone performs a similar function in photosynthesis.[1]

The most direct way to obtain quinone derivatives is oxidation of the corresponding hydroquinones. Whilst several metal-based oxidizing reagents, such as silver oxide,[4] silver carbonate,[5] potassium nitrosodisulfonate,[6] chromium oxidants,[7] hypervalent iodine,[8] and cerium ammonium nitrate (CAN),[9] have been developed, these reagents usually require stoichiometric amounts of metal oxidants, and thus a large amount of waste is formed. In this context, oxidation using molecular oxygen[10] or hydrogenperoxide[11] catalyzed by easily separable heterogeneous catalysts is ideal from the viewpoint of green chemistry, atom economy, combinatorial synthesis, etc.

Recently, we reported that gold nanocluster catalysts immobilized on polystyrene-based polymers with cross-linking moieties, PI Au, were highly effective for aerobic oxidation of alcohols to ketones and aldehydes in the presence of water and a base.[12] Since bases accelerated the alcohol oxidation reactions significantly in this process, we proposed that the α-hydrogens of alcohols were abstracted as protons by bases. On the basis of this assumption, we envisioned that acidic hydroquinones might be potentially reactive substrates for gold-catalyzed aerobic oxidation. Here, we report aerobic oxidation of hydroquinones to quinones catalyzed by PI Au under very mild conditions, and the characteristic role of water in this reaction is also described. To the best of our knowledge, this is the first example of aerobic oxidation of hydroquinones to quinones facilitated by gold catalysts.[13]

PI Au, which was prepared according to the reported method,[12] was used in the aerobic oxidation of methylhydroquinone (**2a**) to toluquinone (**2d**) under atmospheric oxygen. When benzotrifluoride (BTF) was used as a solvent, the desired product was obtained in low conversion and low selectivity (Table 1, Entry 1). Addition of water dramatically increased conversion and selectivity (Entry 2). Screening of organic solvents revealed that dichloromethane is a suitable solvent for achieving high conversions (Entries 2–4). The selectivity was improved when the reaction was carried out at 0 °C or the volume and the ratio of the organic solvent was increased (Entries 5–7, 9, and 10), although the reaction was sluggish in the absence of water (Entries 1 and 11). Similar results were obtained when atmospheric air was used instead of oxygen (Entry 8). Further optimization has revealed that the conditions shown in Entry 12 were the best, where excellent conversion and selectivity have been achieved. It is noted that no leaching of Au to the reaction mixture was observed by Inductive Coupled Plasma (ICP) analysis (<0.04%) (Entries 5–7 and 12).

Table 1. Aerobic oxidation of methylhydroquinone (**2a**) to toluquinone (**2d**) in the presence of PI Au (1 mol %) under O_2

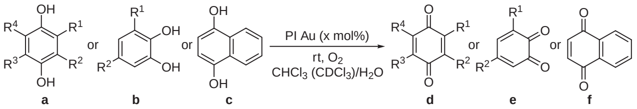
Entry	Solvent (mL/mmol substrate)	T	t/h	Conversion /%[a]	Selectivity /%[a,b]	Yield /%[a]
1	BTF (4.0)	rt	12	12	25	3
2	BTF (4.0)/H_2O(4.0)	rt	12	73	51	37
3	Toluene(4.0)/H_2O(4.0)	rt	12	82	29	24
4	CH_2Cl_2(4.0)/H_2O(4.0)	rt	12	85	24	20
5[d]	CH_2Cl_2(7.6)/H_2O(0.4)	rt	5.5	98	96	94
6[c,d]	CH_2Cl_2(7.6)/H_2O(0.4)	rt	5.5	>99	93	93
7[d]	CH_2Cl_2(22.8)/H_2O(1.2)	rt	1	>99	>99	>99
8[c]	CH_2Cl_2(22.8)/H_2O(1.2)	rt	1	>99	>99	>99
9	CH_2Cl_2(4.0)/H_2O(4.0)	0	6	88	67	57
10	CH_2Cl_2(7.6)/H_2O(0.4)	0	6	91	91	83
11	CH_2Cl_2(8.0)	0	6	13	>99	13
12[d]	$CHCl_3$(7.6)/H_2O(0.4)	rt	1	98	>99	98

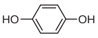
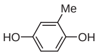
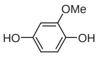
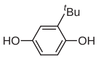
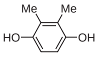
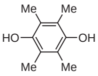
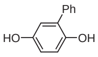
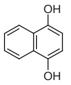
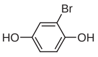
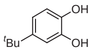
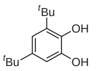
[a]Determined by GC analysis. [b]Selectivity = yield of **2d**/conversion. [c]Atmospheric air was used instead of O_2. [d]No leaching of Au to the reaction mixture was observed by ICP analysis.

With the optimal conditions in hand, several hydroquinone derivatives and catechols were oxidized by PI Au under atmospheric oxygen or air. Hydroquinone (**1a**) was oxidized smoothly to give 1,4-quinone in good yield even in the presence of 0.5 mol % of the catalyst or under atmospheric air (Table 2, Entries 1 and 2). Hydroquinones with alkyl substituents **2**–**6a** were also oxidized to afford the corresponding quinone derivatives in excellent yields (Entries 3–7).[14] Phenylhydroquinone (**7a**) and naphthoquinone (**8c**) were also converted to the oxidized products under the same conditions (Entries 8 and 9). While oxidation of electron poor bromohydroquinone (**9a**) was slow, the reaction was accelerated by addition of a base, affording bromoquinone in moderate yield (Entry 10). Oxidation of catechols **10b** and **11b** was also accelerated by a base, providing the corresponding *o*-quinones in high yields (Entries 11 and 12). It should be noted that in most cases analytically pure products were obtained in excellent yields by simple phase separation without further purification.

Although the extensive mechanistic study has not yet been

Table 2. PI Au-catalyzed oxidation of hydroquinones and catechols



Entry	Substrate /Product	Substrate	CH(D)Cl$_3$/H$_2$O (mL/mmol substrate)	X	Time /h	Yield /%
1	**1a/1d**		47.6/0.4	0.5	1	86[b]
2			47.6/0.4	1	2	84[b, d]
3	**2a/2d**		20.0/1.0	0.25	3	>99[b]
4	**3a/3d**		22.4/1.6	1	1	>99[c]
5	**4a/4d**		22.4/1.6	0.5	2.5	98[a]
6	**5a/5d**		22.4/1.6	0.5	1	92[a]
7	**6a/6d**		22.4/1.6	0.5	1	93[a]
8	**7a/7d**		22.4/1.6	0.5	6.5	98[a]
9	**8c/8f**		22.4/1.6	0.5	3	97[a]
10	**9a/9d**		47.2/0.4, NaHCO$_3$ (1 equiv.)	1	3	55[b]
11	**10b/10e**		23.2/0.8, K$_2$CO$_3$ (0.1 equiv.)	1	23	76[c]
12	**11b/11e**		22.4/1.6, K$_2$CO$_3$ (0.1 equiv.)	1	28	96[a]

[a]Isolated yield. [b]Yield was determined by GC analysis. [c]Yield was determined by ^{1}H NMR spectroscopy using an internal standard. CDCl$_3$ was used as a solvent. [d]Atmospheric air was used instead of O$_2$.

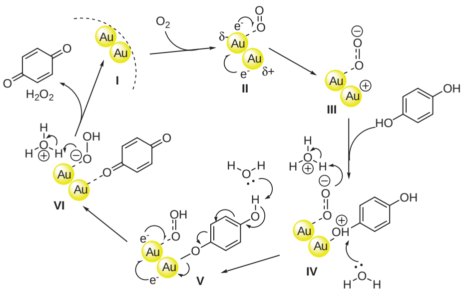


Figure 1. Assumed mechanism.

conducted, a possible mechanism of aerobic oxidation of hydroquinones catalyzed by PI Au is shown in Figure 1. Oxygen is adsorbed on the surface of gold clusters by supplying an electron from the cluster (**II**, **III**). An oxygen of the hydroquinone coordinates to the surface of the gold clusters (**IV**), and the proton on the hydroxy group is abstracted by water. The proton of the other hydroxy group is also abstracted by water, and two electrons are transferred to oxygen through the gold cluster. The fact that water is essential for the oxidation of hydroquinone, and that oxidation of *p*-methoxyanisole and *p*-methoxyphenol was not catalyzed by the PI Au catalyst does not contradict the assumed mechanism. A base is thought to help the abstraction of the hydroxy proton to accelerate the oxidation reaction, although decomposition of the product quinones is caused by the base and water concomitantly. Use of an appropriate amount of base and water is key to achieving high yields and selectivities.

In conclusion, we have found that gold clusters immobilized on a polystyrene-based polymer, PI Au, was highly effective for aerobic oxidation of hydroquinones and catechols to quinones under mild conditions. Water was revealed to be essential for this reaction, high reactivity and selectivity were accomplished by controlling the amount of water and organic solvents. The quinones prepared by this method were analytically pure after phase separation and did not require any further purification. This method is not only an atom-economical and environmental benign synthesis of quinone derivatives, but will also be useful in combinatorial syntheses. Further investigations to clarify the precise mechanism of this oxidation process are currently in progress.

This work was partially supported by a Grant-in-Aid for Scientific Research from Japan Society of the Promotion of Science (JSPS).

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Published on the web (Advance View) March 5, 2008; doi:10.1246/cl.2008.360