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Catalytic oxidation of alcohols to carbonyl compounds over hydrotalcite and hydrotalcite-supported catalysts.

J. K. Mobley and M. Crocker

Abstract

The oxidation of alcohols to carbonyl compounds is an important reaction in synthetic organic chemistry. While stoichiometric oxidants are effective for this transformation, they often produce large amounts of toxic waste, which renders them unacceptable from an environmental and economic perspective. Consequently, there is a strong impetus to develop catalytic processes that utilize environmentally friendly, inexpensive primary oxidants, the use of molecular oxygen being particularly attractive. Recently, hydrotalcites have attracted attention as both catalysts and catalyst supports for the selective oxidation of alcohols to ketones and aldehydes, using either oxygen or TBHP as the oxidant. This review is intended to provide a comprehensive summary of work performed in this area to date. The effects of composition and structure on catalyst properties are highlighted, and mechanistic aspects are discussed.

1   Introduction

The oxidation of alcohols to ketones and aldehydes is a heavily utilized transformation in synthetic chemistry.[1, 2] A number of catalysts and stoichiometric reagents are known which oxidize alcohols to their corresponding carbonyl compounds.[3] Unfortunately, stoichiometric alcohol oxidation often requires environmentally harmful and/or toxic reagents such as Cr(VI) species and permanganate salts. Many catalytic systems involve homogeneous catalysts, which require tedious workups and suffer from thermal instability. On the other hand, supported noble metals have proven to be highly effective heterogeneous catalysts for alcohol oxidations.[4] Another recent development is the use of hydrotalcite-like compounds (HTs) − both as catalyst components and as heterogeneous catalysts in their own right − to achieve alcohol oxidations under environmentally benign conditions.

Hydrotalcite-like compounds, also known as layered double hydroxides (LDHs), are lamellar mixed hydroxides with interlayer spaces containing exchangeable anions. While HTs occur in nature, a far greater range of compositions is known for synthetic materials; in general, these can be conveniently prepared using simple co-precipitation procedures.[5] Other common techniques for their preparation include hydrothermal synthesis, homogeneous precipitation using the urea hydrolysis method, and anion exchange.[6] The general formula to describe the chemical composition is $[M^{2+}_{1-x}M^{3+}_x(OH)_2]A^{n-}_{x/n} \cdot mH_2O$, the most well-known example being the mineral hydrotalcite, which has the formula $[Mg_{0.75}Al_{0.25}(OH)_2](CO_3)_{0.125} \cdot 0.5H_2O$.[6, 7] Structurally, layered double hydroxides are related to brucite, $Mg(OH)_2$. Each Mg^{2+} ion is octahedrally

surrounded by six OH⁻ ions (see Figure 1) and the different octahedra share edges to form infinite sheets. The sheets are stacked one on top of another and are held together by hydrogen bonding and van der Waals forces. If Mg^{2+} ions are partially replaced by cations with higher charge but similar radius (e.g., Al^{3+}, Fe^{3+}), the brucite-type sheets become positively charged. Charge compensating anions located in the interlayer region maintain the charge balance. This gallery also contains water molecules, which occupy the regions between the anions. Hydrotalcites are generally characterized using a combination of analytical methods,[8] including powder X-ray diffraction, elemental analysis, nitrogen physisorption, thermogravimetric analysis and electron microscopy, although X-ray photoelectron spectroscopy and X-ray absorption spectroscopy are also commonly used, particularly for hydrotalcite-supported metal nanoparticles.
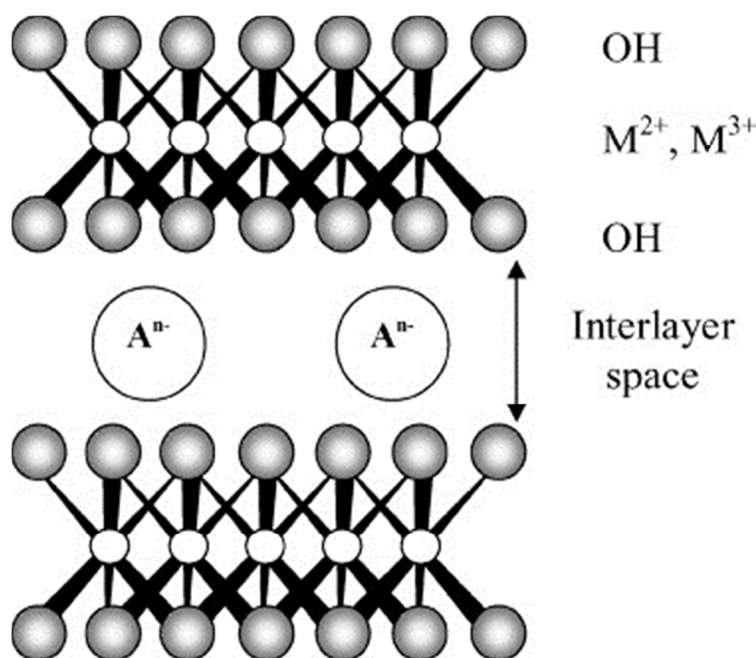

Figure 1. Detail of the HT structure. Reproduced with permission from Ref. [9].

Upon thermal treatment, HTs undergo decomposition to mixed oxides; upon heating to higher temperatures (>700 °C), spinel structures are obtained. The mixed oxides possess a number of properties of interest: increased surface area relative to the initial HT (up to 300 m^2/g)[10]; homogeneous mixing of the different elements; high basicity (higher than the starting LDH); and the "memory" effect (which refers to the re-construction of the original LDH structure upon contacting the mixed oxide phase with an aqueous solution of an appropriate anion).[7]

This review is intended to provide a detailed overview of existing HT catalysts for the oxidation of benzylic and aliphatic alcohols, excluding polyols. For an overview of the oxidation of polyols the reader is referred to the recent reviews by Li[11] and Ebitani[12]. In order to facilitate comparison of the different catalysts discussed below, specific

activities (mmol product/g catalyst*h) or, when appropriate, turnover frequencies (TOF, h^{-1}) are used. When specific activity or TOF values were not reported in a given publication, they were calculated from the data provided.

2   HTs as catalyst

2.1 Ru containing HTs

Ruthenium is recognized to have excellent catalytic properties in the oxidation of a variety of organic functional groups, including alcohols. For example, ruthenium-containing organometallic complexes are well known for their ability to catalyze alcohol oxidations using O_2 as the sole oxidant.[13] However, for ease of product work-up, heterogeneous catalysts are generally preferred to homogeneous catalysts. Recent examples of supported Ru catalysts have been provided by Liu and coworkers[14, 15] who performed the selective oxidation of 5-hydroxymethylfurfural (HMF) to 2,5-diformylfuran (DFF) using carbon-supported Ru in the presence of O_2. Similarly, Takagaki et al.[16] reported the use of Ru/HT for the aerobic oxidation of HMF to DFF. In comparison with other supported Ru catalysts such as Ru/C, Ru/Mg(OH)$_2$, and Ru/Al$_2$O$_3$, Ru/HT had the highest activity and selectivity.

While the catalytic properties of hydrotalcites (HTs) have attracted interest for many years, their use in alcohol oxidations is a relatively recent development.[12] The first such study appeared in 1988 and concerned the photocatalytic oxidation of *iso*-propanol to acetone by polyoxometallate intercalated HT (*vide infra*).[17] Roughly a decade later reports were published concerning the use of isomorphically substituted HTs for the oxidation of alcohols under non-photocatalytic conditions. In the initial article by Kaneda *et al.*[18], Mg-Al-HT was isomorphically substituted with Ru to obtain Ru-HTs with various interlayer anions for the aerobic oxidation of cinnamyl alcohol, CO_3^{2-} having the highest activity of all the anions tested. The same authors indicated that they had also screened HTs isomorphically substituted with Fe, Ni, Mn, V, and Cr in addition to Ru, Ru substituted HTs having the highest activity; however, no data were presented for the other catalysts mentioned. Building on this work, Kaneda and co-workers[19] subsequently evaluated a series of transition metal containing Ru-HTs for the aerobic oxidation of cinnamyl alcohol. Divalent transition metal ions were substituted for Mg in the HT structure (CO_3^{2-} being used as the interlayer anion), Co, Mn, and Fe containing Ru-HTs displaying higher activity than the Mg containing Ru-HT with specific activities of 9.4, 9.2, 5.0 and 2.3 mmol/g*h, respectively. The Co and Mn containing Ru-HTs were particularly active, affording cinnamaldehyde in yields of 94% and 92%, respectively. The authors suggested that the increased activity of the Ru-Co-Al-HT was due to an increase in the oxidation state of Ru. XPS analysis of Ru-Co-Al-HT showed a Ru $3d_{5/2}$ binding energy similar to that of RuO$_3$, which the authors suggested is evidence of an interaction between the transition metal and Ru.

2.2 Ni containing HT/HDs

In a seminal study by Choudary and co-workers[20], Ni containing HTs were synthesized and applied in the aerobic oxidation of alcohols. Notably, this was the first study to suggest activation of O_2 by a Ni-HT catalyst. The oxidation of 4-nitrobenzyl alcohol was studied over a series of Ni-HTs, Ni-Al-HT (2:1) being the most active catalyst. While the specific activity of Ni-Al-HT is much lower (0.65 mmol/g*h) than the values reported by Kaneda and co-workers[18, 19] for Ru containing HTs, the cost of Ni is significantly lower than that of Ru. This report inspired a number of other researchers to examine the catalytic properties of Ni containing HTs in alcohol oxidations. Kawabata *et al.*[21] subsequently systematically substituted Ni for Mg in a Mg-Al-HT, producing a series of catalysts with varying Ni/Mg and (Ni+Mg)/Al ratios. Choudary *et al.*[20] had previously reported low activity for Ni-Al-HT (2:1) in the aerobic oxidation of BA, obtaining a 31% yield after 12 h. Likewise, Kawabata *et al.* oxidized BA using Ni-Al-HT (2:1) under near identical conditions, obtaining similar results. Notably, by varying the Ni content in the HT the conversion was increased to 51.8% with high selectivity to benzaldehyde (97.8% with a 2.5:0.5:1 Mg-Ni-Al-HT). The authors suggested that the increased activity of this catalyst was due to the high surface area and the large amount of atomically isolated Ni(II) sites.

Other examples of Ni containing HTs in the literature include HTs composed solely of transition metals. Choudhary *et al.*[22] examined Ni-Cr and Ni-Fe (in a 3:1 atomic ratio in both cases) in addition to many other transition metal HTs (*vide infra*) for the aerobic oxidation of benzyl alcohol under solvent-free conditions, finding that Ni containing HTs had high selectivity towards benzaldehyde (≥ 97.6%); by-products consisted of benzyl benzoate and benzoic acid. In another publication from this group[23], the same catalysts were used in combination with TBHP (*tert*-butyl hydroperoxide) for benzyl alcohol oxidation (see Table 1). Ni containing HTs were found to afford 100% selectivity to benzaldehyde under solvent-free conditions, albeit Ni-HTs displayed the lowest conversions of the transition metal HTs tested.

In a more recent study by Tang *et al.*[24], Ni-Mn hydrotalcites/mixed hydroxides (HTs/HDs) were synthesized with varying amounts of Ni and Mn. The catalysts were then applied in the aerobic oxidation of BA at 100°C and compared with the results of other HTs reported by Choudary[20], Kawabata[21], and Choudhary[22], as well as Ni(OH)$_2$[25] and various other oxide catalysts. Among the catalysts tested, Ni-Mn-HD (2:3) had the highest specific activity. An 89% conversion of benzyl alcohol was obtained after 1 h, with 99% selectivity to benzaldehyde. The measured apparent activation energy was 37.2 kJ/mol.
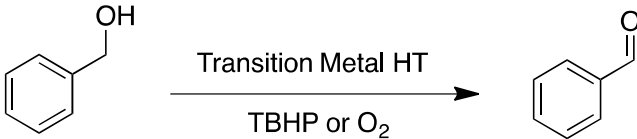
2.3 Other transition metal HTs and HDs

As indicated above, transition metal-containing HTs have been widely studied for alcohol oxidations. Indeed, Choudhary *et al.*[22] reported the use of HTs containing transition metals other than Ni, finding that Cu and Mn containing HT had the highest activity for aerobic benzyl alcohol oxidation under solvent-free conditions. Specific activities for Cu-Al, Zn-Cu-Al, Cu-Cr, and Mn-Cr HTs calculated from the data provided are 11.2, 11.3, 13.8, and 7.2 mmol/g*h, respectively. Mn-Cr-HT afforded the highest selectivity to benzaldehyde (99.5%), Cu-HTs giving lower selectivities to benzaldehyde in

the range 70-84%. In the case of transition metal HT/HDs catalysts using TBHP as oxidant, it was found that the Cu, Co, and Mn containing HT/HDs were the most active.[23] While Cu-HT using O_2 gave the highest specific activity of those compared, the only Cu catalyst that was used with both oxidants was Cu-Cr-HT, which showed specific activities of 13.8 mmol/g*h and 8.0 mmol/g*h with O_2 and TBHP, respectively. However, in general specific activities were higher when TBHP was used as the oxidant, although byproduct selectivity shifted from benzyl benzoate with O_2 to benzoic acid with TBHP. Interestingly, toluene is also seen as a byproduct when Cu catalysts are used in combination with O_2, the toluene likely being formed *via* benzyl alcohol disproportionation.

Recently, Zou *et al.*[26] explored the use of Zn-Co-HT as a catalyst, finding that it displayed good activity for the catalytic oxidation of alcohols with TBHP. Using 5 eq. of TBHP at 65°C and acetonitrile as solvent, benzyl alcohol was oxidized to benzaldehyde with good conversion and selectivity (72% and 90%, respectively). The calculated specific activity was 14.4 mmol/g*h, which is the highest among the transition metal HTs reported in this review.

Table 1. Oxidation of benzyl alcohol using transition metal HT/HDs

| Catalyst	Conversion (%)	Selectivity (%)[b]	Yield (%)[c]	Specific Activity (mmol/g*h)[d]
Cu–Al-HT	41	70.8	29.0	11.2
Zn–Cu–Al-HT	34.8	83.7	29.1	11.3
Zn–Cr-HT	15	97.3	14.6	5.6
Co–Al-HT	11.8 (56.7)	97.3 (77.4)	11.5 (43.9)	4.4 (9.1)
Ni–Al-HT	7 (15.9)	97.6 (100)	6.8 (15.9)	2.6 (3.3)
Mg–Fe-HT	6.5 (19.4)	94.8 (97.7)	6.2 (19.0)	2.4 (3.9)
Co–Fe-HT	12.5 (52.5)	94.3 (79.2)	11.8 (41.6)	4.6 (8.7)
Ni–Fe-HT	4.6 (17)	98.5 (100)	4.5 (17.0)	1.8 (3.5)
Mn–Cr-HT[a]	18.7 (49.8)	99.5 (83.5)	18.6 (41.6)	7.2 (8.7)
Co–Cr-HT	11.7 (59.5)	98.4 (70)	11.5 (41.7)	4.5 (8.7)
Ni–Cr-HT	10.7 (15)	98.2 (100)	10.5 (15.0)	4.1 (3.1)
Cu–Cr-HT[a]	50.9 (51.3)	70.1 (74.9)	35.7 (38.4)	13.8 (8.0)
Mg-Al-HT	(20.2)	(99.3)	(20.1)	(4.2)
Mn-Al-HD	(46.7)	(91.3)	(42.6)	(8.9)
Zn-Al-HT/HD	(10.5)	(100)	(10.5)	(2.2)
Mn-Fe-HT	(53.9)	(70.6)	(38.1)	(7.9)
Zn-Cr-HT/HD	(41.9)	(91.5)	(38.3)	(4.4)
Reaction conditions[22]: 0.5 g of catalyst (3:1 M(II)/M(III) ratio), 5 hours, 96.6 mmol of				

benzyl alcohol, O_2 (6 mL/min), $210^{\circ}C$; Parentheses indicates that the reaction conditions are as described by Choudhary et al.[23]: 52 mmol benzyl alcohol, 68 mmol TBHP (1.3 eq.), $94^{\circ}C$. (a) The catalyst was described as a mixed hydroxide (HD) in the report using O_2 as oxidant[22] but not in the report using TBHP as the oxidant[23]. (b) Selectivity to benzaldehyde. (c) Calculated from conversion and selectivity. (d) Calculated from the data provided.

2.4 Solvent effects

Solvent selection is a critical issue for alcohol oxidations catalyzed by transition metal HTs, the use of polar solvents being particularly challenging. While polar solvents are not as problematic for precious metal-containing HTs, they are less suited for oxidations catalyzed by other transition metal HTs. Using Ru-Mg-Al-HT as catalyst, cinnamyl alcohol was converted to cinnamaldehyde in 95%, 93%, 92% yield in toluene, chlorobenzene, and benzene, respectively.[18] However, when acetonitrile and 1,2-dichloroethane (as well as n-hexane and cyclohexane) were used, the yields decreased to 70-86%, while the yield in methanol was only 27%. When using transition metal HTs, a similar yet more pronounced trend was found. Indeed, Choudary et al.[20] found that Ni-Al-HT (2:1) in methanol and acetonitrile yielded 4-nitrobenzaldehyde from 4-nitrobenzyl alcohol in yields of only 5% and 29%, respectively. When the same reaction was carried out in non-polar solvents such as benzene, cyclohexane, hexane, and toluene, yields were 66-98%. Kawabata et al.[21] noted a similar trend for Ni containing HTs. Polar solvents were found to be ineffective, while non-polar solvents such as toluene gave good yields and selectivity. Polar solvents, which are strongly adsorbed by the active sites in the catalyst, were suggested to prevent the adsorption of alcohols, thereby slowing reaction rates. It should be noted that benzyl alcohol oxidation catalyzed by Zn-Co-HT showed very high activity in acetonitrile; however, the terminal oxidant was TBHP, which may contribute to the increased activity.[26]

2.5 Mechanistic insights

In the case of alcohol oxidation with TBHP, it is thought that the reaction proceeds through a two-step redox mechanism in which production of the ketone is accompanied by reduction of the metal and the production of water. This is followed by re-oxidation of the metal by TBHP to regenerate the metal active site, t-butyl alcohol being generated as a co-product (see Equation 1). Oxidation of the alcohol to the ketone is thought to be the rate-determining step.[23]

$$M^{n+} + C_6H_5CH_2OH \rightarrow M^{(n-2)} + C_6H_5CHO + H_2O$$
$$M^{(n-2)} + (CH_3)_3COOH \rightarrow M^{n+} + (CH_3)_3COH$$
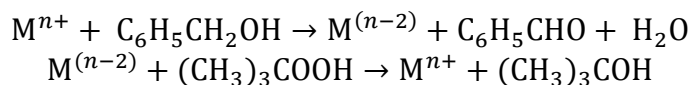
Equation 1. Oxidation of alcohols using TBHP/HT according to Choudhary et al.[23]

In the case of HT-catalyzed oxidation of alcohols with O_2, formation of a metal alkoxide *via* ligand exchange of the metal hydroxide with the alcohol (with the

formation of water) is postulated to be the initial step. This is generally thought to occur through the Lewis acidic M(III) cation; for example, the metal alkoxide is thought to form on Al when present, similar to Oppenauer oxidations.[20, 21] Next, the M(II) site activates oxygen, producing a peroxo species. Finally, the peroxide accepts hydride to produce the ketone and regenerate the active site (Scheme 1). In the case of *iso*-propanol, it has been shown that this reaction doesn't proceed *via* simple dehydrogenative oxidation of the alcohol. Using O_2, near stoichiometric amounts of water and acetone were produced. However, under inert conditions neither acetone nor water were obtained.[21]
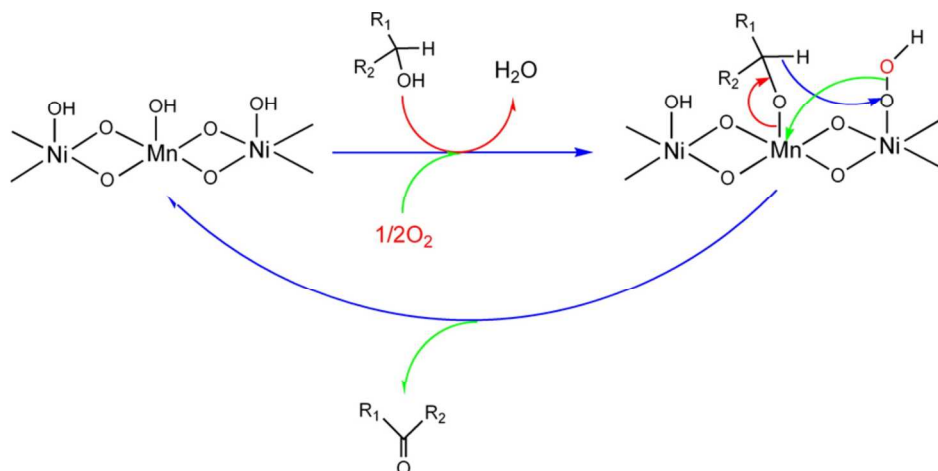
Scheme 1. Proposed mechanism for the aerobic oxidation of alcohols. Reproduced with permission from Ref. [24].

While this mechanism appears plausible, it may not be entirely accurate in its description of the reaction. In the original report from Choudary *et al.*[20], it was suggested that carbonate anions play an integral role in the catalytic activity of HTs. This is likely related to the initial deprotonation stage of the reaction. Indeed, when Choudary and co-workers synthesized Ni-Al HT by means of precipitation with aqueous ammonia, decreased activity was observed for the oxidation of 4-nitrobenzyl alcohol. A similar result was seen when the catalyst was calcined and rehydrated to the HT *via* the "memory effect." In both cases carbonate anions were absent, the catalysts being otherwise the same. Interestingly, a similar result was obtained by Kaneda and co-workers for Ru-HTs prepared with a variety of intercalated anions.[18] Their results showed that CO_3^{2-} intercalated HT had the highest conversions and yields of all the catalyst synthesized. It has been suggested for other transformations catalyzed by HTs that the active sites on the catalyst are located on the (110) crystallographic plane.[12, 27] The (110) plane corresponds to the edges of the HT platelets where coordinatively unsaturated metals ions and the interlayer carbonate ions are exposed. From this it follows that the active sites for alcohol oxidation should likewise be associated with the (110) plane.
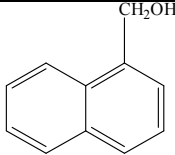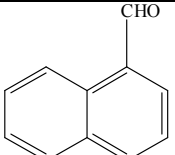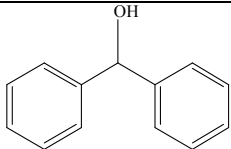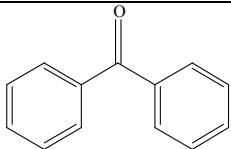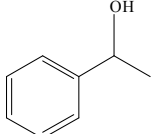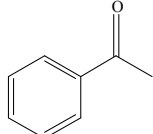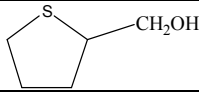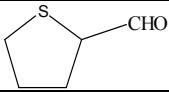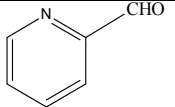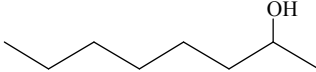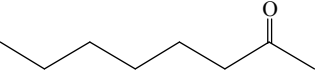
2.6 Activity and Scope

In terms of the scope of substrates that can be oxidized to the desired aldehyde or ketone product, Ru-HT has been shown to be an effective catalyst for a wide range of alcohols (see Table 2 below). Both Ru-Mg-Al-HT[18] and Ru-Co-Al-HT[19] are reported to be efficient catalysts for benzylic alcohol oxidation, albeit Ru-Co-Al-HT affords much higher reaction rates. Electron withdrawing groups (EWGs) decrease the reactivity of benzylic alcohols for both Ru-Mg-Al-HT and Ru-Co-Al-HT catalysts, while electron donating groups (EDGs) show little effect in the case of Ru-Mg-Al-HT. Primary alcohols are oxidized at a faster rate than secondary alcohols in both cases. For both catalysts, allylic alcohols show good to excellent selectivity to the corresponding carbonyl compound. Notably, heteroaromatic alcohols are efficiently oxidized by Ru-Co-Al-HT, although not by Ru-Mg-Al-HT, as are secondary aliphatic alcohols. It is believed the superior oxidizing ability of Ru-Co-Al-HT is derived from the substitution of Mg(II) by Co(II), leading to a higher oxidation state of the active Ru species in the catalyst (*vide supra*).

Table 2. Oxidation of alcohols with Ru-Co-Al-HT. Reproduced from Ref. [19] with permission from The Royal Society of Chemistry

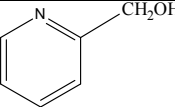| Entry	Substrate	Product	Time	Conversion (%)	Yield[a] (%)
1			40 min	100	94 (89)[b]
2			1.5 h	100	100
3			20 h	99	90
4	EIZ = 3/97	EIZ = 5/95	12 h	86	80
5	EIZ = 98/2	EIZ = 94/6	12 h	89	71
6			1 h	100	96
7			50 min	100	100
8			1.5 h	100	95

9	CH₂OH (1-naphthylmethanol)	CHO (1-naphthaldehyde)	1 h	100	92
10	OH (diphenylmethanol)	O (benzophenone)	1 h	100	96 (98)
11	OH (1-phenylethanol)	O (acetophenone)	1.5 h	100	100
12	CH₂OH (tetrahydrothiophene-2-methanol)	CHO (tetrahydrothiophene-2-carbaldehyde)	40 min	100	91
13	CH₂OH (pyridine-2-methanol)	CHO (pyridine-2-carbaldehyde)	7 h	99	91
14	OH (2-octanol)	O (2-octanone)	2 h	100	97 (82)

Reaction conditions: substrate (2 mmol), Ru-Co-Al-CO₃HT (0.3 g), toluene (5 ml), 60°C, O₂ atmosphere. (a) Yields of aldehydes and ketones were determined by GC analysis using internal standards, based on alcohols. (b) Values in parentheses are isolated yields. In the case of the product isolation experiments, the reaction scale was three times greater than that given in the footnote.

The Ni-Al-HT catalyst studied by Choudary and co-workers[20] also showed excellent activity for a wide range of substrates (Table 3). Unlike the Ru-HT catalysts mentioned above, Ni-Al-HT (2:1) oxidized secondary alcohols faster than primary alcohols. For benzylic alcohols, substitution on the aromatic ring increased reaction rates regardless of EWG or EDG substituents. Cinnamyl alcohols were oxidized selectively to cinnamaldehydes in good to excellent yields, although other allylic alcohols gave only moderate yields. Poor yields were obtained with aliphatic alcohols. Notably, α-ketols were oxidized efficiently to α-dicarbonyls. Contrary to Choudary's report, the Ni-Mg-Al-HT (0.5:2.5:1) catalyst described by Kawabata et al.[21] gave similar results to those obtained using Ru-HTs[18, 19], which had faster reaction rates for primary alcohols than secondary alcohols and decreased rates in the case of para-substitution on the aromatic ring. Primary aliphatic alcohols showed no reaction and cinnamyl alcohol was oxidized to cinnamaldehyde with benzaldehyde as a byproduct. The authors blamed the low selectivities obtained at low conversions on retention of the substrate in the catalyst's layered structure as evidenced by a blank test, which saw 10% of the alcohol retained in the layers without evidence of oxidation.

Table 3. Oxidation of alcohols with molecular oxygen over Ni-Al-HT (2:1). Adapted with permission from Ref. [20].

Entry	R′	R″	Time [h]	Yield [%][a]
	\(\underset{R'\diagup \diagdown R''}{\overset{OH}{|}}\) $\xrightarrow[O_2]{Ni\text{-}Al\text{-}HT}$ \(\underset{R'\diagup \diagdown R''}{\overset{O}{|}}\)			
1	C_6H_5	H	12	31
2	m-MeOC$_6$H$_5$	H	2	88
3	o-NO$_2$C$_6$H$_5$	H	6	76
4	p- NO$_2$C$_6$H$_5$	H	6	98
5	o-MeOC$_6$H$_5$	H	1.5	86
6	o-MeC$_6$H$_5$	H	6	72
7	m-ClC$_6$H$_5$	H	15	63
8	m-PhOC$_6$H$_5$	H	10	71
9	p-MeOC$_6$H$_5$	H	10	88
10	o-ClC$_6$H$_5$	H	10	87
11	p-ClC$_6$H$_5$	H	10	73
12	o,p-MeOC$_6$H$_5$	H	12	88
13	C_6H_5	CH$_3$	12	95 (94)[b]
14	p-MeOC$_6$H$_5$	CH$_3$	6	84
15	p-MeC$_6$H$_5$	CH$_3$	2	96
16	p-NO$_2$C$_6$H$_5$	CH$_3$	3	92
17	C_6H_5	C_6H_5	1.5	95
18	C_6H_5CO	C_6H_5	2.5	93
19	C_6H_5	C_6H_5(OH)CH	1.5	93
20	C_6H_5	CH$_2$CH$_3$	7	72
21	C_4H_3OCO	C_4H_3O	3	96
22	C_6H_4CH=CHCH$_2$	H	6	88
23	o-NO$_2$C$_6$H$_4$CH=CHCH$_2$	H	10	84
24	p-MeOC$_6$H$_4$CH=CHCH$_2$	H	10	96
25	p-BrC$_6$H$_4$CH=CHCH$_2$	H	12	95

Typical reaction conditions: 2 mmol of alcohol, 0.5 g of Ni-Al-HT (2:1) catalyst, and 10 mL of toluene were heated to 90°C with stirring. Oxygen was bubbled through the reaction mixture for the specified amount of time.

a. Yields of isolated products.
b. Yield after the 6th cycle.

In the case of alcohol oxidation over Zn-Co-HT with TBHP, secondary benzylic alcohols showed higher reaction rates and selectivities than primary benzylic alcohols.[26] The lower selectivities obtained for the latter are unsurprising given the oxidizing power of TBHP, which can over-oxidize aldehydes to carboxylic acids. Interestingly, for primary benzylic alcohols *para*-substitution of the aromatic ring with the electron-withdrawing

nitro group increased conversions while not affecting selectivity; in contrast, the electron-donating methoxy group decreased conversion while increasing selectivity to 100%.
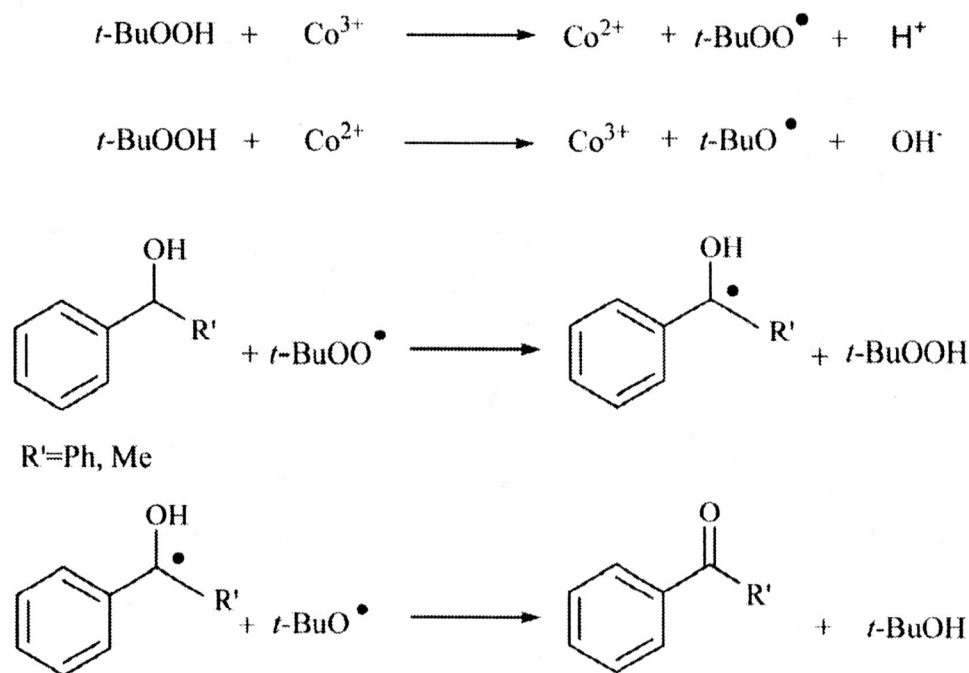
3   Intercalated HTs

It is well established that certain anionic species such as CrO_4^{2-}, MnO_4^-, and polyoxometallates (POMs) can stoichiometrically or catalytically oxidize alcohols. In view of this, several workers have synthesized HTs intercalated with these species for use in alcohol oxidations. One of the earliest examples of intercalated HTs for the oxidation of alcohols was reported by Kwon et al.[17], who synthesized a pillared HT via ion exchange of Zn-Al-HT with decavanadate ($V_{10}O_{28}^{6-}$). The pillared HT was then used for the photocatalytic oxidation of iso-propanol. Under irradiation and an oxygen atmosphere, 6 moles of acetone were produced per mole of decavandate in the catalyst. Moreover, under inert atmosphere only a stoichiometric amount of acetone was produced, suggesting the catalytic nature of the reaction. The catalyst also showed superior catalytic activity to its homogeneous counterpart, which yielded only 2 moles of acetone per mole of decavanadate under the same conditions.

Other researchers have synthesized HTs with intercalated POMs as the charge balancing anionic species. Indeed, Jana et al.[28] synthesized a series of HTs pillared with transition metal substituted POMs, finding that a Co substituted POM (Cu, Fe, Ni, Cr were also tested) gave the highest conversion of cyclohexanol with 100% selectivity to cyclohexanone. Benzyl alcohol was also converted effectively to benzaldehyde in 79% conversion (98.4% selectivity) at 100^oC under O_2. Similar to the findings of Kwon et al.[17], when the non-heterogenized POM was used as a catalyst, slightly inferior results were obtained. Continuing the reaction after the filtration of the intercalated catalyst did not result in a significant increase in conversion, indicating that the reaction does not occur homogeneously. Further, the catalyst was recycled four times with minimal loss of activity, confirming its stability.

HTs have also been intercalated with inert pillars, with the goal of increasing the exposed surface available for catalysis. Baskaran et al.[29] synthesized a Co-Al-HT intercalated with silicate, which was followed by calcination at $400-550^oC$, resulting in spinel and cobalt silicate phases. Catalytic studies were performed using benzhydrol as a probe molecule and TBHP as the oxidant. When the intercalated Co-Al-HT catalysts were compared to Co-Al-HT, the silicate intercalated catalysts displayed superior conversions of benzhydrol to benzophenone. This was attributed to the exposed Co^{2+} and Co^{3+} active species on the catalyst surface, the presence of Co^{2+} and Co^{3+} species being confirmed by XPS. The catalysts proved to be reusable with or without calcination between each recycle, although calcination (550^oC in air to remove adsorbed organic species from the catalyst) did result in a significant decline in selectivity (from 99.6% to 70%). The authors attributed the catalyst's activity to a free radical pathway in which surface Co^{2+} and Co^{3+} sites react with TBHP to give alkoxo and peroxo radicals. The peroxo radical

then abstracts the benzylic hydrogen from the alcohol, giving the radical intermediate shown below (Scheme 2). This radical reacts with the *tert*-butyl alkoxo radical to form the corresponding ketone and *tert*-butyl alcohol. The presence of a radical pathway was confirmed by use of the radical scavenger butylated hydroxytoluene (BHT), which decreased the conversion from *ca.* 86% to 45 %, while selectivity remained similar. Other alcohols were oxidized using this catalyst in modest to good conversions; notably, those with EWG in the *para*-position gave lower yields, which was presumed to be the result of stabilization of the radical intermediate.

Scheme 2: Mechanism for alcohol oxidation using silicate intercalated Co-Al-HT. Reproduced from Ref. [29] **with permission from The Royal Society of Chemistry**

Other anionic species that have been employed for the preparation of intercalated HT catalysts include MnO_4^-, which was intercalated into a series of Mg-Al-HTs with varying Mg:Al ratios[30]. Using TBHP as oxidant, Choudhary *et al*. showed that benzyl alcohol conversions (>99% selectivity to benzaldehyde) trended with the Mg:Al ratio. Indeed, the highest benzaldehyde yield (50%) was obtained using MnO_4^- intercalated HT with a Mg:Al ratio of 10, suggesting that the basicity of the catalyst strongly affected conversion. Interestingly, when Mg-Al-HT itself was used, benzyl alcohol conversion was lower than in the uncatalyzed reaction with TBHP. The authors suggested that this is likely due to radical intermediate termination by the HT. When the catalyst was used under oxidant-free conditions, benzyl alcohol was oxidized to benzaldehyde with a 7.5% yield, which is near stoichiometric with the amount of intercalated MnO_4^-. The authors suggested that the reaction may operate through a redox mechanism (Equation 2). The Mn(VII) species is reduced to Mn(V) upon oxidation

of the alcohol to the aldehyde, with co-production of water. The Mn(V) species is re-oxidized to Mn(VII) upon treatment with TBHP. Oxidation of the alcohol is expected to be the rate-limiting step, which may be facilitated by activation of the alcohol on basic sites.

Equation 2. Oxidation of benzyl alcohol using MnO$_4^-$ intercalated HT and TBHP.[30]

$$Mn(VII)O_4^- + C_6H_5CH_2OH \rightarrow Mn(V)O_3^- + C_6H_5CHO + H_2O$$
$$Mn(V)O_3^- + (CH_3)_3COOH \rightarrow Mn(VII)O_4^- + (CH_3)_3COH$$
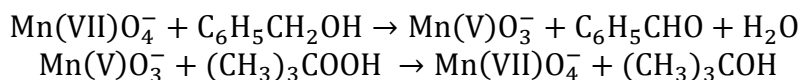
Manayil *et al.*[31] synthesized Co-Al-HTs with both CO_3^{2-} and NO_3^- interlayer species. Upon treatment with chromate solution it was found that the Co-Al-NO$_3^-$ HT (2:1 Co:Al) had a higher ion exchange capacity than its CO_3^{2-} counterpart. Moreover, while the nitrate containing HT exchanged with chromate in the interlayer region, the carbonate containing HT displayed surface adsorption of chromate only. As a result, the nitrate exchanged HT exhibited a lower conversion of benzyl alcohol upon oxidation with TBHP, albeit with higher selectivity to benzaldehyde than the carbonate exchanged sample. However, the carbonate exchanged catalyst showed poor recyclability, owing to leaching of the chromate species into the reaction medium, while the nitrate exchanged species proved to be reusable through 4 cycles with only moderate decreases in conversion (selectivity remaining constant).

Other chromium species to be intercalated in HTs include sulphonato-salen-chromium(III) complexes. When intercalated into Mg-Al-HTs, Wu *et al.*[32] found them to be effective catalysts for benzyl alcohol oxidation with H_2O_2. Interestingly, the catalytic properties of the intercalated species was highly dependent on the coordination environment of the Cr(III) species. Indeed, when the electron-withdrawing *o*-C$_6$H$_4$ group was used in the sulphonato-salen ligand, benzyl alcohol oxidation reached its highest conversion of 65.8% (100% selectivity to benzaldehyde). The authors attributed the increase in conversion to the extended π-network created by the *o*-C$_6$H$_4$ group, which decreased the electron density around the Cr(III) species, facilitating the formation of the active oxochromium intermediate. In all cases, the heterogenized Cr(SO$_3$-salen) complex afforded higher benzyl alcohol conversion and selectivity to benzaldehyde than its homogeneous analogue. The authors suggested that the improved activity of Cr(SO$_3$-salen)-HT may be due to the presence of weak base sites on the HT surface, which hydrogen bond with the H_2O_2, activating it with respect to oxygen transfer. The suggested mechanism (Scheme 3) involves the formation of Cr(V)oxo species through heterolytic cleavage of H_2O_2 by the coordinatively unsaturated Cr(III) site. Hydrogen is then abstracted by the Cr(V)oxo species from the α-carbon, creating a carbocation intermediate. Subsequently, a proton is abstracted from the hydroxyl oxygen generating the product. Re-oxidation of the catalyst by H_2O_2 completes the catalytic cycle.

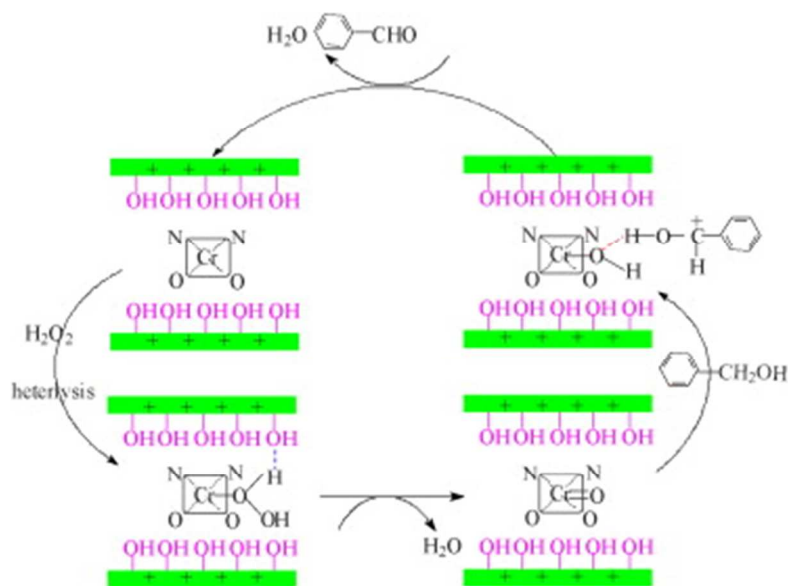**Scheme 3. Suggested mechanism for benzyl alcohol oxidation using Cr(SO₃-salen) intercalated HT. Reproduced with permission from Ref. [32].**

Kantam *et al.*[33] studied the use of the chelating *rac*-BINOL ligand attached to the surface of a Cu-Al-HT for the aerobic oxidation of alcohols. Several Cu-Al-HTs were synthesized with varying Cu:Al ratios, Cu-Al-HT with a ratio of 2.5:1 showing the highest activity for the aerobic oxidation of benzyl alcohol with a benzaldehyde yield of 99%. The catalyst proved to be highly recyclable, with no loss of activity through 5 cycles. Several other benzyl alcohols with EDGs and EWGs were oxidized to their corresponding aldehydes in good to excellent yields. Moreover, *ortho*-substitution of the benzylic alcohol with EDGs resulted in increased reactivity, which the authors suggested might be due to a chelating effect on the catalyst. Secondary alcohols and N-heterocyclic alcohols could also be oxidized to their corresponding carbonyl compounds in good to excellent yields; however, in the case of cyclopentanol, (pyridin-3-yl)methanol, and 1-(pyridin-3-yl)ethanol, an increase in the reaction temperature was required to drive the reaction forward. The suggested mechanism involves the formation of an alkoxide intermediate through interaction of the alcohol with Brønsted basic sites on the catalyst surface. Concomitantly, peroxide is formed on the Cu sites through oxygen activation, facilitated by the *rac*-BINOL ligand. The peroxide species then accepts hydride from the alkoxide intermediate, forming the carbonyl compound. Notably, K_2CO_3 is used as a base in this reaction, although its role in the reaction mechanism is not discussed.

4   Transition metal complexes immobilized on HT

In principal, immobilizing homogeneous catalysts on surfaces allows the high selectivity and activity of homogeneous catalysts to be combined with the most advantageous aspects of heterogeneous catalysts, such as ease of separation from the reaction products. With this in mind, several workers have used HTs as a support for the "heterogenization" of transition metal complexes. Indeed, Uemura and co-workers[34-36] published several studies on the aerobic oxidation of alcohols using a Pd(II)-salt

immobilized on HT. The immobilized Pd(II)acetate-pyridine-complex was successfully synthesized *in situ* by treatment of HT with $Pd(OAc)_2$ and pyridine in toluene as solvent. XRD analysis of the catalyst revealed that the Pd(II) complex was retained on the external surface of the HT particles – as opposed to being intercalated – as evidenced by the unaltered basal spacing.[34] Analysis of the immobilized Pd(II) complex using a variety of spectroscopic methods proved inconclusive; however, the authors confirmed acetate coordination to Pd through intentional leaching of the catalyst in excess pyridine.[35] On this basis, a Pd(II)acetate-pyridine-complex was suggested as the immobilized catalyst. The Pd(II)/HT proved to be active for the oxidation of a variety of alcohols in O_2[35] and air[36], the use of air generally affording decreased reaction rates in comparison with O_2. Notably, this catalyst oxidized allylic alcohols without any isomerization of the alkene, albeit 5 equivalents of pyridine were necessary to enhance reactivity. The authors suggested that pyridine may aid in preventing complexation of the olefin to Pd(II). Unfortunately, as for many immobilized catalysts, leaching is a problem for the Pd(II)/HT. This was evidenced by continued oxidation of benzyl alcohol after removal of the solid catalyst from the reaction mixture[35], as well as decreased benzaldehyde yields upon recycling the catalyst in the aerobic oxidation of benzyl alcohol[35, 36]. In order to resolve the leaching problem, the authors synthesized a second catalyst, Pd(II)/HT(m). This catalyst was synthesized similarly to Pd(II)/HT, however, only half the amount of the Pd(II)-complex was immobilized on the surface. Indeed, this catalyst showed a decreased amount of leaching while retaining similar oxidizing ability, albeit with decreased activity.

Alcohol oxidation is thought to occur *via* the same mechanism postulated for the homogenous catalyst (Scheme 4), in which a metal alkoxide is formed followed by β-hydride transfer to the Pd and the fomation of the carbonyl compound. The catalyst is regenerated through formation of a hydroperoxide from the combination of O_2 and a Pd-hydride. The hydroperoxide species can then react with another equivalent of alcohol to complete the catalytic cycle. The authors suggest that as for the homogeneous system, H_2O_2 may be formed, albeit H_2O_2 was not observed using a KI-starch test. This is thought to be due to decomposition of H_2O_2 prior to iodine indication. Oxidation of benzyl alcohol revealed that O_2 was consumed in a 1:2 ratio to the produced benzaldehyde, supporting the aforementioned aerobic oxidation pathway.
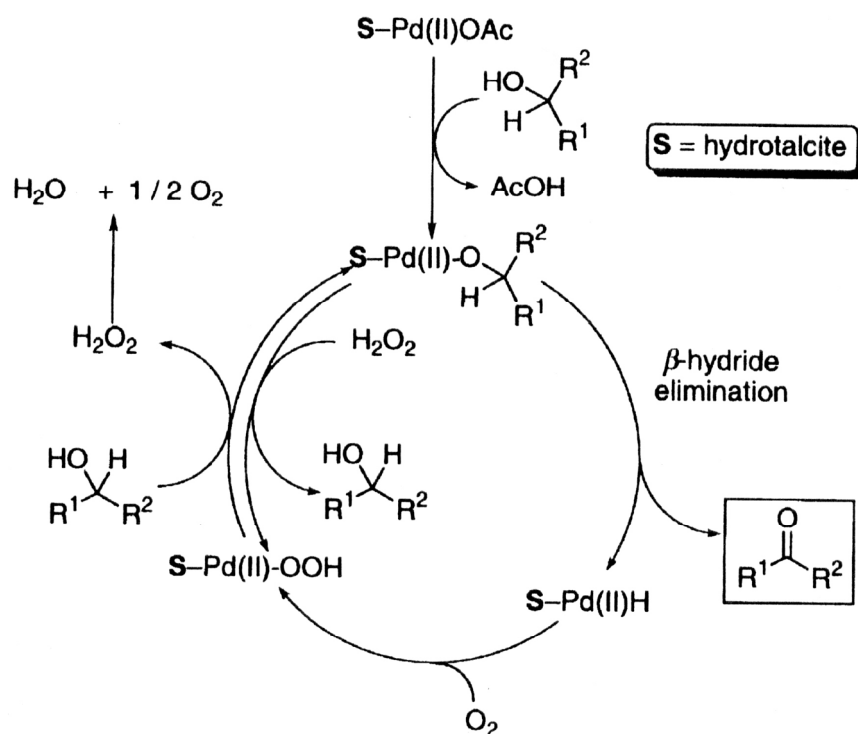
Scheme 4. Reaction mechanism for aerobic oxidation of alcohols using Pd(II)-HT. Reproduced with permission from Ref. [35].

Recently, Sahoo and Parida[37] tethered a Pd(II) species to the surface of Zn-Al-HT using a N-[3-(trimethoxysilyl)-propyl] ethylenediamine (TPED) ligand. The catalyst, denoted as Pd-TPED/HT (with a Pd loading of 16.63 wt. %), efficiently oxidized benzyl alcohol in the presence of O_2 using water as the solvent. Like other Pd(II)/HTs, Pd-TPED/HT required the presence of pyridine for reaction completion. The authors suggest that pyridine serves several functions. Firstly, the pyridine may act as a base, aiding in deprotonation of the alcohol. Secondly, pyridine may function to prevent irreversible reduction of Pd(II) to Pd black (Scheme 5, [III]) *via* π-back-bonding from the aromatic nitrogen. In terms of the scope of substrates that can be oxidized, Pd-TPED/HT was able to convert a variety of primary benzylic and aliphatic alcohols to the corresponding aldehyde with excellent selectivity. The reaction mechanism (Scheme 5), unlike the one described by Uemura and co-workers[35], is thought to be a redox mechansim, in which Pd(II) is reduced to Pd(0) by the alcohol, producing the carbonyl compound and two equivalents of H^{+}. The reduced Pd then reacts with O_2 to form a peroxo species. The peroxo species then combines with the two protons to form hydrogen peroxide, regenerating the Pd(II) catalyst.
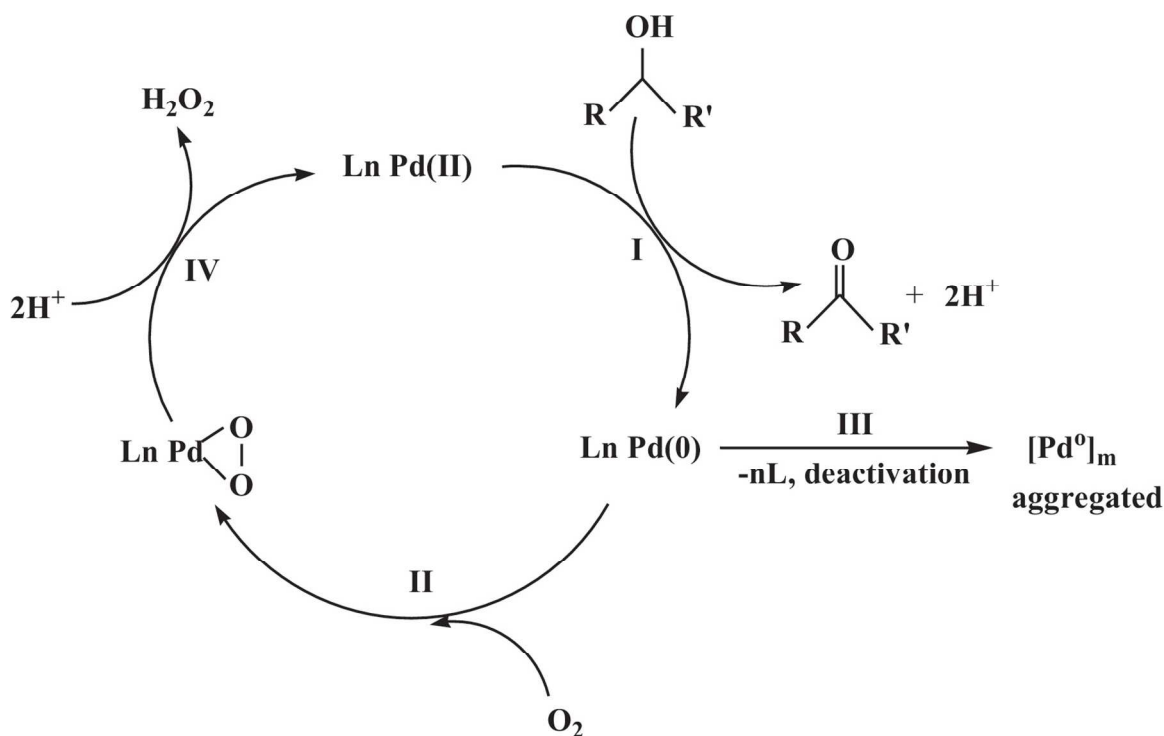
Scheme 5. Possible mechanism of alcohol oxidation catalyzed by Pd-TPED-HT. Reproduced with permission from Ref. [37].

Zn-Al-HT was also employed for the immobilization of a Ce(III)-complex (*via* intercalation) by Singha *et al.*[38] (Scheme 6). The resulting catalyst showed good activity for the oxidation of aliphatic and benzylic primary alcohols, as exemplified by the selective oxidation of benzyl alcohol to benzaldehyde (TOF of 133 h^{-1}). Interestingly, the catalyst showed high chemoselectivity for the oxidation of primary alcohols over secondary alcohols, as revealed by competitive intramolecular oxidation experiments. Competitive intermolecular oxidation experiments also showed higher conversion rates for primary alcohols than secondary alcohols. Notably, the homogeneous Ce(III)-complex catalyst showed decreased activity compared to its heterogenized Ce(III)/HT analogue, which can be attributed to the possible formation of catalytically inactive μ-oxo dimers in the homogeneous system.
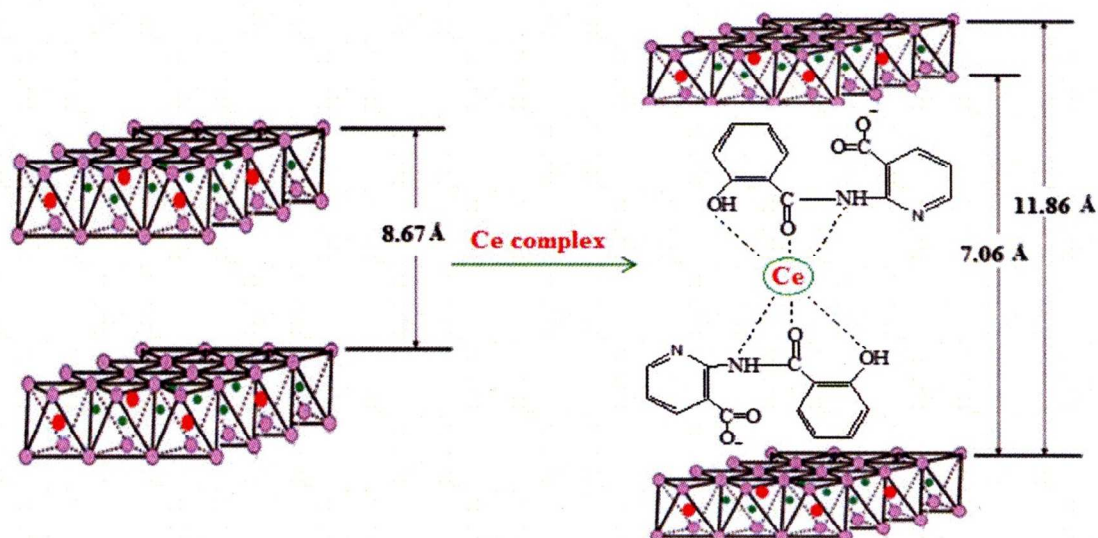
Scheme 6. Ce(III)-complex intercalated HT. Reproduced from Ref. [38] with permission from The Royal Society of Chemistry.

5 Transition metal NPs and oxo clusters supported on HT

Metals loaded on the surface of metal oxide supports are widely used to achieve catalytic transformations. This includes the use of metal nanoparticles (NPs) supported on HT for the oxidation of alcohols. Given the success of Pd complexes immobilized on HT, Chen et al.[39] researched the use of Pd nanoparticles supported on the surface of HT for the aerobic oxidation of benzyl alcohol without the addition of external base. This is particularly notable, given that the aforementioned Pd-complexes immobilized on HT were heavily dependent on the addition of pyridine to facilitate oxidation. The authors concluded that the activity of the catalyst was regulated by surface Brønsted basicity and Pd particle size. Indeed, the catalyst calcined at 300°C (Pd/HT-C3) displayed both the highest basicity and activity of those prepared (Table 4). To prove the dependence on Pd nanoparticle size, two catalysts with similar basicity and different Pd particle sizes were prepared; of these, the catalyst with smaller Pd nanoparticles had higher activity for the aerobic oxidation of benzyl alcohol. The increased activity of smaller Pd nanoparticles is believed to be due to an increase in the amount of coordinatively unsaturated metal sites.

Table 4. Solvent-free aerobic oxidation of benzyl alcohol catalyzed by Pd/HT. Adapted with permission from Ref. [39].

| Sample	Mean size of Pd (nm)	Basicity (mmol CO_2 g^{-1})	Initial conversion rate (mmol h^{-1})[b]	Intrinsic TOF (h^{-1})[c]
HT	0	0.73	0	0
Pd/HT-C1[a]	6.4	0.81	4.1	412.9
Pd/HT-C2[a]	4.9	1.22	8.6	861.9
Pd/HT-C3[a]	4.2	1.60	9.6	964.1
Pd/HT-C4[a]	3.5	1.00	7.8	783.9
Pd/HT-C5[a]	2.6	0.66	6.0	603.8

Reaction conditions: catalysts 0.1 g; benzyl alcohol 48.5 mmol; O_2 atmosphere; temperature 100°C.

a. C1, C2, C3, C4, and C5 refer to the calcination temperatures 100°C, 200°C, 300°C, 400°C, 500°C, respectively.

b. Evaluated from the benzyl alcohol conversion at the initial reaction stage (conversion <20%).

c. Calculated from the initial conversion rate per Pd atom on the catalyst.

In a study by Ebitani et al.[40], heterotrimetallic RuMnMn species were synthesized on the surface of HT. This catalyst was highly effective for the aerobic oxidation of alcohols. K-edge XANES revealed that both Ru and Mn were in the 4+ oxidation state, while EXAFS showed the near absence of Ru-O-Ru bonding. The initial TOF of the catalyst in benzyl alcohol oxidation was found to be 140 h^{-1}, while the calculated TOF at near quantitative conversion was ca. 50 h^{-1}. In both cases the TOF was based on the amount of Ru in the catalyst. Further analysis revealed that Mn played an integral role in the rate-determining β-hydrogen elemination step. Applying Michaelis-Menten kinetics, the value of K_2 (β-hydrogen elemination step) was found to be nearly twice as high for RuMnMn/HT compared to Ru/HT. Additionally, competitive oxidation of benzyl alcohol and $C_6D_5CD_2OH$ resulted in a primary kinetic isotope effect value of 4.2, suggesting that β-hydride elimination is the rate-determining step. Intramolecular competitive oxidation studies showed that the catalyst selectively oxidized primary alcohols, yielding 1-[(4'-formyl)phenyl]ethanol from 1-[(4'-hydroxymethyl)phenyl]ethanol in 98% yield at 40°C. Moreover, the catalyst was highly effective for the oxidation of variety of other alcohols, yielding the corresponding carbonyl compounds with high conversion and selectivity. Mechanistically, alcohol conversion is expected to proceed via an alkoxide intermediate formed by the elimination of water on the Ru site, followed by β-hydride elimination to give the carbonyl compound and a Ru-hydride. Reaction of the Ru-hydride with O_2 then forms a hydroperoxide, which regenerates the Ru-alkoxide upon addition of another equivalent of alcohol (Scheme 7).
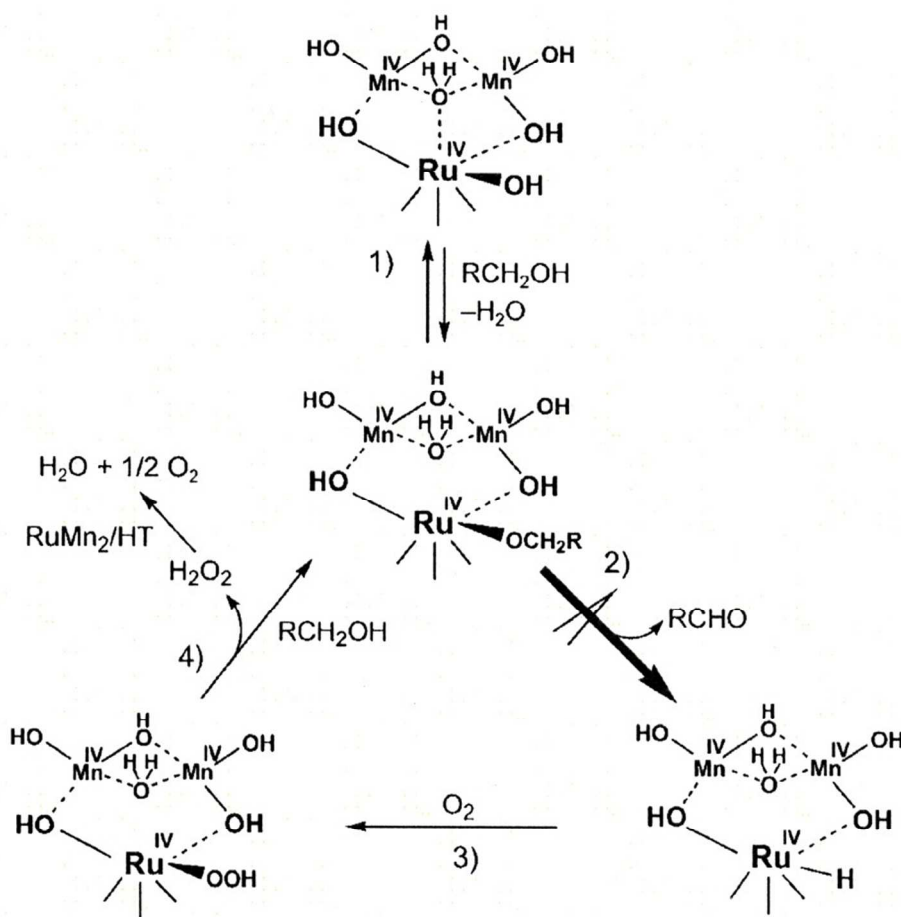
Scheme 7. Proposed mechanism for the aerobic oxidation of alcohols using RuMnMn/HT. Reproduced with permission from Ref. [40].

Nagashima *et al.*[41] synthesized high valent Mn species on the surface of HT (Mn/HT-ox). EXAFS and XANES measurements on this catalyst showed the presence of Mn-oxo clusters in which Mn was present in the 6+ oxidation state. Good selectivity was obtained in the aerobic oxidation of benzyl alcohol and 1-phenyl ethanol, although TOFs were quite low (1.4 and 1.7 h^{-1}, respectively). The catalyst also proved to be readily recycled, oxidizing BA through four cycles without loss of activity. Unlike the aforementioned RuMnMn/HT[40], Mn/HT-ox is expected to catalyze oxidations through a radical pathway as evidenced by the inhibition of the reaction upon addition radical scavengers. The proposed mechanism (Scheme 8) involves proton abstraction from the alcohol by the metal-oxo oxygen, followed by radical hydrogen abstraction from the C_α carbon by a second metal-oxo oxygen, resulting in a reduced Mn(V) species. Formation of the carbonyl compound and water results in a reduced Mn(IV)-oxo species, which is reoxidized to the Mn(VI)-di-oxo species by O_2, thereby completing the catalytic cycle.
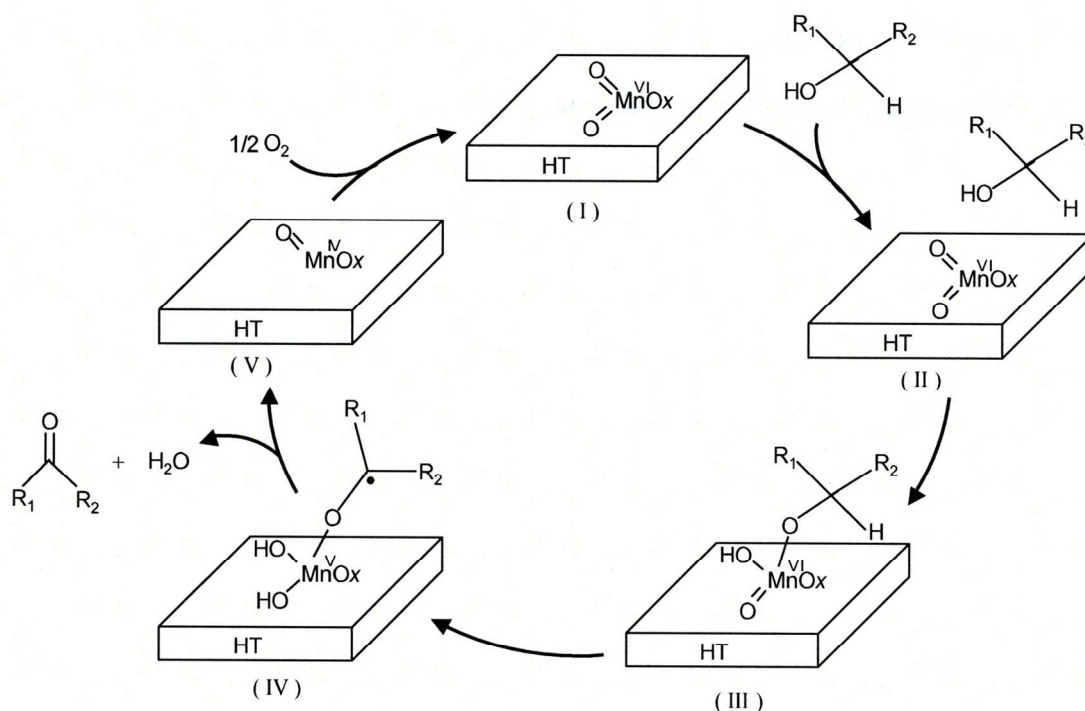
Scheme 8. Oxidation of alcohols with Mn/HT-Ox catalyst. Reproduced from Ref. [41] with permission from The Royal Society of Chemistry

Mitsudome *et al.*[42] explored the use of Cu nanoparticles supported on hydrotalcites for oxidant-free and acceptor-free dehydrogenation of alcohols. While metallic copper nanoparticles on other oxidic supports gave good yields of cyclooctanone from cyclooctanol, Cu/HT gave near quantitative conversion in only 3 h (TOF of 388 h^{-1} under solvent-free conditions). The catalyst was successfully applied to a wide range of substrates, including alicyclic, aliphatic and benzylic alcohols, as well as heteroatom-substituted alcohols, giving the corresponding carbonyl compounds in good to excellent yields. Notably, cyclohexanol, a notoriously difficult substrate to oxidize, gave 99% conversion with 94% selectivity to cyclohexanone. Other cyclohexanol derivatives were also successfully dehydrogenated, with the formation of small amounts of aldol byproduct. Cu/HT proved to be reusable, and according to a hot filtration experiment, truly heterogeneous in nature.

In another study, Mitsudome *et al.*[43] examined the use of Ag nanoparticles on HT for the oxidant-free dehydrogenation of alcohols. Ag/HT showed high activity for the oxidation of 1-phenyl ethanol under Ar atmosphere in *p*-xylene, reaching TON and TOF values of 22,000 and 1,375 h^{-1}, respectively. The TOF was increased to 2,000 h^{-1} by removing co-produced H$_2$ with flowing Ar. A hot filtration experiment revealed the active species was not homogenous and no Ag was leached into the filtrate according to ICP analysis. The catalyst effectively oxidized a series of other benzylic, alicyclic, and allylic alcohols in good to excellent yields. Sterically bulky substrates, as well as

heteroatom-substituted alcohols, were also well-tolerated; however, aliphatic alcohols displayed low conversions (albeit with high selectivity to the desired product). Notably, Ag/HT showed quantitative conversion of cinnamyl alcohol to the aldehyde without isomerization or hydrogenation, which was seen with the tested Ru/HT and Pd/HT (Figure 2). Moreover, when 1-phenyl ethanol was oxidized in the presence of styrene, acetophenone was obtained in 99% yield without formation of ethylbenzene, indicating that hydrogen transfer from Ag-hydride species does not occur. The authors credited the lack of hydrogenation to the weak adsorption of molecular hydrogen by Ag.
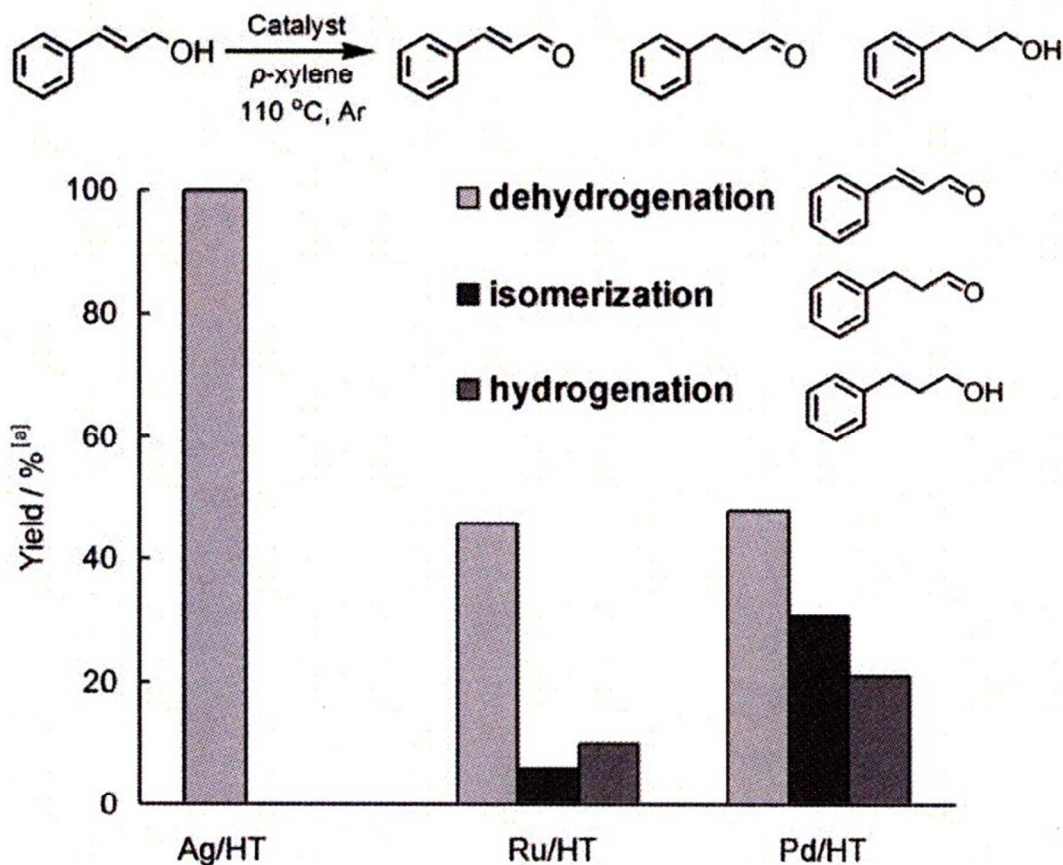
Figure 2. Oxidation of cinnamyl alcohol using Ag/HT, Ru/HT, and Pd/HT. Reaction conditions: catalyst [Ag/HT (Ag:45 nmol), Ru/HT (Ru: 5 μmol), Pd/HT (Pd: 5 μmol)], *p*-xylene (5 mL), cinnamyl alcohol (1 mmol), 110°C, 18 h, Ar atmosphere. The conversions were >99 % (Ag/HT), 72% (Ru/HT), and >99% (Pd/HT), respectively. [a] Determined by GC and GC-MS. Reproduced with permission from Ref. [43].

6   Gold NPs supported on HTs

It wasn't until the 1970s that gold was reported to be catalytically active.[44] Nearly a decade later, pioneering reports by Haruta[45] and Hutchings[46, 47] described gold's activity for the catalytic oxidation of CO and the vapor phase hydrochlorination of acetylene, respectively. In the late 1990's and early 2000's multiple reports appeared describing the aerobic oxidation of alcohols using gold catalysts.[48] Gold is a very attractive catalyst as it is very selective with respect to over-oxidation of the alcohol,

especially in the case of primary alcohols which can form carboxylic acids. Gold can also be used in very low loadings as it tends to be highly active for these transformations. While gold nanoparticles have proved to be an excellent catalyst for alcohol oxidations, a major drawback is the need for the addition of an inorganic base such as NaOH or Na_2CO_3 to aid formation of the alkoxide species. To obviate the need for added base, efforts have been made to employ basic support materials for Au nanoparticles. Examples include reports by Corma and co-workers of Au supported on nanocrystalline ceria[49-51] and more recent reports of Au catalysts incorporating hydrotalcites. It should be mentioned that in many cases the HTs were synthesized *via* alkali co-precipitation, which may mean the active base site is an alkali hydroxide. Nonetheless, these catalysts seem to be active through multiple cycles and further reaction of the catalyst-free filtrate gives no additional reaction, consistent with the heterogeneous nature of the catalysts.

6.1 Au/HT catalysts

The first example of Au supported on Mg-Al HT appears to be a 2009 report by Kaneda and coworkers[52] following a number of reports of gold-catalyzed oxidations with molecular oxygen. Expanding on their prior work concerning Au/HT-catalyzed oxidation of diols to lactones without added base[53], Kaneda and colleagues examined the oxidation of a wide range of alcohols. Substrates such as benzyl, secondary aliphatic, alicyclic, and olefinic alcohols showed good to excellent conversions to the ketone/aldehyde. On the other hand, heteroaromatic alcohols showed lower activity, likely due to strong coordination to active sites in the catalyst, while primary aliphatic alcohols were not oxidized.

In the following years several other research groups described the use of Au/Mg-Al-HT for the oxidation of alcohols. Notably there are two separate protocols for this transformation, based on oxidation using molecular O_2[52, 54-56] and oxidant-free/acceptor-free dehydrogenation[57, 58]. Both Wang *et al.*[54] and Mitsudome *et al.*[52] demonstrated that Au/HT, in combination with O_2, could oxidize a wide range of alcohols with good activity and selectivity to the carbonyl compound. In a later article[56] Wang and colleagues described the oxidation of primary benzylic alcohols, finding them to be less reactive than secondary benzylic alcohols. Notably, benzoic acid and benzyl benzoate were obtained as byproducts in the oxidation of benzyl alcohol. While not explicitly discussed, benzoic acid may be generated from autoxidation of benzaldehyde[59], while benzyl benzoate is likely formed from the oxidation of the hemiacetal intermediate generated by the combination of benzyl alcohol and benzaldehyde[49, 60], or from simple esterification. By performing the reaction at room temperature, selectivity to benzaldehyde was increased to 99%. Other work has been recently reported concerning the use of Au supported on hydrotalcites for the aerobic oxidation of bio-derived molecules such as 5-hydroxymethylfurfural (HMF) to 2,5-furandicarboxylic acid (FDCA). While this is beyond the scope of this review, it should be mentioned that gold supported on hydrotalcite has been shown to be an effective catalyst for the aerobic oxidation of HMF to FDCA in water, without the need for dissolved base.[61]

In the case of the oxidant-free/acceptor-free dehydrogenation route, which was described by Fang *et al.*[57, 58], comparatively higher conversion and selectivity to benzaldehyde were obtained than for the system employing O_2. Indeed, this approach achieved quantitative conversion of benzyl alcohol to benzaldehyde in 9 h[57] as opposed to the 83% yield in 20 h obtained when using O_2 as oxidant.[56] While this improved catalytic activity may be due to the higher temperature and higher catalyst loading used, it should be mentioned that the amount of Au on the catalyst was significantly lower.

6.2 Mechanistic insights: aerobic oxidation *versus* dehydrogenative oxidation

Mechanistically, aerobic oxidation must go through a different oxidation pathway than anaerobic oxidation. While the aforementioned reports of aerobic oxidation do not discuss the use of an inert atmosphere to check for aerobic *versus* anaerobic oxidation, Wang *et al.*[56] performed the temperature programed surface reaction (TPSR) of adsorbed *iso*-propanol, finding that the dehydrogenative ability of Au/HT was better than that of HT; Au/TiO$_2$ and Au/SiO$_2$ displayed no dehydrogenation activity. An XPS study of the same Au/HT, Au/TiO$_2$ and Au/SiO$_2$ catalysts showed that the Au 4f$_{7/2}$ binding energy was lower for Au/HT (83.2 eV) than for Au/TiO$_2$ and Au/SiO$_2$ (83.5 eV and 84 eV, respectively), indicating a stronger interaction of the Au and the HT support and increased negative charge on the Au nanoparticles.[56] This negative charge aids the activation of molecular oxygen *via* electron donation to the LUMO of O_2 (π^*) and facilitates oxidation (Scheme 9).
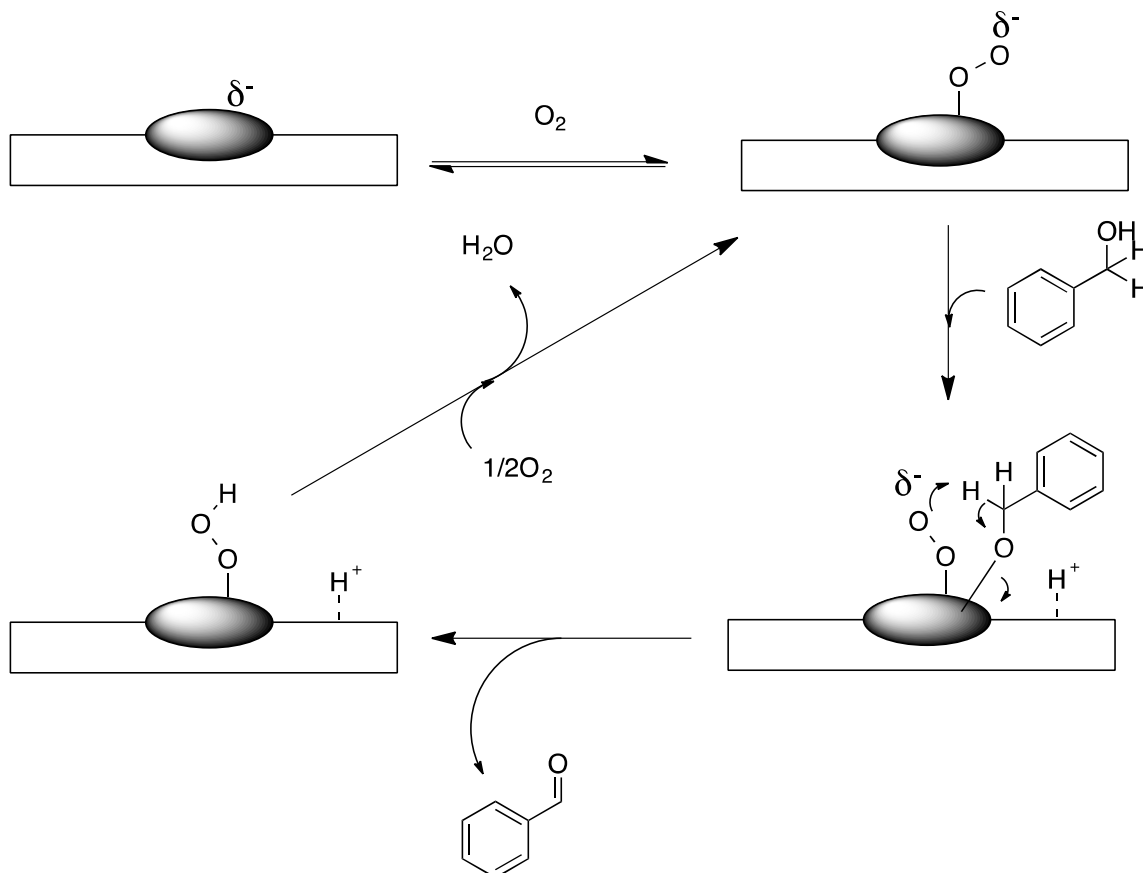
Scheme 9. Plausible mechanism for the aerobic oxidation of alcohols after Nishimura *et al.*[62]

Several studies have been performed with the goal of elucidating the reaction pathway of alcohol oxidation over Au/HT with O_2. In a study by Nishimura *et al.*[62] using Au-Pd nanoclusters (NC) on HT, it was found that the rate of reaction was slowed by addition of radical scavengers (TEMPO and BHT). Similarly, when TEMPO was used as a radical scavenger with Au/NiAl-HT, a slight effect was seen.[27] Based on Lineweaver-Burk plots and the application of Michaelis-Menton kinetics with and without TEMPO, Nishimura *et al.*[62] found that K_m and K_2 were decreased in the presence of TEMPO while K_m/V_{max} was relatively unaffected. This suggests that TEMPO slowed the reaction rate *via* uncompetitive inhibition, combining with an intermediate species. While it is not possible for TEMPO to combine with the alcohol, TEMPO could combine with a peroxo or superoxo species, thereby slowing the reaction. The authors suggest that the formation of the radical-like peroxo/superoxo species is likely due to electron donation from the highly electron rich Au 5d states. In other words, while the alcohol does not oxidize through a radical intermediate, the active oxygen species has radical-like character, which is affected by TEMPO.

A dehydrogenative mechanism (Scheme 10) has been suggested by Fang *et al.*[58] in which the alcohol is activated by the Brønsted basic Mg-OH site forming a metal alkoxide and water. β-hydride elimination then occurs on the gold surface to form the carbonyl. Next, the AlOH Brønsted acid site transfers the water back to Mg, which reacts

with the Au-H moiety to regenerate the Au active site upon loss of H_2. It is expected that the β-hydride elimination is the rate-determining step and that this is facilitated by coordinatively unsaturated Au on the surface. Fang *et al.* also suggested that the main difference between anaerobic dehydrogenation and aerobic dehydrogenation of alcohols is the fact that the Au species is regenerated by O_2, producing water, while in oxidant-free dehydrogenation H_2 is produced. The production of H_2 as a byproduct of the reaction is particularly attractive as it has inherent industrial value in petroleum hydrotreating, H_2 fuel cells, and numerous other applications.
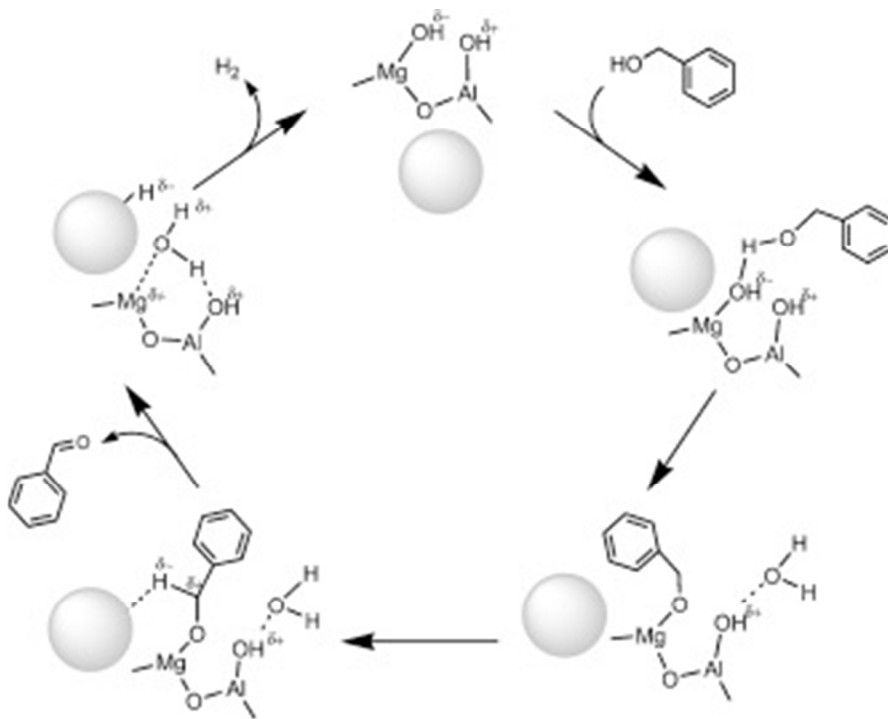
Scheme 10. Dehydrogenative oxidation of alcohols using Au/HT. Reproduced with permission from Ref. [58].

6.3 Effect of particle size and Au loading for Au/HT

Whereas the activity of a heterogeneous catalyst is often directly correlated to the amount of metal loaded on its surface, in the case of alcohol oxidation by Au nanoparticles, and Au/HT in particular, this appears not to be the case. Indeed, many workers have found that optimum catalyst activity is obtained at very low Au loadings. Given the high cost of gold, the ability to use it in small amounts makes these catalysts particularly attractive. The increased activity obtained with smaller amounts of gold is presumably related to increased amounts of coordinatively unsaturated sites resulting from higher Au dispersions and smaller nanoparticles. In many cases authors have found that larger gold nanoparticles (>5 nm) are significantly less active for alcohol oxidation, while ultra-small nanoparticles appear to be highly active at very low Au loadings. The higher activity of small Au NPs supported on HT is in good agreement with results obtained for unsupported gold nanoparticles.[63]

Gold particle size effects were studied in detail by Fang *et al.*[57, 58] An examination of benzyl alcohol conversion as a function of Au loading on HT showed that conversion increased up to 94% as the gold loading was increased to 0.06 wt.%, after which conversion decreased as the gold loading was increased to 0.26 wt.%. This was followed by another gradual increase in conversion as the gold loading was raised to 12 wt.% (Figure 3). The authors explained these observations in terms of the Au particle size distribution. Indeed, TEM measurements revealed the average Au particle size of the 0.26 wt.% catalyst was 13.6 nm, while the 12 wt.% catalyst contained a bimodal particle distribution with smaller particles below 4 nm to which they attributed the increased activity for benzyl alcohol oxidation. The reason for the difference in particle size was unexplained; however, upon further investigation Fang *et al.* found that gold particle size had a direct correlation with turnover frequency (TOF, moles substrate converted/moles of Au*h) in the dehydrogenative oxidation of benzyl alcohol (Figure 4). Nanoparticles of various sizes were synthesized through variations in Au precursor concentration in the aqueous Au media and catalyst aging time. As shown below, even though the Au loading was more or less the same in the synthesized catalysts, TOF (h^{-1}) increased linearly as particle size decreased from 12 nm to 3 nm. As particle size decreased from 3 nm to 2 nm a rapid increase in conversion was seen, the TOF reaching *ca.* 800 h^{-1}. This is in direct contrast to a report by Haider *et al.*[64] who found that gold nanoparticles of medium size (*ca.* 9 nm) had the highest activity in the oxidation of 1-phenyl ethanol catalyzed by Au/Cu-Mg-Al-oxide. Li *et al.*[65] reported similar results to Fang *et al.*, finding that lower Au loadings on Mg-Al-HT afforded higher catalytic activity. Their findings, like those of Fang *et al.*, are likely due to the very small Au particles obtained at the lower loadings.
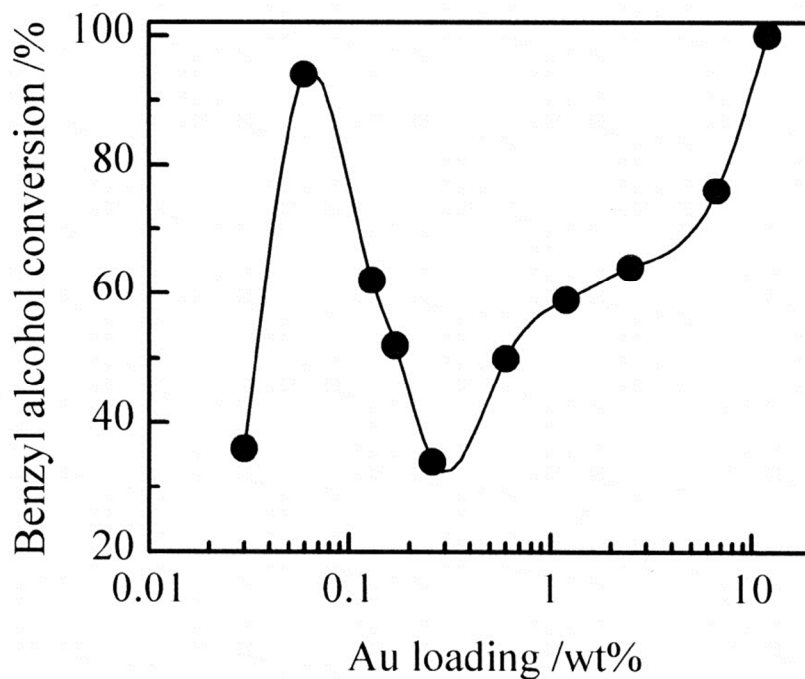
Figure 3. Dependence of benzyl alcohol conversion on Au loadings for Au/HT catalysts prepared by the DP method. Reaction conditions: catalyst, 0.20 g; T = 120 ^{o}C; benzyl alcohol, 1.0 mmol; p-xylene, 5.0 cm^3; Ar, 3 cm^3 min^{-1}; time, 6 h. Reproduced from Ref. [57] with permission from The Royal Society of Chemistry.
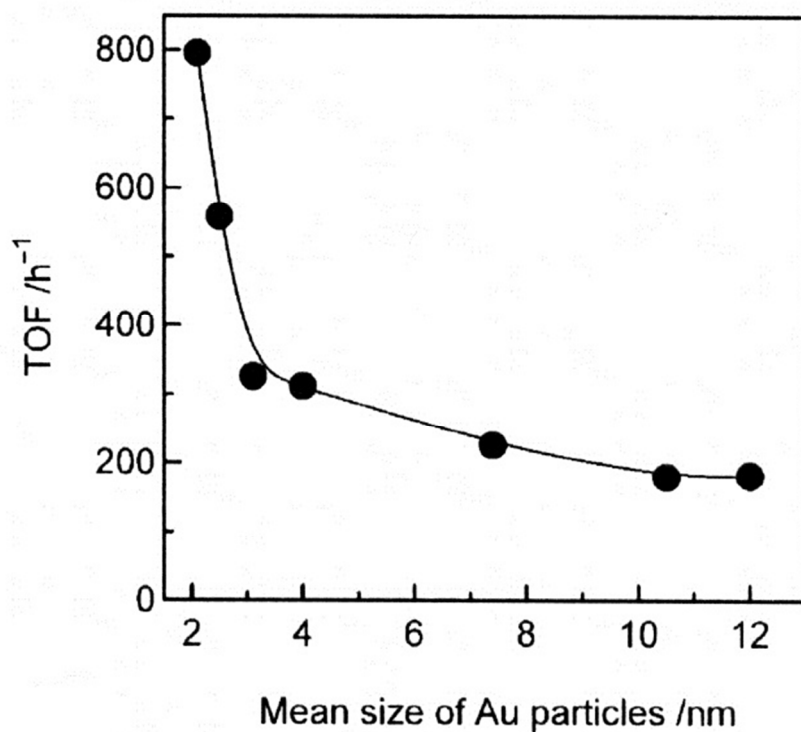
Figure 4. Dependence of TOF on the mean Au particle size for the Au/HT-catalyzed oxidant-free dehydrogenation of benzyl alcohol. Reaction conditions: catalyst 0.10-0.20 g; benzyl alcohol 1-2 mmol; solvent (*p*-xylene) 5 mL; Ar flow rate 3 mL min^{-1}; *T*=393 K. Reproduced with permission from Ref. [58].

Given the inherent dependence of catalyst activity on particle size, Li *et al.*[65] investigated the use of glutathione capped gold colloids for the preparation of Au/HT (Au-NC/HT). The use of the glutathione capping agent allows for the synthesis of ultra-small nanoparticles with a mean diameter of 1.5 +/- 0.6 nm. High TOF values were obtained for the aerobic oxidation of 1-phenyl ethanol using the Au-NC/HT catalyst (Table 5). Indeed, at low conversion (7.6% conversion with 99% selectivity to acetophenone) under solvent-free conditions, TOFs were as high as 38,000 h^{-1}, indicative of the high intrinsic activity of the catalyst. Even at high conversion (74.8% conversion with 99% selectivity to acetophenone) in toluene, a TOF of *ca.* 5,000 h^{-1} was obtained.

Mi *et al.*[66] described the synthesis and catalytic properties of Au/HT coated on the surface of superparamagnetic magnetite (Fe_3O_4) particles. This approach renders recovery of the core-shell type catalyst easy from the reaction mixture using an external magnet. When applied to the oxidation of 1-phenyl ethanol in air at 80°C for 3 h (using toluene as solvent), a TOF of 66 h^{-1} was obtained, similar to the value reported by Mitsudome *et al.*[52] for Au/HT (74 h^{-1}) in toluene at 40°C. However unlike the latter catalyst, which had a mean Au particle size of 2.7 nm, the mean Au particle size in the catalyst prepared by Mi *et al.* was 7 nm. The authors suggest that this catalyst is very active considering the particle size, and could be optimized to give higher TOF with smaller Au particles. The authors also reported the synthesis of transition metal HTs (Ni-Al-HT and Cu-Ni-Al-HT) coated on Fe_3O_4 particles. Given the work by others discussed below, this may make for an interesting area of study for novel magnetite core-shell catalysts. Interestingly, the particles seem to have vertically oriented Mg-Al-HT platelets. This finding may mean increased activity for core-shell catalysts of the non-gold type as the pronounced (110) plane is typically thought to be the active site for catalysis by transition metal hydrotalcites (*vide supra*).

Table 5. Comparison of Au/Mg-Al-HTs in the oxidation of 1-phenyl ethanol and benzyl alcohol

Catalyst	Substrate	Au loading (wt%)	Au NP mean size (nm)	Solvent	Oxidant	Temperature (°C)	Time (h)	Conversion (%)	Selectivity (%)[a]	TOF (h⁻¹)	Reference
Au/HT[b]	1-PE	0.89	2.7	None	Air	---	24	94[c]	99	8,300	52
Au/HT[d]	1-PE	1.8	1-5	None	O_2	160	0.5	--	--	21,040	56
Au-NC/HT	1-PE	0.23	1.5 +/- 0.6	None	O_2	160	0.5	7.6	99	38,000	65
Au-NC/HT	1-PE	0.23	1.5 +/- 0.6	Toluene	O_2	80	1	74.8	99	4,987	65
Au/HT-Fe$_3$O$_4$	1-PE	0.5	7	Toluene	Air	80	3	99[d]	--	66	66
Au/HT	BA	0.59	3.1	Toluene	O_2	100	0.5	29[d]	--	390	67
Au/HT	BA	0.4	2.1	*p*-xylene	None	120	6	>99	>99	--	58

(a) Selectivity to the corresponding ketone or aldehyde. (b) Reaction temperature not reported. (c) Calculated from the reported yield and selectivity. (d) % Yield (conversion not reported).

6.4 Support effects

In light of the success of Au/HT in a variety of oxidation reactions, many authors have explored the properties of the support as a tunable feature for improved catalyst activity. Indeed, as discussed above, many transition metal containing HTs have been found to be active in the absence of Au[18-24, 26]; thus, the addition of gold may impart higher activity. This was first explored by Liu *et al.*[67] who synthesized a series of HTs *via* transition metal doping of Mg-Al-HTs. Their results, shown in the table below (Table 6), suggest that the addition of transition metals resulted in higher catalyst activity for the oxidation of benzyl alcohol to benzaldehyde. In all cases catalyst activity and product yield were higher than for non-HT catalysts, namely, Au/TiO$_2$, Au/CeO$_2$, Au/Ga$_3$Al$_3$O$_4$ and Au/Cr$_2$O$_3$. The highest activity was seen in the case of Cr, corresponding to a TOF of 930 h^{-1}. Co-precipitation was also used to prepare a Au/Mg-Cr-HT catalyst, this method affording a highly active catalyst (TOF of 1880 h^{-1}) despite its low Au loading and surface area. Using TPSR of adsorbed *iso*-propanol, the authors found that Au/Mg-Cr-HT exhibited the highest dehydrogenation activity. This suggests that Mg-Cr-HT functions as a solid base for the cleavage of O-H bonds, while Cr may also serve to facilitate C-H bond cleavage, thereby hastening the rate-determining step.

Table 6. Oxidation of benzyl alcohol to benzaldehyde using Au supported on transition containing HTs. Adapted from Ref. [67] with permission from The Royal Society of Chemistry

Catalyst	S_{BET}/m^{2}g^{-1}	d_{Au}/nm	Au loading (wt.%)	Basicity[a] (pH)	Yield[b] (%)	TOF/h^{-1}
Au/HT	27	3.1	0.59	8.0	29	390
Au/Cr-HT	79	3.9	0.49	8.3	58	930
Au/Mn-HT	90	2.8	0.75	8.4	47	490
Au/Fe-HT	48	3.0	0.70	8.3	55	610
Au/Co-HT	83	3.8	0.75	8.1	50	520
Au/Ni-HT	82	3.2	0.64	8.2	51	630
Au/Cu-HT	74	2.7	0.91	7.5	45	400
Au/Zn-HT	77	3.3	0.85	7.8	46	430
Au/TiO$_2$	50	2.2	0.98	5.8	8(20)[c]	60(160)[c]
Au/CeO$_2$	73	3.5	1.49	6.6	10	50
Au/Ga$_3$Al$_3$O$_9$	225	3.3	0.94	6.5	26	220
Au/Cr$_2$O$_3$	3	4.3	0.90	6.9	6(27)[c]	50(230)[c]
Au/Mg-Cr-HT	42	2.8	0.32	8.7	76	1880
a. Suspension of 10 mg catalyst sample in 3 mL distilled H$_2$O.						
b. Yield of benzaldehyde determined by GC-FID. Reaction conditions: 50 mg catalyst, 1 mmol BA, 0.5 mmol *n*-dodecane, 10 mL toluene, 373 K, 20 mL min^{-1} O$_2$, t = 0.5 h.						
c. Data in parentheses were obtained by adding 1 mmol K$_2$CO$_3$.						

Other groups have looked into the use of Ni containing HTs as a support for Au.[60, 65] Wang et al.[27] described the use of Au/Ni-Al-HT, finding that the optimal Ni/Al ratio was 2:1 (Au/Ni-Al-HT-2, see Table 7). They attributed the increased activity of Au/Ni-Al-HT-2 (compared to other Ni-Al-HTs) to the synergistic effect of the Au NPs and the support provided by the uniform charge density of the Ni-Al-HT-2 layers. Using the Au/Ni-Al-HT-2, a high TOF of 1101 h^{-1} was obtained in the aerobic oxidation of 1-phenyl ethanol in toluene. Notably, this catalyst displayed better activity than Au/Al$_2$O$_3$ in the same reaction, with or without the addition of base. Similarly, Zhao et al.[68] used Au loaded into a Ni-Al-oxide support (Au/NiAlO) derived from Ni-Al-HT. The Au/NiAlO catalyst showed an initial TOF of 830 h^{-1} for the oxidation of benzyl alcohol, the optimal Ni/Al ratio being 2.5:1. When a 2:1 Ni/Al ratio was used, the TOF dropped to 560 h^1. XPS data suggest the enhanced activity of Au/NiAlO-2.5 over Au/Al$_2$O$_3$ and Au/NiO is due to the lower Au $f_{7/2}$ binding energy (83.3, 83.4, and 83.7 eV, respectively, vs. 84 eV for bulk gold), consistent with electron donation from the support and the creation of negatively charged Au NPs which facilitate O$_2$ activation.

Table 7. Aerobic oxidation of 1-phenyl ethanol using Au/HT. Adapted with permission from Ref. [27].

Entry	Catalyst	Conv.[a] [%]	Sel.[a] [%]	TOF[b] [h^{-1}]
1	Au/Ni–Al-1	83	>99	80
2	Au/Ni–Al-2	>99	>99	96
3	Au/Ni–Al-3	91	>99	91
4	Au/Ni–Al-4	76	>99	76
5[c]	Au/Ni–Al-2	95	>99	1101
6[d]	Au/Ni–Al-2	<1	>99	---
7	Au/Mg–Al-2	22	>99	22
8[e]	Au/Mg–Al-2	62	>99	59
9[f]	Au/Ni–Al-2	97	99	93

Reaction conditions: 1-phenyl ethanol (1 mmol), toluene as a solvent (20 mL), catalyst (50 mg, Au 1 wt.%), mole ratio of alcohol/Au = 400, O$_2$ bubbled at 15 mL min^{-1}, T = 80°C, reaction time 4 h.
[a] Determined by GC and GC-MS.
[b] TOF values were calculated with respect to the total loading of Au after 4 h reaction.
[c] T = 100°C, reaction time 20 min.
[d] Absence of O$_2$, N$_2$ bubbled 5 min, then sealed.
[e] Ni-Al-2 (50 mg).
[f] 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO, 2 equiv. with respect to Au) was added.

Miao et al.[60] supported gold on a Ni-Al-HT/graphene composite (denoted as Au/Ni-Al-HT-RGO), finding that the HT composite enhanced catalyst activity. In the solvent-free oxidation of benzyl alcohol the TOF (calculated by dividing the provided

TON by the reaction time) was increased from 1202 h^{-1} for Au/Ni-Al-HT to 1789 h^{-1} for Au/Ni-Al-HT-RGO. The reduced graphene oxide (RGO) in the catalyst was suggested to be responsible for enhancing the dispersion of the Au NPs as a result of their interaction with RGO's defect and oxygenic functional sites, while the Ni-Al-HT prevented RGO agglomeration as well as providing base sites for alcohol activation.

Li *et al.*[65] also studied the use of transition metal HTs as supports for Au nanoclusters (Au-NC), finding that gold supported on Ni-Al-HT and Co-Al-HT showed higher activity in the aerobic oxidation of 1-PE than Au/Mg-Al-HT (Table 8). Indeed, when the Au-NC/Ni-Al-HT and Au-NC/Co-Al-HT catalysts were used under solvent-free conditions, TOFs were among the highest reported in the literature. TPSR of *iso-*propanol adsorbed on the catalysts showed enhanced dehydrogenation activity for the Au/Ni and Au/Co containing HT. Additionally, Au/Mg-HT prepared by deposition of glutathione-capped Au NPs showed enhanced activity over the analogous catalyst prepared by DP (deposition-precipitation). Unlike Liu *et al.*[67], who saw no correlation between activity and electronegativity, Li *et al.* found that activity trended with electronegativity, meaning Au/HT with more electronegative metals in the support showed higher activity (Ni>Co>Mg). The different results in the two studies may be explained by differences in the synthetic techniques applied, the catalysts employed by Liu *et al.* being synthesized by means of "memory impregnation", while those studied by Li *et al.* were synthesized by co-precipitation. According to XPS and CO adsorption/FTIR studies, Au-NCs were more negatively charged in the Ni and Co containing catalysts than in the parent Au/HT.[65] These negatively charged Au clusters are suggested to aid in the activation of O$_2$ by generation of a superoxo-like species through electron transfer from the negatively charged Au core to the LUMO of the O$_2$ (π*).

Table 8. Aerobic oxidation of 1-PE using Au-NC catalysts. Adapted with permission from Ref. [65] from The Royal Society of Chemistry.

Entry	Catalyst	Au loading^a [wt.%]	D$_{Au}$^{b}/nm	Conv.[%]	Sel. [%]^c	TOF^d/h^{-1}
1	Au-NC/Mg$_3$Al-HT	0.83	2.5 $\pm$ 0.7	48.2	99	3213
2	Au-NC/Mg$_3$Al-HT	0.59	2.0 $\pm$ 0.7	60.6	99	4040
3	Au-NC/Mg$_3$Al-HT	0.23	1.5 $\pm$ 0.6	74.8	99	4987
4	Au-NC/Mg$_3$Al-HT	0.11	1.5 $\pm$ 0.6	73.4	99	4893
5	Au-NC/Ni$_3$Al-HT	0.22	1.5 $\pm$ 0.5	85.3	99	5687
6	Au-NC/Co$_3$Al-HT	0.20	1.5 $\pm$ 0.6	78.0	99	5200
7	Au/Mg$_3$Al-HT(DP)	0.26	5.0 $\pm$ 2.5	36.6	99	2040
8	Au-NC/Mg$_3$Al-HT^e	0.23	1.5 $\pm$ 0.6	7.6	99	38000
9	Au-NC/Ni$_3$Al-HT^e	0.22	1.5 $\pm$ 0.5	9.3	99	46500
10	Au-NC/Co$_3$Al-HT^e	0.20	1.5 $\pm$ 0.6	8.4	99	42000
Reaction Conditions: 1-Phenyl ethanol (10 mmol), catalyst (Au: 0.015 mol%), toluene (10 mL), O$_2$ bubbling (20 mL min^{-1}), 80°C, 1 h. a. Measured by ICP.						

b. Obtained from High Resolution Transition Electron Microscopy (HRTEM).
c. Selectivity to acetophenone.
d. Moles of alcohol converted per mole of Au per hour.
e. 1-Phenyl ethanol (100 mmol), catalyst (Au: 4.0 x 1.0^{-4} mol%), O_2 (20 mL min^{-1}), 160°C, 30 min

6.5 Novel alloys

While supported Au NP/NCs are highly active for alcohol oxidations, many researchers have looked to enhance the activity of these catalysts by alloying Au with Pd.[62, 69, 70] Inspired by the findings of Prati[71] and Hutchings[72] in the selective oxidation of D-sorbitol and alcohols, respectively, Shi *et al.*[69] performed aerobic alcohol oxidations over HT supported bimetallic catalysts in water. Catalysts with varying amounts of Au and Pd were prepared, in addition to monometallic Au/HT and Pd/HT catalysts, HT loaded with 1 wt.% Au and 1 wt.% Pd having the highest activity. Both Au/HT and Pd/HT showed comparatively low activity in the oxidation of 1-phenyl ethanol, affording the ketone in 10.5% and 18% yield, respectively, after 10 minutes, while a physical mixture of the two gave a 14% yield (i.e., the average of the yields obtained with the monometallic catalysts). However, Au$_1$Pd$_1$/HT produced the ketone in 35% yield under the same conditions with a TOF of 140.7 h^{-1}, suggestive of a strong electronic interaction between the two metals. Notably, the support alone exhibited no conversion in 1-phenyl ethanol oxidation. XPS analysis of the catalysts revealed a partial positive charge on the Pd, while the Au was partially negative. XRD data suggested that alloying between the Pd and Au did not occur, the Au diffraction lines in Au-Pd/HT being similar to those in Au/HT.

In another study concerning supported Au-Pd nanoclusters, Nishimura *et al.*[62] correlated the activity of poly(N-vinyl-2-pyrrolidone) capped Au-Pd nanoparticles supported on HT (Au-Pd-PVP/HT) catalysts to the negative charge density on Au. In the aerobic oxidation of 1-phenyl ethanol, the Au-Pd catalysts displayed higher activity compared with their monometallic counterparts. The importance of negative charge accumulation on Au was also highlighted by Tsunoyama *et al.*, who noted that PVP aids in charge transfer to the gold core in PVP stabilized Au-NPs, resulting in negatively charged and catalytically active Au clusters for aerobic oxidation.[73] In the case of Au-Pd-NPs, XPS measurements showed that with increasing Pd content, the Au 4f binding energy decreased (relative to pure gold foil, 4$f_{5/2}$ and 4$f_{7/2}$ binding energies were 88 and 84 eV, respectively) indicative of charge transfer from the Pd to the Au[62], as also noted by Shi *et al.*[69] However, unlike the latter report, Nishimura *et al.*[62] were able to confirm the presence of a Au-Pd alloy using Au L_3 XANES, STEM-HDAAF, and UV/Vis spectroscopy. From Au L_3-edge XANES spectra, the authors measured the white-line (WL) feature related to the 2p electronic transition to the unoccupied 5d states. Gold has no holes in the 5d state ([Xe]6$s^1$4f^{14}5d^{10}), however, due to s-p-d hybridization bulk gold displays a white line feature at 11.295 keV due to 5d to s-p states. Notably, Au$_x$Pd$_y$-PVP/HT samples had lower white line features at 11.295 KeV, indicative of higher 5d

electron density. The area of the WL feature was plotted as a function of acetophenone yield, from which it emerged that 5d electron density strongly correlated to catalyst activity. Thus $Au_{0.6}Pd_{0.4}$-PVP/HT had the highest 5d electron density and the best conversion.

Assuming Michaelis-Menten kinetics, K_m and K_2 values were calculated to be much higher for the $Au_{0.6}Pd_{0.4}$-PVP/HT nanocluster catalyst than for Au/HT, suggesting that the rate-limiting step of β-hydride elimination is facilitated by the Au-Pd catalyst. It is also worth noting that Au-Pd-PVP/HT gave the highest reported TOF of the catalysts included in this review for the solvent-free oxidation of 1-PE at 423 K, corresponding to a value of 69,100 h^{-1} (119,260 h^{-1} when calculated on the basis of Au).

6.6 Solvent effects and scope of substrates

While Au/HTs exhibit high activity and selectivity for the oxidation of a variety of alcohols, their catalytic properties are to some degree dependent on the solvent employed. Indeed, while solvents mainly affect the kinetics of the reaction, non-polar (and therefore non-coordinating) solvents tending to give faster rates[52], in the case of water product selectivity is also affected. The effect of water is most pronounced in the oxidation of primary alcohols, which tend to undergo further oxidation to carboxylic acids in aqueous solution.[56, 69] This was also seen in the case of benzyl alcohols aerobically oxidized in water over polymer stabilized Au nanoclusters.[74] When water was used as the solvent for the oxidation of benzyl alcohol and 1-phenyl ethanol, BA afforded a higher conversion but was less selective to the desired ketone. The authors attributed the better activity of BA to a higher degree of solvation of BA than 1-PE in water.[56] Indeed, the poor solubility of some alcohols in water can be problematic, although alcohol solubility can be increased in oxidation reactions *via* the addition of surfactants.[75]

In terms of the scope of substrates, it appears that Au/HT has very few limitations. In general, heteroatom-substituted alcohols give low reaction rates as do primary aliphatic alcohols, which in the former case is likely due to the multiple sites available for coordination to the catalyst. On the other hand, benzyl alcohol generally exhibits good reactivity over Au/HT, with excellent selectivity to benzylaldehyde. This is particularly notable, given that the oxidation of benzyl alcohol is notoriously slow over unpromoted transition metal HTs. Alicyclic, aliphatic, and alkenic alcohols can be oxidized with varying degrees of success, although most catalysts are able to oxidize all three classes of alcohol to some extent. In the case of alkenic alcohols, while high reaction rates are obtained, selectivity to the desired oxidation product is only moderate, possibly due to transfer hydrogenation, resulting in the saturated ketone, hydrogenolysis and decarbonylation products.

7   Outlook

HT materials have proven to be useful catalysts for the oxidation of alcohols under mild conditions using either oxygen or TBHP as the terminal oxidant. Moreover,

dehydrogenative oxidation of alcohols under anaerobic conditions over HT supported Group IX metals has recently been demonstrated. The utility of these catalysts stems from their ease of preparation, low cost, and ability to be tuned *via* modification of the HT composition. Although significant progress has been made in the last two decades, improvements to these catalysts are still needed. While the oxidation of benzylic alcohols generally proceeds with good rates, selective oxidation of alicyclic and aliphatic alcohols can be problematic. In this respect, improvements in synthetic techniques leading to increased exposure of interlayer anions such as CO_3^{2-} or POMs may aid oxidation activity. Improvements in catalyst activity may also be realized by tuning the basicity of the catalyst through synthetic approaches. Indeed, increased basicity may be achieved in HT-derived mixed metal oxides through doping of the HTs with rare-earth metals[76], or the application of sonication during HT synthesis[10]. While gold is a highly active area of research, the use of other transition metal HTs may also prove beneficial, especially in the cases of Cu and Ag, which have received little attention to date. Finally, it should be noted that gold based catalysts appear to be of particular interest not only due to their high activity and selectivity, but also their tolerance to a wide range of solvents, including water. This renders them particularly well suited for the oxidation of polar molecules, such as those derived from biomass.

8   Acknowledgements

9   References

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