

A novel gold-catalyzed chemoselective reduction of α,β -unsaturated aldehydes using CO and H₂O as the hydrogen source†

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Chemoselective reduction of α,β -unsaturated aldehydes in the presence of CO and H₂O proceeds effectively over a ceria-supported gold catalyst system, providing a novel, efficient and clean approach to produce useful primary allyl alcohols with excellent activity and selectivity.

Recent state-of-the-art research in organic chemistry requires the design of ultrasensitive catalytic systems for the production of fine chemical and pharmaceutical intermediates.¹ In this context, the chemoselective reduction of α,β -unsaturated aldehydes to the corresponding unsaturated alcohols, an important step in the industrial synthesis of fine chemicals, is a long-standing scientific and technological challenge in heterogeneous catalysis.² It is well known that classical hydrogenation metal catalysts (Pt, Pd, Ru, Rh *etc.*) show no or low selectivity towards the specific hydrogenation of the C=O bond.³ Therefore, great efforts have been made to overcome this problem over the past decades, including introducing special additives (promoters or inhibitors), modifying the active metal with a second metal component, or tuning the particle sizes of the catalysts.^{3b,4} Although these modified systems are effective, catalyst preparation often remains critical, and the amount of the modifying agent must be precisely controlled.⁴ Alternative economical and eco-friendly heterogeneous reduction protocols that would ensure the preferred hydrogenation of the C=O group *versus* C=C is highly desirable.

Supported gold nanoparticles have recently emerged as active and selective catalysts for a broad array of organic transformations⁵ including chemoselective reduction of unsaturated carbonyl compounds by molecular hydrogen.⁶ The pioneering works by Hutchings *et al.*^{2c,7} and Claus *et al.*⁸ have shown that supported gold nanoparticles are highly selective for the hydrogenation of the conjugated C=O bond, reaching in some cases exceptionally high values of selectivity towards the unsaturated alcohol. One critical limitation associated with the current Au-catalyzed hydrogenation process, however, is the unfavorably low hydrogen-delivery capacity compared to the conventional hydrogenation metals.^{5e,6a} In view of the excellent performance of supported gold for low temperature water-gas shift (WGS) reaction⁹ (CO + H₂O = CO₂ + H₂, generally in the temperature range of 150–250 °C) to produce

high purity H₂ for a number of technological applications, it is conceivable that a combination of the direct hydrogenation and WGS reaction over supported gold may provide an attractive alternative for more efficient green reductions. Very recently, we have described a highly effective gold-catalyzed, CO/H₂O-mediated reduction that bypasses inconvenient H₂ activation to enable the rapid, efficient, and chemoselective reduction of a wide range of organic nitro compounds under very mild conditions.¹⁰ Herein, we demonstrate for the first time that gold supported on ceria can catalyze the reduction of α,β -unsaturated aldehydes to the corresponding unsaturated alcohols in high yields in the presence of CO and H₂O. Compared with those conventional catalytic hydrogenation processes, the present Au-catalyzed CO/H₂O-mediated reduction system has the following significant advantages: (i) unprecedented high chemoselectivity and high yields in the reduction of α,β -unsaturated aldehydes; (ii) mild conditions; and (iii) without the direct use of molecular hydrogen.

Initially, crotonaldehyde (CAL) was chosen as a model substrate to study the catalytic activity of the various catalysts under 5 atmospheres of CO in water. The most salient feature in Table 1 is the high chemoselectivity attained using supported gold nanoparticles as catalysts for the production of crotyl alcohol (CROL) (Table 1, entries 1–3), conditions under which the Pt, Pd, and Ru catalysts, previously known for their high hydrogenation activity,¹¹ were totally ineffective (Table 1, entries 5–7). In all cases, the main by-products (butanal (BAL) and butanol (BOL)) did not exceed 15% with no detectable amount of other side products. Among the catalysts examined, Au deposited on CeO₂ (denoted as Au/CeO₂, see details in the ESI†) showed the highest activity and selectivity (Table 1, entry 1). Thus, using CO and H₂O as the reductant, complete reduction of CAL occurred in 5 h over Au/CeO₂. Remarkably, an excellent yield up to *ca.* 82% can be achieved for CROL production, in stark contrast to the poor selectivity (<30%) as reported for catalytic liquid phase CAL hydrogenation (10 atm H₂) by gold supported on CeO₂.¹² Of particular note is that the reaction can proceed efficiently even at atmospheric pressure (Table 1, entry 8), which permits the use of common glass reactors thus eliminating the need for a specialized apparatus. No conversion was found in the absence of catalysts or in the presence of Au-free CeO₂ catalyst under identical conditions (entry 4), illustrating that the presence of gold was indispensable for high catalytic activity of the titled reaction.

The Au/CeO₂ catalyst was stable and can be easily reused in the CO-induced reduction of CAL. After the first CAL reduction under the conditions in entry 1 of Table 1, the catalyst was separated from the reaction mixture by filtration,

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Table 1 Catalytic performance of various catalysts for the reduction of crotonaldehyde by CO/H₂O^a

Entry	Catalyst	P _{CO} (atm)	t/h	Conv. ^c (%)	Sel. (%) ^{b,e}		
					CROL	BAL	BOL
1	Au/CeO ₂	5	4.5	96	85	4	11
2 ^c	Au/TiO ₂	5	4.5	67	87	5	8
3 ^c	Au/Fe ₂ O ₃	5	4.5	9	88	10	2
4	CeO ₂	5	4.5	n.r.	—	—	—
5 ^c	Ru/Al ₂ O ₃	5	4.5	n.r.	—	—	—
6 ^c	Pd/C	5	4.5	n.r.	—	—	—
7 ^c	Pt/CeO ₂	5	4.5	n.r.	—	—	—
8	Au/CeO ₂	1	11	94	84	3	13
9 ^d	Au/CeO ₂	5	4.5	91	85	5	10

^a Reaction conditions: 1 mmol substrate, 2.8 mol% metal, 20 mL H₂O, 96 °C. ^b CROL: crotyl alcohol, BAL: butanal, BOL: butanol. ^c Au/TiO₂, Au/Fe₂O₃ provided by the World Gold Council. Pt/CeO₂, prepared by wet impregnation. Pd/C, Ru/Al₂O₃ provided by Alfa Aesar. ^d Results for the third run. ^e Conversion and selectivity were determined by GC and GC-MS. n.r. = no reaction.

thoroughly washed with acetone then water, and reused for the next run under the same conditions. The catalytic results indicate that there is no appreciable loss in either activity or selectivity between the first and third runs (Table 1, entries 1 and 9). This was also consistent with the characterization results for this catalyst. TEM and XPS results (Fig. S1, S2 and S3 in ESI[†]) showed essentially no changes, after three successive runs in the mean diameters of the Au nanoparticles or metallic state of Au, respectively. Moreover, it was confirmed by ICP that the Au content of the reused Au/CeO₂ catalyst remains unchanged and that no Au was in the filtrate.

To examine the scope of the present system with Au/CeO₂ in the presence of CO/H₂O, we extended our studies to a range of α,β -unsaturated aldehydes. As depicted in Table 2, various structurally diverse α,β -unsaturated aldehydes, including aliphatic, aromatic ones could be transformed into the corresponding unsaturated alcohols in high to excellent yields. Notably, selectivity up to >85% was achieved in the initial stage (0.5 h) for all cases and decreased only slightly at high conversion. As far as we know, few simple heterogeneous reduction systems are available that enable such high chemoselectivity. Table 2 also points to a marked substrate structure effect on the chemoselective reduction of various α,β -unsaturated aldehydes. For example, CAL displayed a significantly higher activity than 2-methyl-2-pentene aldehyde (Table 2, entries 1, 2), revealing that the activity is largely influenced by the presence of a β -bulky group due to steric hindrance. In addition, cinnamaldehyde with electron-withdrawing groups on the benzene ring reacted smoothly (entry 5), while the substitution of electron-donating groups decreased the reactivity (entry 4). Moreover, in the transformations of chloro-cinnamaldehyde, high selectivity could also be attained with no observation of dehalogenation or ring reduction (entry 5).

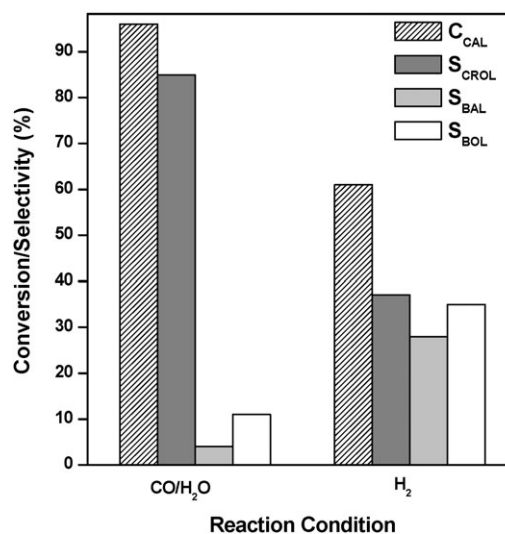
It may be assumed that the present gold-catalyzed reaction proceeds through the reduction of α,β -unsaturated aldehyde with hydrogen gas *in situ* generated from the low-temperature WGS reaction, particularly on considering that Au/CeO₂ is

Table 2 Reduction of α,β -unsaturated aldehydes to unsaturated alcohols by CO/H₂O^a

Entry	Substrates	t/h	Con. ^b (%)	Sel. ^c (%)
1	CH ₃ CH=CHCHO	0.5	50	88
		4.5	96	85 (84)
2	CH ₃ CH ₂ CH=C(CH ₃)CHO	0.5	28	91
		7.5	95	84
3 ^b		0.5	36	94
		6	96	90
4 ^b		0.5	31	90
		7	90	84
5 ^b		0.5	42	95
		5	94	93 (92)

^a Reaction conditions: 1 mmol substrate, Au/CeO₂ (Au: 2.8 mol%), 20 mL H₂O, 96 °C, 5 atm CO. ^b 1 mmol substrate, Au/CeO₂ (Au: 2.8 mol%), 10 mL H₂O, 10 mL EtOH, 1396 °C, 5 atm CO. ^c Conversion and selectivity were determined by GC and GC-MS. Numbers in parenthesis refer to selectivity of isolated products.

often the catalyst of choice for the latter process.^{9a,14} However, it is worth noting that a stoichiometric amount of CO₂ (1 mol of CO uptake per mole of substrate conversion) without accompanying H₂ was formed at the end of the reduction. In addition, control experiments in the absence of aldehydes indicated that the independent low temperature WGS could not be ignited under the experimental conditions as employed in this work. Moreover, when molecular hydrogen was applied instead of CO, a significantly decreased reduction rate and selectivity were identified for CAL reduction with Au/CeO₂ (see Fig. 1). Therefore, the seemingly simple and straightforward reduction of the aldehyde *via* hydrogen gas *in situ*

**Fig. 1** Reduction of crotonaldehyde by CO/H₂O or H₂ (C_{CAL}: conversion of crotonaldehyde, S_{CROL}: selectivity to crotyl alcohol, S_{BAL}: selectivity to butanal, S_{BOL}: selectivity to butanol). Reaction conditions: 1 mmol substrate, Au/CeO₂ (Au: 2.8 mol%), 20 mL H₂O, 96 °C, 5 atm CO or H₂, 4.5 h.

generated from the WGS reaction is thought to be unlikely in the present reaction system.

While further work is needed to fully understand the mechanism of the present gold-catalyzed reaction under CO/H₂O conditions, we believe that the transient Au⁰-H species¹⁵ formed by the CO-induced reduction of H₂O is indispensable for the genesis of catalytically active sites for aldehyde reduction. Although the Au-catalyzed WGS reaction needed a much higher temperature, it is reasonable that ceria supported small Au nanoparticles with superior redox reactivity can readily form Au⁰-H in this procedure.¹⁶ Once being formed, the Au⁰-H species should be rapidly consumed together with a final formation of the α,β -unsaturated alcohol product without liberation of molecular hydrogen, which may account for the enhanced efficiency in the CO/H₂O-mediated reduction of α,β -unsaturated aldehydes.

In summary, we have developed an efficient gold-catalyzed approach for the chemoselective reduction of a range of α,β -unsaturated aldehydes using cheap and easily accessible CO and H₂O as the hydrogen source. The present clean synthesis of primary allyl alcohols may be viewed as an appealing and economical alternative for existing protocols.

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