Synthetic Application of PVP-stabilized Au Nanocluster Catalyst to Aerobic Oxidation of Alcohols in Aqueous Solution under Ambient Conditions

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Gold nanoclusters ($\phi = 1.3$ nm) stabilized by poly(*N*-vinyl-2-pyrrolidone) (Au:PVP) were found to show a high catalytic activity toward the aerobic oxidation of alcohols. Various kinds of primary and secondary alcohols were converted to the corresponding carboxylic acids and ketones, respectively, in basic aqueous media at 300–360 K under air.

Gold nanoclusters (NCs) supported on metal oxides have paid much attention to develop aerobic oxidation catalysts since the landmark report by Haruta and co-workers.[1–3] On the other hand, catalytic activities of homogeneous or colloidal Au^0 NCs have been studied only recently.[4] We have recently reported that gold nanoclusters stabilized by the water-soluble polymer poly(*N*-vinyl-2-pyrrolidone) (Au:PVP) perform as excellent catalysts in the aerobic oxidation of benzylic alcohols in water under ambient conditions.[5] Notable features of alcohol oxidation catalyzed by Au:PVP clusters are listed as follows: 1) Au:PVP is easily prepared from commercially available precursors. Au:PVP is nonhazardous and can be stored for months either as a solid powder or an aqueous dispersion.[6a] 2) Au:PVP behaves as a *quasi*-homogeneous catalyst in aqueous solution and can be recovered by centrifugal ultrafiltration.[5–7] 3) Au:PVP catalyzes oxidation of primary benzylic alcohols to the corresponding aldehydes/carboxylic acids in water under ambient conditions. No additional co-oxidant such as peroxides is needed, which enables safer operation.[5] 4) The catalytic activity per unit cluster surface area increases rapidly with decreasing size from ca. 10 to 1.3 nm. The smallest Au:PVP clusters ($\phi = 1.3 \pm 0.3$ nm) exhibit the highest activity probably due to their non-metallic electronic structures.[5b] 5) At ambient temperature (300 K), Au:PVP clusters can oxidize benzylic alcohols at a rate much higher than that obtained for Pd:PVP clusters of comparable size.[5,8] In addition, gold atoms are not leached out from the clusters whereas atomic leaching is often observed in Pd clusters. These advantages of Au:PVP prompted us to investigate the applicable scope of Au:PVP as an oxidation catalyst in organic synthesis. We report reactions with various kinds of alcohols and the possible reusability of the Au:PVP catalyst.

Au:PVP with an average cluster size of $\phi = 1.3 \pm 0.3$ nm was chosen as the catalyst since it has already been demonstrated to be the most active in the size range of 1.3–10 nm.[5–7] All the reactions were performed in basic aqueous solution (K_2CO_3) under aerobic conditions unless otherwise noted. Although there are several catalytic reactions for direct oxidation from primary alcohols to the corresponding carboxylic acids, such as TEMPO/NaClO,[9a] TEMPO/$NaClO_2$,[9b] TEMPO/$ArI(OAc)_2$,[9c] $RuCl_3/NaIO_4$,[9d] $RuCl_3$/TCCA,[9e] Na_2WO_4/H_2O_2,[9f] or PCC/H_5IO_6,[9g] examples under aerobic (or O_2) conditions are still rare.[10,11] The results in Table 1 clearly demonstrate that the Au:PVP catalyst is a good reagent for this purpose. As shown in Entries 1–9, most of the primary benzylic alcohols were readily oxidized at 300 K to give the acids in excellent yields except for *o*- and *p*-hydroxybenzyl alcohol (**1b**, **1d**: Entries 3 and 5), which were selectively converted to the corresponding aldehydes as reported previously.[5] By-products often observed in the K_2CO_3 conditions were the ester derivatives (Entry 1), whose formation was suppressed by changing the base to KOH due to fast promotion of hydrolysis (Entry 2). The pyridine ring did not interfere with the reaction as shown in Entries 10 and 11. Contrary to the benzylic alcohols, the primary aliphatic alcohols required slightly elevated temperatures, such as 320 or 340 K, to undergo the oxidation (Entries 12–14). It is noteworthy that the carbon–carbon double bond was tolerant to oxidation under the reaction conditions (Entry 13). The initial rate constants for oxidation of a series of para-substituted benzyl alcohols (Entries 1 and 6–9) were determined.[12] The rate constants showed a linear relationship against the σ_p^+ constants and the ρ value was determined to be -0.66 by the least-squares method. This ρ value is comparable to those obtained in hydride transfer or radical processes (usually between -0.3 and -1.5).[13]

Table 1. Aerobic oxidation of primary alcohols

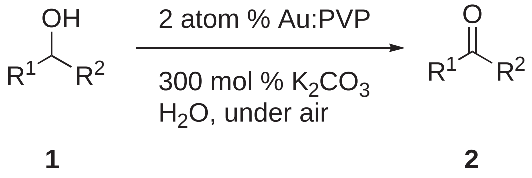
$$\underset{\mathbf{1}}{\text{R}-\text{CH}_2\text{OH}} \xrightarrow[\substack{300\text{ mol \% }\text{K}_2\text{CO}_3\\ \text{H}_2\text{O, under air}}]{2\text{ atom \% Au:PVP}} \underset{\mathbf{3}}{\text{RCO}_2\text{H}} + \underset{\mathbf{2}}{(\text{RCHO})}$$

Entry	R	Temp /K	Time /h	**2** /%	**3** /%	Recovery of **1**/%
1[a,b]	Ph (**1a**)	300	6	0	85	0
2[c]	Ph (**1a**)	300	6	0	98	0
3[b]	*o*-HOC_6H_4 (**1b**)	300	24	54	0	34
4[b]	*m*-HOC_6H_4 (**1c**)	300	8	34	52	3
5[b]	*p*-HOC_6H_4 (**1d**)	300	8	91	0	3
6[c]	*p*-$CH_3C_6H_4$ (**1e**)	300	4	0	91	0
7[c]	*p*-$MeOC_6H_4$ (**1f**)	300	3	0	93	0
8[c]	*p*-ClC_6H_4 (**1g**)	300	6	0	78	0
9	*p*-$NO_2C_6H_4$ (**1h**)	300	24	0	99	0
10	2-Py (**1i**)	300	3	0	72	8
11	3-Py (**1j**)	320	24	0	76	8
12	*n*-C_5H_{11} (**1k**)	340	24	0	>99	0
13	$CH_2{=}CH(CH_2)_3$ (**1l**)	320	24	0	94	0
14	$Ph(CH_2)_3$ (**1m**)	320	24	trace	95	0

[a]Ester was formed in 10% yield. [b]Ref. 5a. [c]KOH was used as a base.

Next, oxidation of secondary alcohols was examined (Table 2). In every case, the corresponding ketone derivative **2** was obtained as a sole product with recovery of **1**, and no other products such as esters (Baeyer–Villiger product) were detected. As for the acyclic alcohols, slightly elevated temperatures were

Table 2. Aerobic oxidation of secondary alcohols



Entry	R^1	R^2	**1**	Temp /K	Time /h	Yield /%	Recovery of **1**/%
1	Ph	CH_3	**1n**	320	24	98	1
2[a]	1-hydroxyindane		**1o**	300	1	>99	0
3	1-hydroxytetraline		**1p**	300	1	>99	0
4	$PhCH_2CH_2$	CH_3	**1q**	340	24	93	1
5	n-C_8H_{17}	CH_3	**1r**	360	24	63	23
6	$-(CH_2)_5-$ (cyclohexanol)		**1s**	300	24	36	58
7	$-(CH_2)_6-$ (cycloheptanol)		**1t**	300	24	81	9

[a] 0.5 atom %, rt, 2.5 h, >99% yield.

required to promote the reaction (Entries 1, 4, and 5). In contrast, oxidation of cyclic secondary alcohols proceeded at 300 K (Entries 2, 3, 6, and 7). Benzylic alcohols especially, such as **1o** or **1p**, readily underwent oxidation within 1 h, giving **2o** or **2p**, quantitatively.

Finally, reusability of the Au:PVP catalyst was investigated. Oxidation of 1-hydroxyindane (**1o**) was so fast that the TOF reached a value of 14 $min^{-1}\cdot atom^{-1}$ (approx. 770 min^{-1} $cluster^{-1}$)[14] in the first 5 min when the reaction was performed in the presence of 0.5 atom % Au:PVP. In the present study, **1o** was used as a substrate to check the reusability of Au:PVP catalyst. To clarify the change in catalytic activity, the reaction was quenched after 30 min in every cycle. The yields of **1o** in the first 5 cycles were 97, 95, 94, 85, and 84% yields, respectively.[12] Catalytic activity gradually diminished but remained sufficiently high for practical use even after the fifth run. Judging from UV spectra, slight growth of the Au cluster occurred, with the average size approximately 1.5 nm after the fifth run.[5b,12] However, we have already reported that Au clusters less than 2 nm in size possess high catalytic activity toward aerobic oxidations.[6b,7] Therefore, the Au:PVP can be applied as a reusable catalyst for several cycles at least despite the gradual decrease in catalytic activity observed due to growth of the clusters.

As described above, Au:PVP clusters with a size of $\phi = 1.3 \pm 0.3$ nm were found to show a high catalytic activity toward the aerobic oxidation of various kinds of alcohols. We have already reported that Au:PVP acts as an excellent catalyst not only for alcohol oxidation but also for homo-coupling of organoboron compounds[6] and generation of hydrogen peroxide.[7] In view of the advantages listed in the introduction, we hope that Au:PVP clusters will be added as a new entry to join the ranks of conventional catalysts for aerobic oxidation such as palladium-based complexes[8,15] and nanoclusters.[8]

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