Selective Oxidation of Alcohols to Carbonyl Compounds and Carboxylic Acids with Platinum Group Metal Catalysts

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Abstract: The use of platinum group metal (PGM) catalysts for the selective oxidation of various primary and secondary alcohols under mild conditions is described. High throughput screening (HTS) techniques have been used to identify trends in catalyst activity and product selectivity. Using air as oxidant and water as solvent 5% Pt, 1% Bi/C has been identified as an efficient catalyst for the transformation of 2-octanol to 2-octanone and 1-octanol to octanoic acid. To improve aldehyde selectivity the promotion of Pt/Al_2O_3 and Ru/C catalysts has been investigated. The use of H_2O_2 as oxidant has been demonstrated as a suitable alternative to air.

Keywords: air; alcohol; carbonyl; hydrogen peroxide; platinum group metals; selective oxidation

Introduction

The oxidation of alcohols to carbonyl functionalities is an important reaction in the fine chemicals industry. Traditional methods employed stoichiometric quantities of either inorganic oxidants (such as chromate)[1,2] or organic oxidants (such as activated DMSO).[3] The use of such reagents leads to environmental and economic problems associated with recycling or disposal of the reduction by-products.[4–7] The desire for developing cleaner processes has led to research in catalytic selective alcohol oxidation using molecular oxygen or hydrogen peroxide.[8,9] The advantage of using such oxidants lies in their low cost and the formation of water as the sole by-product.

Both homogeneous as well as heterogeneous catalysts for alcohol oxidation with dioxygen or hydrogen peroxide in the liquid phase are known. Particularly efficient homogeneous catalyst systems that also enable the oxidation of non-activated alcohols with dioxygen are those based on palladium,[9–15] ruthenium,[16,17] copper[18] and those based on TEMPO in the presence of a co-catalyst.[19–25] With respect to alcohol oxidation with aqueous hydrogen peroxide, notably homogeneous catalysts based on tungsten are efficient.[26–29]

The study of heterogeneous catalysts for the selective oxidation of alcohols has been established for a number of years.[30,31] Much of the research has investigated the use of Pt or Pd/C catalysts for the oxidation of water-soluble carbohydrates with molecular oxygen.[32,33] The reaction is termed oxidative dehydrogenation where the adsorbed alcohol will dehydrogenate on the metal surface to give the respective carbonyl whilst the abstracted hydrogen reacts with oxygen to produce water as the benign by-product.[34] The breakthrough in this field of research came with the discovery that the incorporation of a secondary metal component, mainly Pb and Bi, would prolong catalyst lifetime.[34] Aside from carbohydrates Mallat et al. have used a Pt-Bi/Al_2O_3 catalyst for the selective oxidation of cinnamyl alcohol to cinnamaldehyde.[35] Under basic conditions and a water/surfactant system they were able to obtain high yields of the aldehyde product by controlling the flow rate of air into the reactor. A very recent second breakthrough was found by Kaneda et al., who achieved very high turnover numbers without a secondary metal by immobilising Pd on a hydroxyapatite.[36] This system is also active for the oxidation of usually poorly reactive *aliphatic* alcohols, of which fewer examples exist in heterogeneous catalysis. Heterogeneous catalysts offer obvious advantages with respect to catalyst recycling, although very recently a number of water-soluble homogeneous catalyst systems have been developed that allow facile catalyst recycling *via* simple separation of the catalyst containing aqueous phase from the organic phase.[9,37] Besides the aforementioned Pt or Pd catalysts, aerobic oxidation of various alcohols, including aliphatic alcohols, with heterogeneous Ru catalysts[38,39,40] or an Mn[41] based molecular sieve has recently been described. Hydrogen peroxide has been used as the oxidant in the presence of TS-1 as a heterogeneous catalyst for oxidation of secondary aliphatic alcohols.[42,43] The latter two catalysts can only be applied to alcohols that are small enough to enter the microporous channels of the molecular sieve catalyst. This problem is not encountered with *supported* hetero-

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geneous catalysts, where the active sites on the outside surface are more readily accessible. In addition, the properties of the supported catalysts can be varied broadly through the choice of the metal and support. We therefore studied the supported platinum group metal (PGM)-catalysed oxidation of both activated and unactivated alcohols, including primary aliphatic alcohols, which provide oxidation products, (aldehydes as well as carboxylic acids), that are of importance in the fragrance and pharmaceutical industries.

Previously we have demonstrated the effectiveness of supported heterogeneous PGM catalysts for the selective oxidation of primary and secondary alcohols under mild conditions (<70 °C and <5 bar) using air as oxidant.[44] The paper concluded that toluene and xylene are the most effective solvents and that Pt/C is the most active catalyst. The use of organic solvents demonstrates that the supported PGM-catalysed oxidation is not limited to water-soluble alcohols.[15] When an aliphatic primary alcohol is used Ru/C leads to high aldehyde selectivity and Pt/C yields measurable quantities of the carboxylic acid. A study of pentanol revealed that the ease of oxidation follows the trend 1-pentanol > 2-pentanol > 3-pentanol. The study also showed that the oxidation of geraniol to citral could achieve 100% yield under high throughput screening (HTS) conditions. The effect of base in the reaction was also studied where it was shown to have a beneficial effect on conversion. The base can also be added as a secondary component but is preferentially a property of the catalyst. In addition it was demonstrated that water plays an influential role in the reaction and a mechanism was proposed.

In this paper we report a more detailed study of the use and efficiency of various mono- and bimetallic Pt and Ru catalysts for the oxidation of 1-octanol, 2-octanol, geraniol and 2-*n*-butyl-4-chloro-5-hydroxymethylimidazole (HMI). These alcohols, shown in Figure 1, have been chosen since their oxidation products are important materials in the fragrance and pharmaceutical industries. The formyl oxidation product of 2-*n*-butyl-4-chloro-5-hydroxymethylimidazole (HMI) is an intermediate in the production of angiotensin II inhibitors. In addition we report on the comparison of air (dioxygen) and H_2O_2 as the oxidant with Pt/Bi/C catalysts. An example of the use of H_2O_2 as oxidant in combination with a PGM catalyst is described in a patent by Lonza.[45]

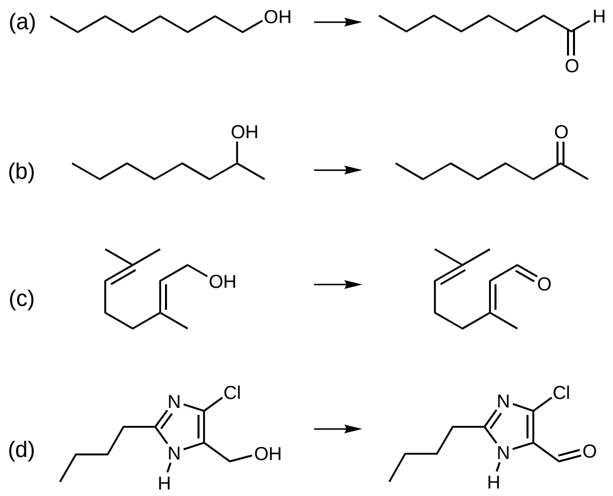

Figure 1. Selective oxidation of (a) 1-octanol, (b) 2-octanol, (c) geraniol, (d) 2-*n*-butyl-4-chloro-5-hydroxymethylimidazole to the respective carbonyl compound.

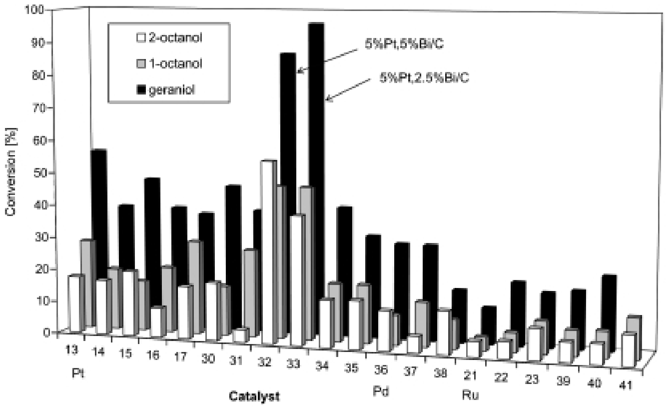

Figure 2. Results of catalyst screening in the selective oxidation of 1-octanol, 2-octanol and geraniol. Conditions: 1 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 3 bar air, 200 rpm, 6 h.

Results and Discussion

Catalyst High Throughput Screening (HTS) Studies

The catalysts used in the HTS tests, (1 mmol reactant), are shown in Table 1. The array consists mainly of Pt and Ru mono- and bimetallics supported on carbon or alumina. The results of the HTS for the selective oxidation of 1-octanol, 2-octanol and geraniol are compared in Figure 2. Each screen used 1 mmol reactant in toluene and a reactant:metal molar ratio of 80:1.

Figure 2 shows that Pt-based catalysts provide the highest activity and Bi-promoted Pt/C (catalysts 32 and 33) give the highest conversion in all three tests. The conversion of 2-octanol is selective to 2-octanone with >95% mass balance. For the selective oxidation of geraniol a potential product is geranic acid, yet the reaction is selective to *cis*-citral even at 95% conversion (catalyst 33). Further, a 5% Pt, 1% Bi/C catalyst was found to display similar activity to catalysts 32 and 33 in these reactions; this catalyst was used in subsequent studies.

A stirred autoclave reactor was used in larger scale testing, (15 mmol reactant), using 5% Pt, 1% Bi/C catalyst. In order to provide an accurate comparison

Table 1. Array of catalysts used in high throughput screening studies.

No.	Catalyst	pH	No.	Catalyst	pH
13	5% Pt/C	Basic	35	4.7% Pt,0.3% Au/C	Basic
14	5% Pt/C	Neutral	36	4% Pd/Al_2O_3 - 2	Basic
15	5% Pt/C	Acidic	37	4% Pd,1% Pt/C	Basic
16	5% Pt/Graphite	Basic	38	4% Pd, 1% Au/C	Neutral
17	5% Pt/Al_2O_3-1	Basic	21	5% Ru/C	Basic
30	5% Pt/C	Neutral[a]	22	5% Ru/C	Neutral
31	5% Pt/Al_2O_3-2	Basic	23	5% Ru/Al_2O_3-1	Basic
32	5% Pt, 5% Bi/C	Basic	39	5% Ru/C	Basic
33	5% Pt, 2.5% Bi/C	Basic	40	5% Ru/C	V. Basic
34	4% Pt, 1% Au/C	Basic	41	4% Ru, 1% Pt/C	V. Basic

[a] Hydrophobic support

Table 2. Comparison of results for the scaled-up testing performed in a stirred autoclave reactor. Conditions: 15 mmol reactant in toluene, reactant:metal molar ratio 80:1, 5% Pt, 1% Bi/C, 60 °C, 3 bar air, 1200 rpm. Figures in parenthesis are carboxylic acid selectivity (%).

Reactant	Reaction Time [h]	Conversion [%]
1-Octanol	0.5	89 (15)
1-Octanol	3.5	100 (65)
2-Octanol	6.0	95 (0)
Geraniol	6.0	100 (trace)
HMI[a]	6.0	88 (0)

[a] Methanol as solvent.

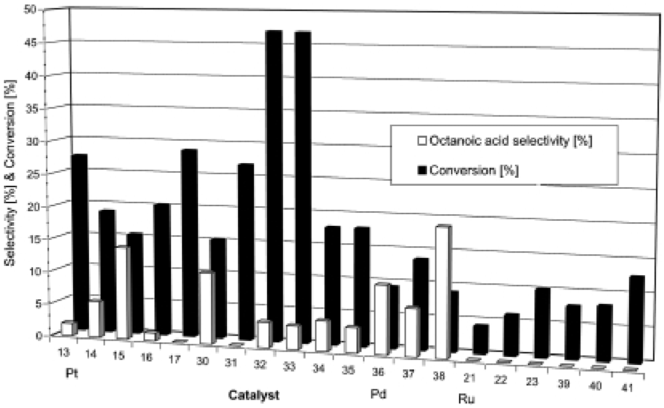

Figure 3. Comparison of the 1-octanol conversion and octanoic acid selectivity. Conditions: 1 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 3 bar air, 200 rpm, 6 h.

with the HTS studies the reactant:metal molar ratio was maintained at 80:1. The results shown in Table 2 indicate that high conversion is achievable for all reactants. The rate of reaction of 1-octanol is fast (89% conversion, 0.5 h), which leads to a problem in the control of selectivity. After 3.5 h octanoic acid is the major product, thus the challenge in aliphatic primary alcohol oxidation is to control this over-oxidation. In the case of geraniol the selective oxidation also takes place with high conversion and again the reaction is selective to the aldehyde (*cis*-citral). For 2-octanol the conversion is 95% after 6 h and the sole reaction product is 2-octanone. After the same period of reaction, 88% conversion was achieved for the selective oxidation of 2-*n*-butyl-4-chloro-5-hydroxymethylimidazole (HMI) to the corresponding formyl compound. The reaction is selective to the aldehyde derivative and no evidence of the carboxylic acid was observed. The 2-octanol experiment was repeated using a reactant:metal molar ratio of 700:1 and a system consisting of 50% 2-octanol/50% water and 0.5 molar equivalent NaOH. The first test achieved 93% conversion, which after two recycles showed no loss in activity. This result demonstrates that the selective oxidation reaction is achievable in high yields under mild conditions with a catalyst loading that is even lower than the Pd loading used by Kaneda for oxidations in organic solvents[36] or that by Sheldon[9,14,15] for oxidations in water.

For the selective oxidation of 1-octanol the selectivity towards octanal and octanoic acid is dependent on the catalyst used. The respective conversion and octanoic acid selectivity are shown in Figure 3.

Figure 3 indicates that the highest octanoic acid selectivity arises from either non-basic or Pd-based catalysts. Consequently the highest octanoic acid selectivity is provided by catalyst 38 which is *both* Pd and non-basic. The same figure also reveals that catalysts 17 and 31 (Pt/Al_2O_3) and catalysts 21–23, 39–41 (Ru-based) have 100% selectivity to the aldehyde. These observations provided the basis for further investigation into aldehyde-selectivity.

Oxidation of Alcohols to Aldehydes

A: Pt as Catalyst

In cases where the aldehyde oxidation product is desired, optimisation of the catalyst and reaction conditions so as to facilitate this reaction without subsequent formation of the carboxylic acid is required. This was investigated using two different Pt/Al_2O_3 catalysts in the selective oxidation of 1-octanol. These catalysts were prepared by the same method using two different alumina support materials, (Al_2O_3-1 surface area 180 m^2/g, pore volume 1.7 cm^3/g, Al_2O_3-2 surface area 140 m^2/g, pore volume 0.9 cm^3/g). It has been shown that greater conversion is obtained at high pH, therefore the reaction was compared under neutral and basic conditions by addition of aqueous NaOH and aniline (Table 3).

The results from Table 3 show that similar results were obtained with both Pt/Al_2O_3 catalysts and that addition of aqueous NaOH inhibits the activity of Pt/Al_2O_3 but not Pt/C. This effect can be attributed to the presence of water which will strongly adsorb onto the hydrophilic Al_2O_3 surface. When placed into the organic reaction mixture the catalyst draws into a tight sphere and the outer hydrophilic layer may act as a diffusion barrier to the reactant. The same effect was observed whether Pt/Al_2O_3 was dried or not, prior to use. The addition of aniline also has a detrimental effect on catalyst activity by reducing the conversion from ~30% to ~5%. It is known from catalytic hydrogenation studies that amine groups can strongly bind onto the surface of the PGM thereby poisoning the catalyst.[46]

In an attempt to improve the activity of the Pt/Al_2O_3 catalysts, as observed in the case of Pt/C, Bi-promoted materials were prepared. Table 4 compares the performance of both the Pt- and $Pt\text{-}Bi/Al_2O_3$ catalysts for the selective oxidation of 1-octanol in the absence of NaOH.

Table 3. Selective oxidation of 1-octanol using Pt/Al_2O_3 and Pt/C under neutral and basic conditions. Conditions: 1 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 3 bar air, 200 rpm, 6 h. Figures in parenthesis are octanoic acid selectivity (%).

Catalyst	Catalyst number	Conversion [%]		
		No added base	0.5 equiv. NaOH[a]	0.5 equiv Aniline
Pt/Al_2O_3-1	17	29 (0)	2	2 (66)
Pt/Al_2O_3-2	31	27 (0)	1	5 (55)
Pt/C	13	27 (2)	42 (59)	1 (32)

[a] Added as a 1M NaOH solution.

The results from Table 4 show that activity of Pt/Al_2O_3 can be significantly enhanced by the addition of Bi. The activity can be further improved by subjecting the $Pt\text{-}Bi/Al_2O_3$ catalyst to treatment under H_2. A direct comparison of Pt-Bi/C and H_2-treated $Pt\text{-}Bi/Al_2O_3$ reveals that the latter is more selective to the aldehyde.

In the presence of solid NaOH in the reaction mixture containing 1-octanol, only octanoic acid and its corresponding ester, identified as octyl octanoate by GC-MS, were observed as reaction products. Based on the HTS results, Pt-Bi catalysts supported on Al_2O_3 appear to be more selective to the aldehyde than those supported on carbon, however, the addition of NaOH serves to promote formation of the carboxylic acid derivative.

B: Ru as Catalyst

The initial HTS studies for the selective oxidation of 1-octanol demonstrated that Pt/C is more active than Ru/C but the latter is more selective to the aldehyde product. To investigate the effect of Pt promotion a range of Ru-Pt catalysts (5% total metal weight) were prepared. In a separate treatment a fraction of the mixed-metal catalyst was heated to 100 °C under H_2 for 2 h. The H_2 treatment is designed to enhance the Ru-Pt interaction thus allowing its effect on activity to be determined. In addition, to investigate the promotional effect of Bi a 5% Ru, 1% Bi/C catalyst was prepared. The catalysts were used in a HTS for the selective oxidation of 1-octanol and the results are shown in Table 5.

In the absence of NaOH the conversion and octanoic acid selectivity increase as the catalyst is enriched with Pt. Based on these observations there is little to suggest that a synergistic effect between Ru and Pt is occurring. Addition of 1% Bi to 5% Ru/C increases the conversion from 7% to 18% without altering the aldehyde selectivity. The selectivity at high conversion is not known but these results suggest that Bi addition is a more effective route to promoting Ru catalysts. The H_2 treatment has minimal impact on the activity of Ru-rich catalysts.

Table 4. Selective oxidation of 1-octanol using Pt/Al_2O_3 catalysts in the absence of NaOH. Conditions: 1 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 3 bar air, 200 rpm, 8 h. Figures in parenthesis are octanoic acid selectivity (%).

Catalyst	Catalyst number	Conversion [%]	Aldehyde selectivity [%]
5% Pt/Al_2O_3-1	17	34	94 (6)
5% Pt/Al_2O_3-2	31	21	100 (0)
5% Pt, 0.25% Bi/Al_2O_3-1	17 modified	53	86 (14)
5% Pt, 1% Bi/Al_2O_3-1	17 modified	53	88 (12)
5% Pt, 1% Bi/Al_2O_3-1	17 modified (H_2 treated)	66	87 (13)
5% Pt/C	13	29	86 (14)
5% Pt, 1% Bi/C	13 modified	60	81 (19)

Table 5. Selective oxidation of 1-octanol using catalysts of various Ru-Pt compositions. Tests performed under neutral conditions and with 0.5 equivalent of NaOH added. Conditions: 1 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 3 bar air, 200 rpm, 8 h. Figures in parenthesis are octanoic acid selectivity (%).

Catalyst	Conversion [%]		
	No NaOH	H_2 treated[a]	0.5 equiv. NaOH[b]
5% Ru/C	7 (0)	–	5 (65)
4% Ru, 1% Pt/C	13 (0)	11 (0)	14 (22)
2.5% Ru, 2.5% Pt/C	16 (0)	16 (0)	18 (25)
1% Ru, 4% Pt/C	27 (14)	28 (11)	68 (60)
5% Pt/C	40 (15)	–	84 (61)
2.5% Ru, 2.5% Pt/G	20 (12)	15 (0)	16 (47)
5% Ru, 1% Bi/C	18 (0)	13 (0)	22 (46)

[a] H_2 treatment 100 °C, 2h, no NaOH added.

[b] NaOH added as 1 M solution and neutralised with HCl after reaction.

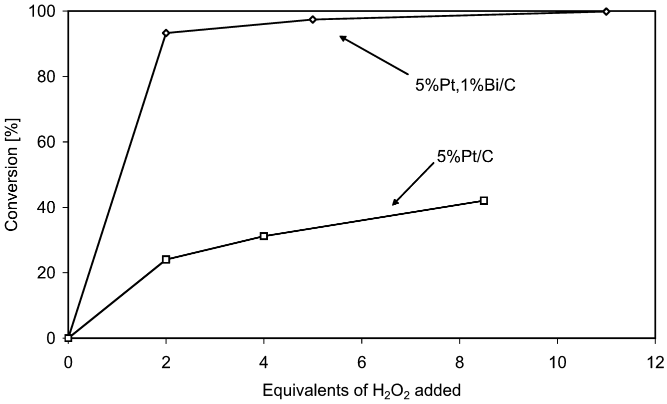

Figure 4. Comparison of 1-octanol conversion for 5% Pt/C and 5% Pt, 1% Bi/C using H_2O_2 as oxidant. Conditions: 15 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, atmospheric pressure, 1200 rpm, 1 equivalent/hour addition rate (30% H_2O_2).

Inspection of 1% Ru, 4% Pt/C reveals that the octanoic acid selectivity drops slightly after H_2 treatment. It is possible that this effect could be attributed to an alloying of Ru and Pt. Under basic conditions the HTS results indicate that Ru-rich catalysts are not promoted by the addition of NaOH. In all tests the presence of NaOH promotes the octanal to octanoic acid reaction.

H_2O_2 as Oxidant

Selective oxidation using H_2O_2 as oxidant is preferably performed in a reactor in which the peroxide can be fed continuously during reaction, since contact of H_2O_2 on the catalyst surface leads to rapid decomposition of the peroxide. Therefore, to utilise the oxidant efficiently, the rate of addition should be matched to its consumption in the reaction. To compare the oxidation of the various reactants the following standard conditions were employed: 30% H_2O_2 (1 molar equivalent h^{-1}), 60 °C, 1200 rpm, atmospheric pressure.

The first experiment compared the use of Pt/C and Pt-Bi/C for the selective oxidation of 1-octanol (Figure 4). After 2 equivalents of H_2O_2 had been added, the 5% Pt/C catalyst attained 24% conversion compared to 94% for 5% Pt, 1% Bi/C. The effect of bismuth is documented in the literature and a number of hypotheses to its role have been put forward. The possibility that Bi suppresses catalyst poisoning from by-product formation,[47] or that it protects the PGM from over-oxidation by acting as a co-catalyst,[48] would fit with the significant promotional effect observed for this study. Subsequent tests using H_2O_2 as oxidant have used 5% Pt, 1% Bi/C as catalyst. A comparison between air and H_2O_2 as oxidants is shown in Table 6. The results show that the selective oxidation of 1-octanol, 2-octanol and geraniol give $>90\%$ conversion with either oxidant. For HMI the conversion achieved with H_2O_2 is slightly lower than that observed with air. Use of H_2O_2 in the selective oxidation of 1-octanol leads to significant octanoic acid formation. The formation of water from the decomposition of H_2O_2 provides a driving force for the over-oxidation reaction.[44] The H_2O_2 addition rate must be tailored to the catalyst employed in order to maximise aldehyde yields; this will be investigated in subsequent studies.

Oxidation of Alcohols to Carboxylic Acids

Development of improved catalytic routes for the production of carboxylic acids *via* oxidation of aliphatic alcohols is increasingly important since these materials are also extensively used in the fine chemicals industry. Hence the conversion of 1-octanol to octanoic acid has also been investigated as part of this study.

The results from Table 2 indicate that when using a reactant:metal molar ratio of 80:1 the transformation of 1-octanol to octanoic acid may be fast. Lowering the amount of platinum metal to a ratio of 700:1 requires the reaction to be promoted. It has been proposed that the presence of water in the reaction media can have two effects.[44] First, the water can act as a weak base and assist in the abstraction of hydrogen from the alcohol. Secondly, water can react with the aldehyde to generate an aldehyde hydrate which rapidly reacts with oxygen to form the carboxylic acid. Based on these proposals the conversion of 1-octanol to octanoic acid was run in a 50% 1-octanol/50% water system for 24 h. The results (Table 7) indicate that high conversion and high selectivity to octanoic acid can be achieved at low catalyst loadings, although a small amount of ester by-product

Table 6. Comparison of air and H_2O_2 as oxidant in the selective oxidation of alcohols using 5% Pt, 1% Bi/C. Conditions: 15 mmol reactant in toluene, reactant:metal molar ratio 80:1, 60 °C, 1200 rpm.

Reactant	Oxidant			
	Air[a]		H_2O_2[b]	
	Conversion [%]	Acid Selectivity [%]	Conversion [%]	Acid Selectivity [%]
1-octanol[d]	89	15	76	11
1-octanol[e]	100	65	100	62
2-octanol	95	0	96	0
Geraniol	100	trace	100	1
HMI[c]	88	0	76	0

[a] 3 bar air, 6 h.

[b] 1 equivalent/hour addition rate (30% H_2O_2), atmospheric pressure.

[c] Methanol used as solvent.

[d] 0.5 h in air, 1 equiv. H_2O_2.

[e] 0.35 h in air, 9 equiv. H_2O_2.

Table 7. Selective oxidation of 1-octanol using 5% Pt, 1% Bi/C. Conditions: 15 mL 1-octanol/15 mL water, reactant:metal molar ratio 700:1, 60 °C, 1200 rpm, 3 bar air (20 mL/min), 24 h.

Reaction	Fresh Catalyst	Catalyst Recycle 1	Catalyst Recycle 2
Conversion [%]	96	92	81
Product Selectivity [%]			
Octanal	2	6	9
Octanoic acid	97	93	86
Octyl octanoate	1	1	5

was observed. Furthermore the catalyst can be recycled twice without significant loss of activity.

Conclusions

This work demonstrates that supported PGM catalysts are effective for the selective oxidation of 1-octanol, 2-octanol, geraniol and HMI using air as oxidant. The ratio of aldehyde to carboxylic acid obtained in the oxidation of 1-octanol depends on the nature of the catalyst and reaction conditions employed. Attempts at improving the activity of the aldehyde-selective Pt/Al_2O_3 and Ru/C catalysts have shown that bismuth is an effective promoter. For Ru/C the incorporation of Pt will increase conversion but at the expense of aldehyde selectivity. For $Pt\text{-}Bi/Al_2O_3$ H_2 treatment may play an important role and this merits further investigation. The use of H_2O_2 as oxidant demonstrated the need for incorporating Bi into the catalyst formulation as a means of improving activity and lifetime. Comparing the results of the selective oxidation of 1-octanol, 2-octanol and geraniol, H_2O_2 was revealed as a suitable alternative to air. The use of H_2O_2 requires further investigation to address the balance between the addition rate and rate of consumption in the reaction. Using a reactant:metal molar ratio of 700:1 the selective oxidation of 2-octanol to 2-octanone maintained >90% conversion after 2 recycles using water as solvent and NaOH as promoter. Likewise the conversion of 1-octanol to octanoic acid achieved high conversion with water as solvent. The catalyst could be recycled with minimal loss in activity and conversion.

Experimental Section

A range of supported platinum group metal (PGM) catalysts (Table 1) were used for the initial HTS studies. The catalysts are commercially available and were prepared by Johnson Matthey proprietary methods. Several of the catalysts were subjected to treatment under a H_2 atmosphere: $Pt\text{-}Bi/Al_2O_3$ 200 °C, 2 h and Ru-Pt/C 100 °C, 2 h.

Catalyst testing was performed in three different reactors:

(a) HTS studies using air as oxidant. A stainless steel multi-well reactor was employed, which agitates the sample by means of an orbital shaker and has the capability of testing up to 40 catalysts at a time. The conditions used were 60 °C, 200 rpm, 3 bar air, 1 mmol reactant in toluene (2 mL), reactant:metal molar ratio 80:1.

(b) Autoclave studies using air as oxidant. A glass-lined stirred autoclave reactor (working volume 50 mL) was used under the following conditions (unless otherwise stated): 60 °C, 1200 rpm, 3 bar air (5 mL/min flow), 15 mmol reactant in toluene (30 mL), reactant:metal molar ratio 80:1.

(c) Autoclave studies using H_2O_2 as oxidant. A stainless steel stirred autoclave reactor (working volume 50 mL) fitted with a feed line from an HPLC pump was used. 30% H_2O_2 was pumped from an ice-water/NaCl bath (<8 °C) directly into the reaction solution. The conditions (unless otherwise stated) were: 60 °C, 1200 rpm, atmospheric pressure, 15 mmol reactant in toluene (30 mL), reactant:metal molar ratio 80:1, 30% H_2O_2 added at a flow rate of 1 molar equivalent h^{-1} (0.028 mL/min).

Samples of the product mixture were taken from the reactor at room temperature. Analysis of the 1-octanol, 2-octanol and geraniol reactions were performed by GC using a ZB Wax column and mesitylene as internal standard. The HMI experiments were analysed by HPLC using a Luna 5µ C18 column, $\lambda = 195$ nm and a mobile phase of 50% methanol/50% water. The identification of by-products was performed by GC-MS.

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References and Notes

[1] G. Cainelli, G. Cardillo, G. *Chromium Oxidations in Organic Chemistry*, Springer Verlag, Berlin, **1984**.

[2] F. A. Luzzio, *Organic Reactions.* Vol. 53, Wiley, New York, **1998**, p. 1.

[3] T. T. Tidwell, *Organic Reactions.* Vol. 39, Wiley, New York, **1990**, p. 297.

[4] C. Chapius, D. Jacoby, *Appl. Catal.* **2001**, *221*, 93-117.

[5] R. L. Augustine, *Heterogeneous Catalysis for the Synthetic Chemist*, Marcel Dekker Inc., New York, **1996**, pp. 551-573.

[6] R. A. Sheldon *J. Chem. Tech. Biotechnol.* **1997**, *68*, 381-388.

[7] L. Schmieder-van de Vondervoort, S. Bouttemy, J. M. Padrón, J. Le Bras, J. Muzart, P. L. Alsters, *Synlett* **2002**, *2*, 243-246.

[8] Review: R. A. Sheldon, I. W. C. E. Arends, A. Dijksman, *Catal. Today* **2000**, *57*, 157-166.

[9] R. A. Sheldon, I. W. C. E. Arends, G. J. ten Brink, A. Dijksman, *Acc. Chem. Res.* **2002**, *35*, 774-781.

[10] B. A. Steinhoff, S. R. Fix, S. S. Stahl, *J. Am. Chem. Soc.* **2002**, *124*, 766-767.

[11] B. A. Steinhoff, S. S. Stahl, *Org. Lett.* **2002**, *4*, 4179-4181.

[12] T. Nishimura, Y. Maeda, N. Kaikiuchi, S. Uemura, *J. Chem. Soc. Perkin Trans. 1* **2000**, 4301-4305.

[13] T. Nishimura, T. Onoue, K. Ohe, S. Uemura, *J. Org. Chem.* **1999**, *64*, 6750-6755.

[14] G. J. ten Brink, I. W. C. E. Arends, R. A. Sheldon, *Science* **2000**, *287*, 1636-1639.

[15] G. J. ten Brink, I. W. C. E. Arends, R. A. Sheldon, *Adv. Synth. Catal.* **2002**, *344*, 355-369.

[16] I. Marko, P. R. Giles, M. Tsukazaki, I. Chellé-Regnaut, C. J. Urch, S. M. Brown, *J. Am. Chem. Soc.* **1997**, *119*, 12661-12662.

[17] M. Hasan, M. Musawir, P. N. Davey, I. V. Kozhevnikov, *J. Mol. Catal.* A, **2002**, *180,* 77-84.

[18] I. Marko, P. R. Giles, M. Tsukazaki, I. Chellé-Regnaut, A. Gautier, S. M. Brown, C. J. Urch, *J. Org. Chem.* **1999**, *64*, 2433-2439.

[19] R. Ben-Daniel, P. Alsters, R. Neumann, *J. Org. Chem.* **2001**, *66*, 8650-8653.

[20] J. M. Jetten, R. T. M. van den Dool, W. van Hartingsveldt, M. T. R. van Wandelen, *WO* 00/50621, **2000**.

[21] M. Fabbrini, C. Galli, P. Gentilli. D. Macchitella, *Tetrahedron Lett.* **2001**, *42*, 7551-7553.

[22] G. Ragagnin, B. Betzemeier, S. Quici, P. Knochel, *Tetrahedron*, **2002**, *58*, 3985-3991.

[23] A. Cecchetto, F. Fontana, F. Minisci, F. Rucupero, *Tetrahedron Lett.* **2001**, *42*, 6651-6653.

[24] A. Dijksman, A. Marino-Gonzalez, A. Mairata i Payeras, I. W. C. E. Arends, R. A. Sheldon, *J. Am. Chem. Soc.* **2001**, *123*, 6826-6833.

[25] A. Dijksman, I. W. C. E. Arends, R. A. Sheldon, *Platinum Metals Rev.* **2001**, *45*, 15-19.

[26] K. Sato, M. Aoki, J. Takagi, R. Noyori, *J. Am. Chem. Soc.* **1997**, *119*, 12386-12387.

[27] R. Neumann, M. Gara *J. Am. Chem. Soc.* **1995**, *117*, 5066-5074.

[28] C. Venturello, M. Gambaro, *J. Org. Chem.* **1991**, *56*, 5924-5931.

[29] Y. Ishii, K. Yamawaki, T. Ura, H. Yamada, T. Yoshida, M. Ogawa *J. Org. Chem.* **1988**, *53*, 3587-3593.

[30] J. W. E. Glattfeld, S. Gershon, *J. Am. Chem. Soc.* **1938**, *60*, 2013-2023.

[31] K. Heyns, H. Paulsen, *Newer Methods of Preparative Organic Chemistry*, Academic Press, **1963**, *II*, pp. 303-335.

[32] P. Vinke, D. de Wit, A. T. J. W. de Goede, H. van Bekkum, *New Developments in Selective Oxidation by Heterogeneous Catalysis, Studies in Surface Science and Catalysis*, Elsevier, Amsterdam, **1992**, *72,* pp. 1-19.

[33] P. Gallezot, *Catal. Today,* **1997**, *37*, 405-418.

[34] M. Besson, P. Gallezot, *Catal. Today,* **2000**, *57*, 127-141.

[35] T. Mallat, Z. Bodnar, P. Hug, A. Baiker, *J. Catal.* **1995**, *153*, 131-143.

[36] K. Mori, K. Yamaguchi, T. Hara, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Am. Chem. Soc.* **2002**, *124*, 11572-11573.

[37] D. Sloboda-Rozner, P. L. Alsters, R. Neumann, submitted to *J. Am. Chem. Soc.*

[38] K. Yamaguchi, N. Mizuno, *New J. Chem.* **2002**, *26*, 972-974.

[39] H. Ji, T. Mizugaki, K. Ebitani, K. Kaneda, *Tetrahedron Lett.* **2002**, *43*, 7179-7183.

[40] K. Yamaguchi, K. Mori, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Am. Chem. Soc.* **2002**, *124*, 7144-7145.

[41] Y.-C. Son, V. D. Makwana, A. R. Howell, S. L. Suib, *Angew. Chem. Int. Ed.* **2001**, *40*, 4280-4283.

[42] A. J. H. P. van der Pol, J. H. C. van Hoof, *Appl. Catal.* A **1993**, *106*, 97-113.

[43] F. Maspero, U. Romano, *J. Catal.* **1994**, *146*, 476-482.

[44] K. G. Griffin, P. Johnston, S. Bennett, S. Kaliq, *Proceedings of the 19th Organic Reactions and Catalysis Society*, (Ed.: D. G. Morrell), Marcel Dekker, Inc., New York, **2002**, pp. 169-178.

[45] J. Heveling, A. Wellig, K. Wallis, *U. S. Patent* 5,917,051.

[46] M. Freifelder, *Pratical Catalytic Hydrogenation*, John Wiley & Sons, Inc., New York, **1971**, pp. 39-47.

[47] T. Mallat, A. Baiker, *Appl. Catal.* **1991**, *79*, 41-58.

[48] M. Besson, F. Lahmer, P. Gallezot, P. Fuertes, G. Flèche, *J. Catal.* **1995**, *152*, 116-121.