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Communication

Silver Nitrate-Catalyzed Selective Air Oxidation of Benzylic and Allylic Alcohols to Corresponding Aldehydes or Ketones

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The liquid phase selective air oxidation of benzylic and allylic alcohols to corresponding aldehydes or ketones has been achieved in high yields with catalytic amount of $AgNO_3$ and in the presence of Na_2CO_3.

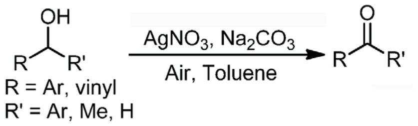
Keywords: Oxidation; Silver nitrate; Selectivity; Alcohols.

INTRODUCTION

The selective oxidation of alcohols to aldehydes or ketones is a very important organic transformation, especially in preparing for some important precursors and intermediates for drugs, fine chemicals, vitamins and fragrances.[1] Many catalysts have been developed for this transformation, such as DDQ-$Mn(OAc)_3$,[2] Au-Cs_2CO_3,[3] Ru-[4-5] or Pd-based complexes.[6-10] But these methods suffer from some drawbacks, such as expensive metals, tedious work up procedure, toxic reagents or producing large amounts of waste. As a green, environmental friendly and readily available oxidant, O_2/air was preferably used in oxidation reactions.[11] However, the selective oxidation of benzylic and allylic alcohol with air or oxygen as the only oxidant is still a challenging task.

Silver-based catalyst is widely used in gas-phase oxidation processes, such as the oxidation of ethylene to ethylene oxide,[12] benzyl alcohol to benzaldehyde,[13] and so on. However, high-temperature is inevitable to such a process. Recently, a few studies reported that supported silver catalysts are catalytically active in the liquid phase oxidation of alcohols.[14-19] Nevertheless, except for the inconvenience of fussy procedure of preparing supported silver catalysts, there is some other shortcomings such as low conversion,[14] need of co-catalyst,[15-16] exclusion of substrates with electron withdrawing groups,[17-18] without the chemoselective oxidation of benzylic and allylic alcohols,[17,19] and so on. To the best of our knowledge, there is no report yet of successfully applying an unsupported silver-based catalyst to the liquid phase selective oxidation of benzylic and allylic alcohols. Herein we report a simple and efficient protocol for the air oxidation of benzylic and allylic alcohols to corresponding aldehydes or ketones using $AgNO_3$ as catalyst and in the presence of Na_2CO_3 (Scheme 1).

Scheme 1 Silver-catalyzed oxidation of benzylic and allylic alcohols



RESULTS AND DISCUSSION

The air oxidation of benzyl alcohol to benzaldehyde catalyzed by $AgNO_3$ in toluene was chosen as a model reaction. It was found that a relative weak inorganic base (Na_2CO_3), rather than a strong inorganic base (NaOH) or an organic base (NEt_3), resulted in better yield of benzaldehyde (Table 1, entry 1-3). No reaction would take place in the absence of a base (Table 1, entry 4). When the reaction was performed under argon atmosphere, no product was detected (Table 1, entry 5). Prolonging reaction time to 6 hours, benzyl alcohol was almost completely and selectively converted to benzaldehyde even only 2 mol% of $AgNO_3$ was used (Table 1, entry 6-9). Further lowering the amount of $AgNO_3$ or Na_2CO_3 caused certain decrease in yield (Table 1, entry 10-11). Ag_2CO_3 was found to be less active than $AgNO_3$ (Table 1, entry 12). The yield of benzaldehyde versus time with different loading amount of $AgNO_3$ was also investigated. As shown in Fig. 1, the reaction can proceed smoothly when 2 mol% of $AgNO_3$ was used, while increasing the catalyst loading amount did not reduce the reaction time, and decreasing the $AgNO_3$ load-

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Table 1. Optimization of reaction conditions for oxidizing benzyl alcohol to benzaldehyde[a]

Entry	$AgNO_3$ (mol %)	Base	t (h)	Yield[b] (%)
1	20	NaOH	2	10[c]
2	20	Na_2CO_3	2	36
3	20	NEt_3	2	trace
4	20	-	2	0
5	20	Na_2CO_3	2	0[d]
6	20	Na_2CO_3	6	100
7	10	Na_2CO_3	6	100
8	5	Na_2CO_3	6	100
9	2	Na_2CO_3	6	96, 80, [e] 45[f]
10	1	Na_2CO_3	6	85
11	2	Na_2CO_3	6	88[g]
12	1	Na_2CO_3	6	74[h]

[a] Reaction condition: benzyl alcohol (1 mmol), Na_2CO_3 (2 mmol), $AgNO_3$, air atmosphere, toluene 2.5 mL, reflux.

[b] Based on GC analysis.

[c] Small amount of benzoic acid was detected after treated with 0.1 M HCl.

[d] Under Ar atmosphere.

[e] Second run for the reuse of the catalytic system.

[f] Third run for the reuse of the catalytic system.

[g] 1 mmol Na_2CO_3 was used as base.

[h] 1 mol% Ag_2CO_3 was used instead of $AgNO_3$.

ing amount to 1 mol% led to obvious decrease in yield. The optimized reaction conditions were thus established as follows: 2 mol% $AgNO_3$ as catalyst, 2 equiv. Na_2CO_3 as base, reflux in toluene and in air atmosphere.

To demonstrate the recoverability of the catalyst system, the solid filtrated from the reaction mixture was applied directly to the next run after dried under vacuum. A moderate yield of 80% could be obtained in the second run. Unfortunately, the yield decreased dramatically (Table 1, entry 9) when the catalyst was reused for second time (third run).

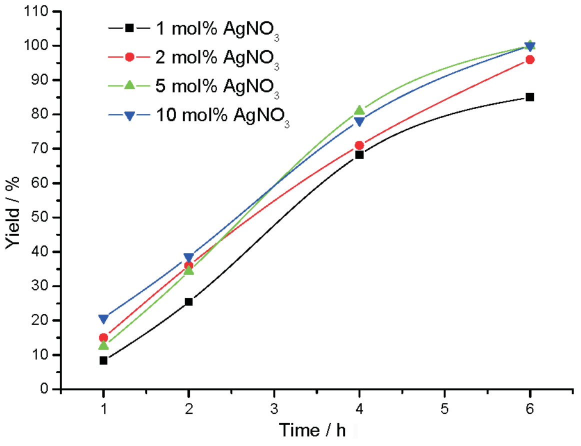
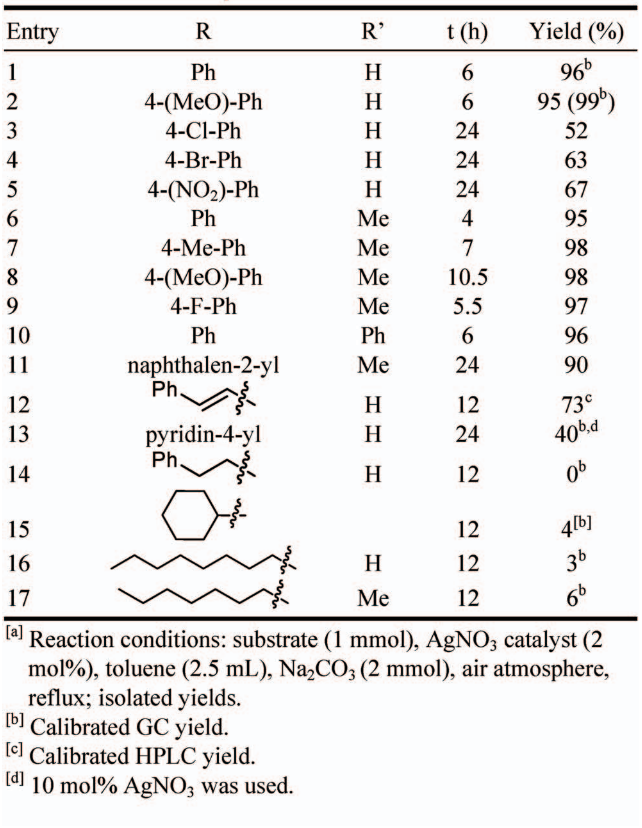


Fig. 1. Yield of benzaldehyde versus time with different loading amount of $AgNO_3$. Reaction conditions: 1 mmol benzyl alcohol, x mol% $AgNO_3$, 2 mmol Na_2CO_3, refluxed in toluene and in air atmosphere.

Table 2. Substrate scopes[a]



Entry	R	R'	t (h)	Yield (%)
1	Ph	H	6	96[b]
2	4-(MeO)-Ph	H	6	95 (99[b])
3	4-Cl-Ph	H	24	52
4	4-Br-Ph	H	24	63
5	4-(NO_2)-Ph	H	24	67
6	Ph	Me	4	95
7	4-Me-Ph	Me	7	98
8	4-(MeO)-Ph	Me	10.5	98
9	4-F-Ph	Me	5.5	97
10	Ph	Ph	6	96
11	naphthalen-2-yl	Me	24	90
12	Ph	H	12	73[c]
13	pyridin-4-yl	H	24	40[b,d]
14	Ph	H	12	0[b]
15			12	4[b]
16		H	12	3[b]
17		Me	12	6[b]

[a] Reaction conditions: substrate (1 mmol), $AgNO_3$ catalyst (2 mol%), toluene (2.5 mL), Na_2CO_3 (2 mmol), air atmosphere, reflux; isolated yields.

[b] Calibrated GC yield.

[c] Calibrated HPLC yield.

[d] 10 mol% $AgNO_3$ was used.

Then, the air oxidation of various alcohols, including benzylic alcohols, allylic alcohols, aromatic and aliphatic alcohols, were investigated under optimized conditions. The oxidation of 4-methoxybenzyl alcohol went smoothly and very high isolated yield was achieved after 6 hours (Table 2, entries 2). Only moderate yields were obtained even with longer reaction time when less active electron deficient primary benzylic alcohols, 4-chlorobenzyl alcohol, 4-bromo benzyl alcohol and 4-nitrobenzyl alcohol were used (Table 2, entries 3–5). For secondary alcohols, both the electron rich and electron deficient secondary benzylic alcohols delivered the products with good to excellent yields (Table 2, entries 6–9). Bulky sec-alcohol substrates such as benzhydrol also gave excellent yield (Table 2, entry 10). For the oxidation of 1-(naphthalen-2-yl) ethanol, longer time was needed to get satisfied yield (Table 2, entry 11). Allylic alcohol was also tolerated, thereby affording the corresponding α,β-unsaturated carbonyl compound without the disruption of the double bond (Table 2, entry 12). The yield for the oxidation of pyridinemethanol was poor even under 10 mol% catalyst and longer reaction time (Table 2, entry 13). As the oxidation of primary and secondary aliphatic alcohols, such as 2-phenylethanol, cyclohexanol, 1-octanol and 2-octanol, were effectively prohibited (entry 14-17), high chemoselective oxidation of benzylic and allylic alcohols to corresponding aldehydes or ketones was achieved with this oxidation system.

To identify the possible mechanism for the oxidation of alcohols by $AgNO_3/Na_2CO_3$ system, the catalyst system was filtrated after the reaction and characterized by TEM and XPS (Fig. 2). As shown in Fig. 2a, the silver nanoparticles were well dispersed on the surface of Na_2CO_3 after the reaction. In Fig. 2b, the black line shows the Ag 3d region of the XPS spectrum for the filtered $AgNO_3/Na_2CO_3$ catalyst. It can be seen that all the Ag 3d peaks are asymmetric, suggesting that there are at least two kinds of silver species on the sample surface.[20] The curve fitting patterns (red lines) are also shown in Fig. 2b with binding energy of 368.77 and 367.68 eV for Ag $3d_{5/2}$, which implies the existence of both Ag^0 nanoparticles[21] and Ag_2CO_3.[22] As shown in Fig. 3a, during the reaction, Ag(I) from $AgNO_3$ is reduced by alcohols to generate Ag^0 nanoparticles deposited on the surface of sodium carbonate. The Ag^0 nanoparticles can also be produced from Ag_2CO_3 generated by the reaction of Ag^+ and sodium carbonate. As $AgNO_3$ exhibited much higher catalytic activity than Ag_2CO_3 at same Ag dosage and the yield with reused catalyst system decreased remarkably (Table 1, entries 9 and 12), it was speculated that: (i) higher degree of ionization of $AgNO_3$ makes it more efficient than Ag_2CO_3; (ii) the decrease in yield with recycle catalyst might due to the formation of Ag_2CO_3, aggregation of Ag nanoparticles and/or leaching of Ag during the catalyst recovering procedure. With these results in hand, we proposed that alcohol oxidation occurs on the silver nanoparticles on the surface of sodium carbonate.[15] As shown in Fig. 3b, after adsorption of benzyl alcohols on the silver surface, the alcohol is dehydrogenated and then benzaldehyde is formed in the presence of Na_2CO_3 and molecular oxygen. To confirm the hypothesis, we also synthesized Ag nanoparticles according to the literature[23] with some modifications and test their catalytic activities in oxidation of benzyl alcohol to benzaldehyde (See supplementary material for details). It was found that a moderate yield of 42.4% can be obtained in 4 hours when 2 mol% Ag nanoparticles were used as catalyst. Further increasing reaction time did not improve the yield, which may caused by

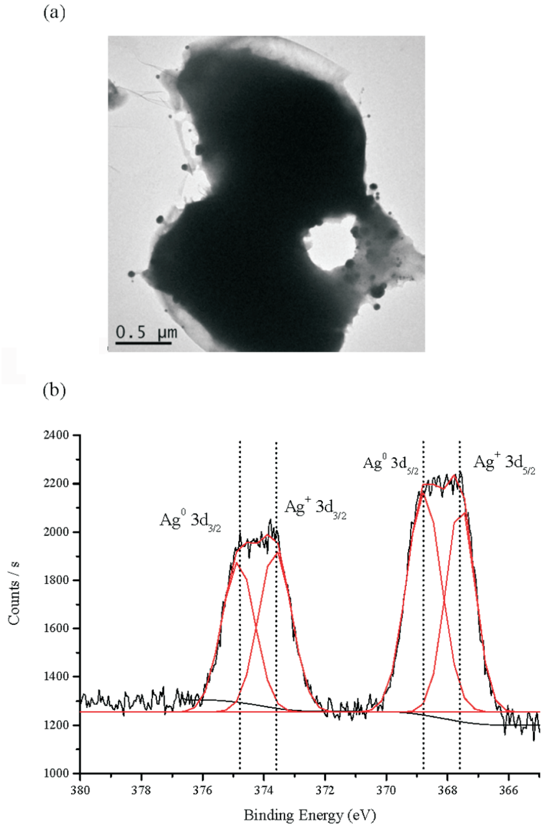


Fig. 2. TEM image (a) and Ag 3d region of the XPS spectrum (b) for filtered $AgNO_3/Na_2CO_3$ after reaction.

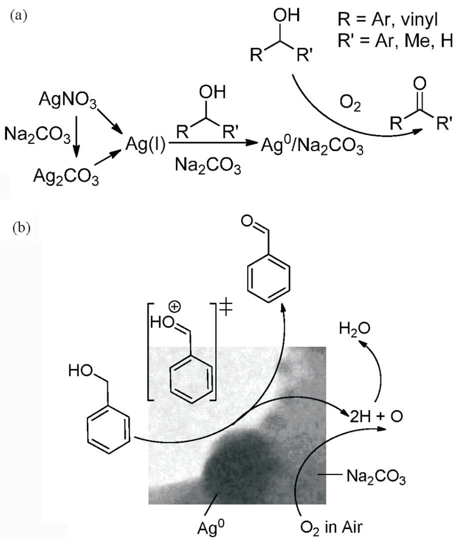


Fig. 3. Transformation of silver nitrate during the reaction and proposed reaction mechanism.

Ag nanoparticles aggregation or agglomeration during the reaction. Although, the results indicated that Ag nanoparticles could catalyze the reaction, which was in coincidence with our proposed mechanism.

CONCLUSIONS

In conclusion, we have developed a simple and efficient method for the selective oxidation of benzylic and allylic alcohols to corresponding aldehydes or ketones using $AgNO_3$ as catalyst, air as the sole oxidant, and in the presence of sodium carbonate. Given the highly selective nature of this oxidation, we believe that this method might be applicable to the chemoselective oxidation of alcohols in multistep synthesis.

EXPERIMENTAL

General: All chemicals were of analytical grade and used as received. To obtain the GC yield, the combined organic phase was analyzed by a gas chromatograph (GC) equipped with a flame ionization detector (FID) detector using dodecane as an internal standard (Angilent 7890A, HP-5, 30 m ×0.32 mm). The ^{1}H NMR spectra were recorded on a Bruker WP-400SY (400 MHz) spectrometer with $CDCl_3$ as the solvent and TMS as the internal standard. GC mass spectra were recorded using a HP 6890 gas chromatograph and HP 5973 mass selective detector. Analytical thin-layer chromatography (TLC) was carried out on precoated plates (silica gel 60 F254), and spots were visualized with ultraviolet (UV) light.

General procedure for the oxidation of alcohols: Alcohol substrate (1 mmol), toluene (2.5 mL), $AgNO_3$ (2 mol%) and Na_2CO_3 (2 mmol) were added to a 25 mL round-bottom flask, which was then heated to reflux. After the reaction was finished as monitored by thin layer chromatography (TLC), the reaction was cooled to room temperature. The resulting reaction mixture was filtered and the filter mass was washed three times with dichloromethane (2 mL × 3). The combined filtrate was concentrated via rotary evaporation under reduced pressure. The residue was purified by flash column chromatography (Ethyl acetate: Petroleum ether = 1:5 ~ 1:10) to afford pure product. The ^{1}H-NMR, ^{13}C-NMR and GC-MS data of representative compounds are given in supplementary material. All synthesized compounds are known and compared with literature.

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