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ARTICLE TYPE

N,O-Ligated Pd(II) Complexes for Catalytic Alcohol Oxidation

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N,O-ligated Pd(II) complexes show considerable promise for the oxidation of challenging secondary aliphatic alcohols. The crystal structures of the highly active complexes containing the 8-hydroxyquinoline-2-carboxylic acid (HCA) and 8-hydroxyquinoline-2-sulfonic acid (HSA) ligands have been obtained. The (HSA)Pd(OAc)₂ system can effectively oxidise a range of secondary alcohols, including unactivated alcohols, within 4-6 h using loadings of 0.5 mol%, while lower loadings (0.2 mol%) can be employed with extended reaction times. The influence of reaction conditions on catalyst degradation was also examined in these studies.

1. Introduction

Palladium (II) complexes have shown significant potential as catalysts for a variety of oxidation reactions.¹ Alcohol oxidation has been an area in which extensive work has been focused due to the high demand for carbonyl compounds within organic chemistry.² There have been numerous developments in this area in recent years with the advent of ligand modulated catalysts that can undergo O₂ coupled turnover without the need for co-catalysts such as benzoquinone or metal salts.³ The majority of studies have utilised nitrogen donor ligands, such as pyridines,⁴ (-)-sparteine,⁵ triethylamine,⁶ quinolines⁷ and phenanthrolines^{8,9,10} while *N*-heterocyclic carbene (NHC) type ligands have also been explored.¹¹ Such ligands allow facile re-oxidation of Pd(0) to Pd(II); without such ligands precipitation of inactive Pd species (e.g. "Pd black") is normally observed. Compared to other areas of homogeneous catalysis, relatively few ligands have been studied thus far. In terms of performance, there are a few systems worth highlighting. Sheldon and co-workers demonstrated that bidentate phenanthroline derivatives such as neocuproine gave good performance even for challenging unactivated aliphatic alcohols.^{9c} Sigman and co-workers found that the NHC-based complex [Pd(IiPr)(OAc)₂(H₂O)] where IiPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene showed excellent activity for the oxidation of a range of alcohols.¹¹ More recently we found that *N,O*-ligands could result in catalysts with good performance

for the oxidation of 2-octanol.¹² We screened a range of *N,O*-ligands and found that ligands that had multiple acidic donors near the metal centre delivered superior rates compared to other similar analogues. Figure 1 highlights some of these ligands, demonstrating the influence of such acid groups. 8-hydroxyquinoline-2-carboxylic acid (HCA) and 8-hydroxyquinoline-2-sulfonic acid (HSA) had the highest turnover frequencies (TOFs). We also found that the performance under some conditions was superior to neocuproine⁹ which had been the previous benchmark in terms of reaction rates for the oxidation of aliphatic alcohols.

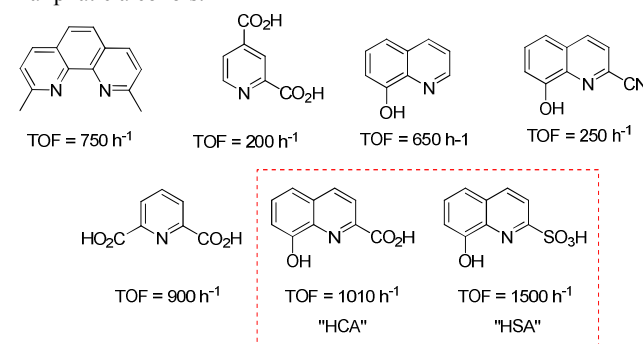


Figure 1: Comparative initial TOFs for oxidation of 2-octanol¹²

In 2012 Cámpora and co-workers reported the use of Pd complexes with bidentate *N,O*-ligands of the type [Pd(CH₂CMe₂Ph)(N–O)(L)] where L = pyridine or a pyridine derivative and N–O is a bidentate, anionic ligand (e.g. 2-pyridylacetate, 2-pyridinecarboxylate, quinoline-2-carboxylate, pyridine-2-sulfonate).¹³ They examined a range of these complexes and their study gave further understanding for Pd complexes with *N,O*-ligands for alcohol oxidation. In terms of

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†Electronic Supplementary Information (ESI) available detailing crystal structure data. See DOI: 10.1039/b000000x/

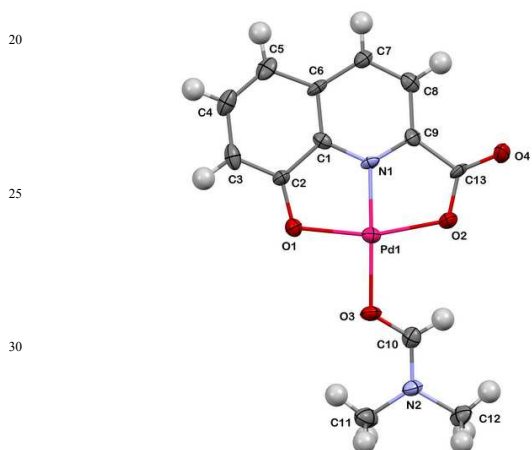
catalyst performance, a catalyst loading of 1 mol%, 100 °C and 12 hours was required. This is not as efficient as Sheldon's neocuproine⁹ or Sigman's NHC¹¹ systems, however it is better than other catalysts, e.g. the pyridine⁴ or triethylamine⁶ systems.

5 Herein, we report the crystal structures of Pd(II) complexes with both the HCA and HSA ligands. We also examine the use of (HSA)Pd(OAc)₂ for the aerobic oxidation of range of secondary alcohols as well as studying the influence of reaction conditions on catalyst degradation.

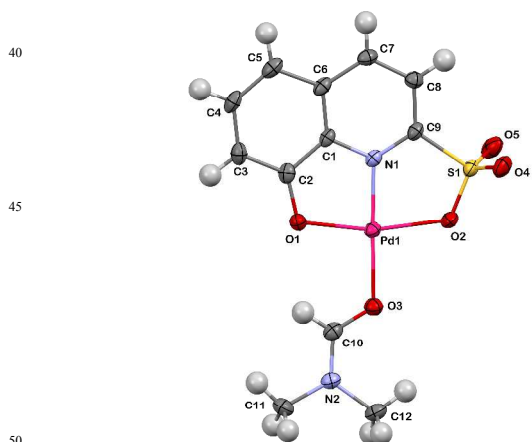
10 2. Results and Discussion

2.1 Crystal Structure and Implications

In our initial report, we had been unable to obtain crystals of the Pd(II) complexes utilising HCA and HSA, the best performing ligands. We have since been able to obtain crystal structures for 15 Pd(II) complexes with these two ligands, shown in Figures 2 and 3 and selected bond distances and angles are shown in Tables 1 and 2.



35 **Figure 2:** Crystal Structure of Pd(HCA)(DMF). Displacement ellipsoids – 50% probability.



40 **Figure 3:** Crystal Structure of Pd(HSA)(DMF). Only one independent molecule is shown ($Z' = 2$). Displacement ellipsoids – 50% probability.

Table 1: Selected bond distances for Pd(HSA)(DMF) second row 55 corresponds to the second independent molecule present in the asymmetric part of the unit cell.

<i>bond</i>	<i>Pd(HCA)(DMF)</i> [Å]	<i>Pd(HSA)(DMF)</i> [Å]
Pd1 – N1	1.893(8)	1.921(3)
Pd2 – N101	-	1.920(3)
Pd1 – O1	2.047(7)	2.006(2)
Pd2- O101	-	2.002(2)
Pd1 – O2	2.047(7)	2.087(3)
Pd2- O102	-	2.080(3)
Pd1 – O3	2.048(7)	2.034(2)
Pd2- O103	-	2.032(2)

Table 2: Selected angles for Pd(HSA)(DMF) second row corresponds to 60 the second independent molecule present in the asymmetric part of the unit cell).

<i>Angle</i>	<i>Pd(HCA)(DMF)</i> [°]	<i>Pd(HSA)(DMF)</i> [°]
N1–Pd1–O1	83.3(3)	83.85(11)
N101–Pd2–O101	-	84.07(11)
N1–Pd1–O2	80.2(3)	82.93(11)
N101–Pd2–O102	-	82.96(11)
N1–Pd1–O3	177.8(3)	177.38(11)
N101–Pd2–O103	-	178.04(11)
O1–Pd1–O3	95.6(3)	97.34(10)
O101–Pd2–O103	-	96.05(10)
O2–Pd1–O3	101.0(3)	96.03(10)
O102–Pd2–O103	-	96.91(10)
O1–Pd1–O2	163.4(3)	166.28(10)
O101–Pd2–O102	-	167.03(10)

Previously we had suggested that these *N,O*-ligands may result 65 in anionic Pd (II) complexes. Anionic Pd complexes have been isolated previously when phosphine ligands with acidic groups were employed;¹⁴ however the structures we obtained do not prove this is the case for our catalysts. In order to obtain satisfactory crystal growth, a variety of solvent combinations 70 were tested. The best crystals obtained were grown by the diffusion method using dimethylformamide (DMF) with diethyl ether as the diffusion solvent. These Pd(HCA)(DMF) and Pd(HSA)(DMF) complexes are neutral with the coordinating solvent DMF acting as a ligand. These crystal growth conditions 75 are not representative of the conditions of the reaction. For example, these crystals were also obtained without an additional source of [OAc]⁻ which is used as a base and present in excess in the catalytic reactions.

As can be seen from the crystal structures of Pd(HCA)(DMF) 80 and Pd(HSA)(DMF) (Figures 2 and 3) the ligand is coordinated in an (*O,N,O*)-type fashion. Previous work by Sheldon⁹ and Waymouth¹⁰ found that tridentate ligand binding shows little or no activity in alcohol oxidation. This suggests that the *O,N,O* binding observed in the crystal structures is hemi-labile under the 85 reaction conditions. Previously, Cavell and co-workers examined the use of bidentate *N,O* ligands (such as 2-pyridinecarboxylate) for Pd-catalysed carbonylation reactions.¹⁵ In these studies, they discuss the lability of such ligands, however in those cases they believed that it was the nitrogen donor which was labile. In the

Pd(HSA)(DMF) complex the Pd-sulfonate bond distances suggest that it is the sulfonate group which is most likely to be labile in these complexes.

This hemilabile binding may explain the high activity of this system by combining both complex stability through the tridentate ligand whilst providing an open coordination site which allows β -hydride elimination to take place. As we will discuss, the labile O-donor may help promote the reaction by acting as an acid and base at different stages of the catalyst cycle.

A number of excellent mechanistic studies have given us insight into the details of the catalytic cycle for Pd(II) catalyzed alcohol oxidation.^{9,11,16} Such mechanistic understanding is extremely important for helping interpret the observed catalytic activity and also for the development of new catalysts. Figure 4 illustrates the generally accepted catalytic cycle for alcohol oxidation catalysed by ligand modulated Pd(OAc)₂, in this case exemplified for a bidentate ligand (L---L), a case which has been well-studied.

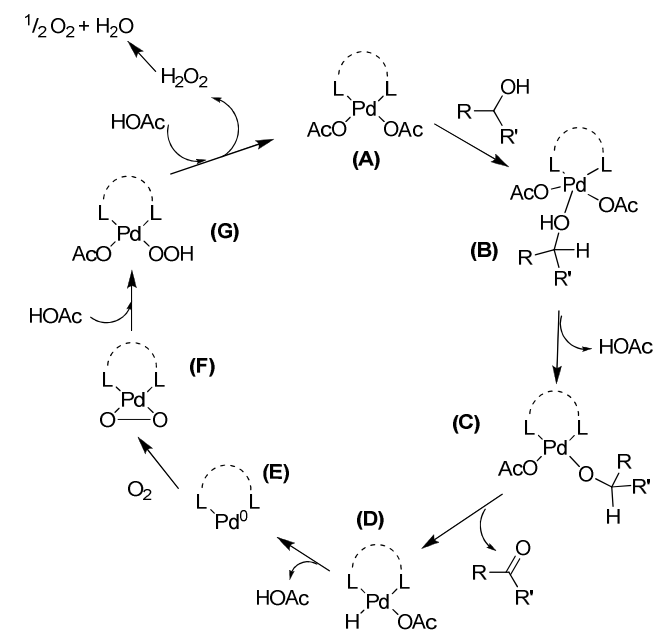


Figure 4: Schematic representation of the catalytic cycle for alcohol oxidation by ligand modulated Pd(OAc)₂.

The first step involves coordination of the alcohol (A→B) followed by deprotonation of the coordinated alcohol. In many examples, acetate is utilised as both a labile ligand and a base. For that reason, excess acetate (in the form of salts such as sodium acetate or tetrabutylammonium acetate ([NBu₄][OAc])) is often added to the reaction. Deprotonation of the alcohol results in the formation of a coordinated alkoxide (C) and formation of acetic acid. The carbonyl product is then formed *via* a β -hydride elimination reaction, forming a palladium hydride species (D). A reductive elimination reaction then results in the formation of another equivalent of acetic acid along with a Pd(0) species (E). The Pd(0) species is then re-oxidised directly by dioxygen. Initially, O₂ forms a Pd-peroxo species (F) which is protonated by one equivalent of acetic acid to form a hydroperoxide species (G). The second equivalent of acetic acid then regenerates the

initial Pd(II) catalyst (A) and results in the production of hydrogen peroxide, which normally breaks down quickly under the reaction conditions to form water (and $\frac{1}{2}$ O₂).

As can be seen from the catalytic cycle, both acid and base are crucial at various stages of the mechanism, therefore the role of the acetate anion, either as a ligand or acting as a base, is central to the activity of the system. In our reaction conditions, an excess of [NBu₄][OAc] is present in the reaction mixture. However, there is also the possibility that *N,O*-ligands have the potential to be involved in this acid/base chemistry. In the recent study by Campora and coworkers¹³ examining bidentate *N,O*-ligands they suggested that the carboxylate group of the ligand was labile and was intrinsically involved in the mechanism, “facilitating the proton transfer from the substrate (alcohol) to the final electron acceptor (oxygen)”. In our own studies, we found that when screening ligands,¹² that there was a beneficial effect in having acidic groups close to the metal centre (see Figure 1), so we believe that such involvement in the mechanism is very possible.

2.2 Substrate Scope

Our previous study concentrated on examining ligand effects, and we compared the initial TOFs for the oxidation of 2-octanol. In that ligand study, reactions were carried out in neat substrate however for our substrate scope study we wished to use an additional solvent, enabling solid substrates to be examined. We examined a range of organic solvents (Figure 5) using 0.1 mol% (HSA)Pd(OAc)₂ at 60 °C, and compared the rate of reaction over a 4 hour time period (sampling every hour).

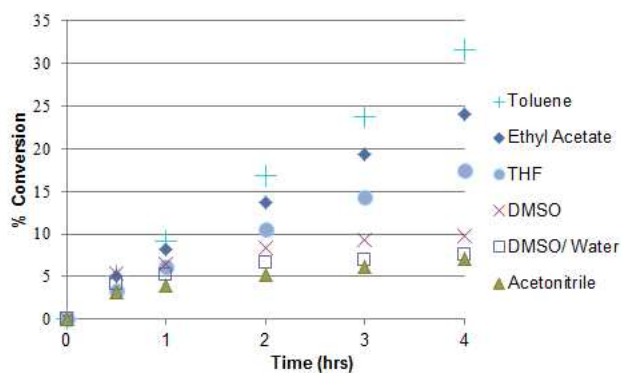


Figure 5: Solvent screen for the oxidation of 2-octanol. 0.1 mol% catalyst, 4 mol% [NBu₄][OAc], 4mL solvent, 60 °C

Under these conditions, we found that toluene delivered the best performance, which fits well with other studies as toluene is commonly used as the solvent of choice in Pd(II) catalysed oxidation of alcohols.⁴ Perhaps the weakly coordinating nature of toluene favours alcohol oxidation with homogeneous Pd(II) catalysts. Based on the mechanism shown in Figure 4 a strongly coordinating solvent could slow the reaction by coordinating to the Pd and hindering coordination of the substrate and/or β -hydride elimination. Due to toluene delivering the best rates we then applied the (HSA)Pd(OAc)₂ catalyst to a range of secondary alcohols, using toluene as the solvent and the results are shown in Table 3.

Table 3 Oxidation of secondary alcohols

Entry	Starting Material	Product	Yield ^a
1	1a	2a	93%
2	1b	2b	88%
3	1c	2c	78%
4	1d	2d	>99%
5	1e	2e	89% ^b
6	1f	2f	95% ^b
7	1g	2g	80%
8	1h	2h	85%
9	1i	2i	70%
10	1j	2j	74%
11	1k	2k	89%
12	1l	2l	98%

^a Yield determined by GC using biphenyl as an internal standard,^b Reactions run for 4 hours

For the substrates shown in Table 3 we employed 0.5 mol% (HSA)Pd(OAc)₂ at 100 °C in air (30 bar). We found that these conditions delivered good-to-excellent yields within 6 hours. For activated substrates such as **1e** and **1f** the reaction time could be reduced even further. In the case of **1g** a minor product (~10%)

was identified as 1-phenylpropane-1,2-dione, caused by oxidation of the benzylic position of the homobenzylic alcohol. Impressively the bulky secondary aliphatic alcohol **1d** was oxidised with a very high yield within 6 hours. Sterically hindered alcohols such as **1d**, **1j** and **1l** were also oxidised with good yields.

The catalyst can oxidise primary alcohols, but we focused on secondary alcohols, because we think the performance of other catalyst systems is better. In the case of activated alcohols such as cinnamyl alcohol and benzyl alcohol we found that it was possible to obtain good selectivity to the corresponding aldehydes, but in the case of unactivated alcohols (1-octanol in this case) the selectivity to the aldehyde was poor. The catalyst could convert over 90% of the alcohol, but the selectivity to octanal was around 10%, with the majority of the product being octanoic acid, along with substantial quantities (10 %) of ester (octyl octanoate) being produced. We believe that for selectively oxidising primary alcohols to aldehydes, the aerobic Cu/TEMPO catalyst system is a superior method,^{17,18} but the Cu/TEMPO system is unable to readily oxidise secondary alcohols, particularly unactivated or bulky alcohols. There have been recent developments in this area, with unhindered nitroxyl radicals replacing TEMPO and enabling the efficient oxidation of secondary alcohols, but these radicals are expensive commercially (at the present time) and some require a substantial number of synthetic steps to prepare.^{17,19}

2.3 Catalyst Degradation

For the substrates shown in Table 3 we utilised 0.5 mol% loading and air at a pressure of 30 bar. Although this loading is comparatively low and in line with benchmark systems,^{9,11} we would have liked to have used lower catalyst loadings. Additionally, we would have preferred to use a non-flammable gas mixture however to achieve high yields proved difficult and we will discuss some of the challenges involved.

If these reactions were to be scaled it up they would likely need to be carried out under *limiting oxygen concentrations* (LOCs), to avoid explosive O₂ / organic mixtures.²⁰ The LOC depends on the organic material and the reaction conditions, but typically for most organic solvents this means using gas mixtures containing less than 10% O₂. Under the reaction conditions in Table 3 (0.5 mol% catalyst, 100°C) we found substantial differences when using 30 bar of air compared to 30 bar of O₂:N₂ (8:92). In Figure 6, we compare air with O₂:N₂ (8:92) and with O₂:CO₂ (8:92) at 80 and 100 °C.

It is clear that there is a negative impact by going from air to the more dilute O₂:N₂ (8:92) gas mixture at this catalyst loading. When using O₂:N₂ (8:92) the system is mass transfer limited in O₂. Previous studies have shown that in these Pd(II) systems, oxidation of the alcohol is the rate determining part of the catalytic cycle.^{9,16} If there is sufficient O₂ present then re-oxidation of the Pd(0) back to Pd(II) is kinetically invisible under the reaction conditions. If the concentration of O₂ affects the rate then it is indication that the system is mass transfer limited in O₂.^{16d} Being mass transfer limited in O₂ will slow down catalytic turnover and also lead to catalyst degradation as it will increase the lifetime of Pd(0) species. As well as using the LOC conditions with O₂/N₂ we also looked at 8% O₂ in CO₂, which is of course another suitable diluent as it is non-flammable. Indeed,

from a safety point of view CO₂ is superior to N₂ as a non-flammable diluent as it has a higher molar heat capacity.²⁰ As can be seen in Figure 6, the use of 8% O₂ in CO₂ gave very similar results to those obtained in air. Switching from N₂ to CO₂ as the diluents resulted in quite a dramatic improvement in performance and enabling a safe O₂ concentration to be employed.

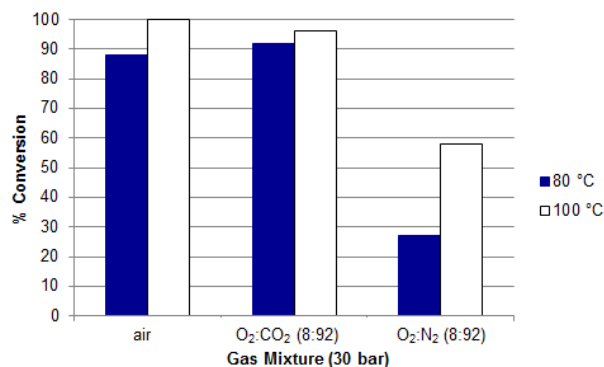


Figure 6: Effect of gas mixtures on the conversion of 2-octanol using 0.5 mol% (HSA)Pd(OAc)₂, 5 mol% [NBu₄][OAc] in toluene, 4 hours.

We examined the influence of CO₂ further, which we will discuss below, but first we wish to deal with perhaps a more obvious question; if we wish to use lower catalyst loadings, why not do so and simply leave the reaction for a longer time? The answer is that we found that at lower catalyst loadings and / or temperatures we observed the catalyst becoming inactive over time. In Figure 7, we show such an example with the oxidation of 2-octanol at 60 °C using 0.1 mol% catalyst. At this loading and temperature, the system is not mass transfer limited in O₂ and the same rate is obtained in both air and 8% O₂ in N₂. Therefore the catalyst should not degrade due to it being limited in O₂. However, as it can be seen in Figure 7 the catalyst starts to become less active after a few hours.

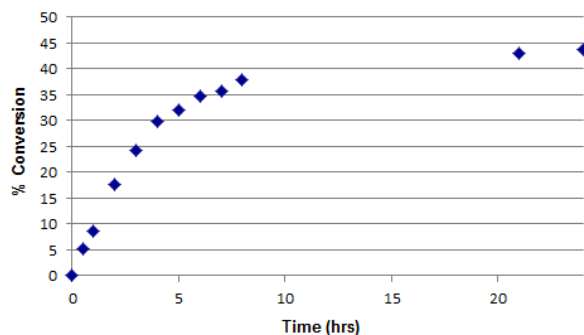


Figure 7: Graph showing catalytic activity for the oxidation of 2-octanol catalysed by 0.1 mol% (HSA)Pd(OAc)₂ with 4 mol% [NBu₄][OAc] in toluene at 60 °C with 30 bar air.

We believe that this is due to the perennial problem that affects homogeneous Pd catalysis; aggregation of Pd(0) species.²¹ Although we do not observe any “Pd black” it is likely that aggregation of Pd(0) into inactive clusters/nano-particles are cause of this deactivation. As we mentioned, re-oxidation of Pd(0) back to Pd(II) is kinetically invisible if the system is not limited in O₂. However, it seems clear that the Pd(0) species have

sufficient lifetime that will enable them to aggregate under homogeneous conditions. The same pattern of catalyst deactivation was observed in other solvents and also at different catalyst loadings. At very low catalyst loadings, the catalyst still became inactive on a similar timescale although higher TOFs and TONs are obtained in those cases. This trend is in accordance with mechanistic work reported by Stahl and co-workers who observed both unimolecular and bimolecular catalyst decomposition pathways in the Pd(OAc)₂/DMSO system.^{16d} By reducing the catalyst concentration the bimolecular catalyst decomposition pathway is reduced. So as it can be seen, in order to obtain high yields of product is necessary to utilise higher loadings. In Table 3 we utilised 0.5 mol%, however we found that it was possible to get high yields using 0.2 mol% at 100 °C, albeit at longer reaction times (see Figure 8). Interestingly, when the temperature is raised to 100 °C the differences in reactivity in toluene and DMSO/water solvent mixture is less pronounced. At 0.2 mol% catalyst loading it is initially faster in toluene but the end result is the same in both solvents (Figure 8).

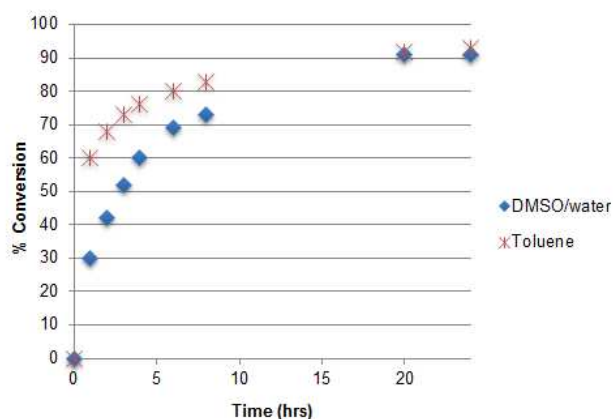


Figure 8: Oxidation of 2-octanol with 0.2 mol% (HSA)Pd(OAc)₂ in DMSO/water (50:50 vol%) and toluene, 100 °C, 30 bar air.

In our previous study,¹² we compared HSA to neocuproine at 100 °C, using air, in DMSO/water (50:50 vol%) using catalyst loadings of 0.5 mol%. Under those conditions (HSA)Pd(OAc)₂ can oxidise 2-octanol completely in just 1h. However, when we use these conditions in toluene (*i.e.* those used in Table 3) we obtain 70% yield in 1 hr. So it seems that at higher temperatures and loadings, DMSO/water enables shorter reaction times, nonetheless toluene is a arguably a more desirable solvent than DMSO.²² There are a few potential reasons as to why DMSO/water gives a higher yield in 1 hr with 0.5 mol% catalyst at 100 °C; presumably catalyst deactivation is somewhat slower in DMSO/water and this could be because this coordinating solvent mixture stabilises Pd(0) species. It could also simply be that the catalyst deactivates more slowly because the catalyst is turning over more slowly in DMSO/water. A slower turnover will reduce the concentration of Pd(0) species at any given time, which could consequently reduce the rate of aggregation and deactivation. A similar argument has been made by Sigman and co-workers with regards to the influence of acetic acid on their NHC catalyst system.^{11b}

With regards to the influence of CO₂ that we observed (Figure 6) we wanted to examine the effect of CO₂ under conditions that were not mass transfer limited. Compared to many gases (e.g. N₂) CO₂ has excellent solubility in organic solvents and this can have 5 benefits. It is known that CO₂ can lead to improved solubility of other gases, including O₂,²³ and also improve mass transport properties of systems,²⁴ therefore the benefit that we saw under the conditions used in Figure 6 may be due to improved O₂ solubility and mass transport. We examined CO₂ at 100 °C and a 10 catalyst loading of just 0.01 mol%. As can be seen from Figure 9 there is a clear impact of switching from N₂ to CO₂.

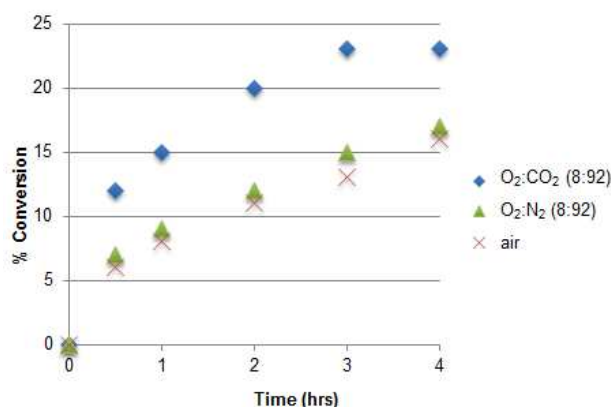


Figure 9: Effect of different catalyst loadings and gas mixtures on the conversion of 2-octanol at 100°C.

15 By dropping the catalyst loading to 0.01 mol%, it can be seen that there is no difference between using air and O₂/N₂ (8:92), so we are not mass transfer limited under these conditions. Changing the gas mixture to O₂/CO₂ (8:92) shows a significant increase in initial conversion although after 24 hours the overall alcohol 20 conversion is similar in CO₂ and N₂ systems (33% conversion in O₂/CO₂ (8:92) and 31% conversion in air). These reactions are another illustration of the problems of catalyst degradation. Given that the catalyst loading is just 0.01 mol%, it is clear in Figure 9 that the catalyst has an excellent TOF and TON in these first few 25 hours and then the effects of aggregation begin to take hold. In terms of the initial rate enhancement delivered by CO₂ we believe that this could be due to a number of reasons. CO₂ could be improving the reaction rate due to the presence of acid. CO₂ will react with any water present to form carbonic acid. Additionally 30 it can react with alcohols to form alkylcarbonic acids.²⁵ CO₂ has also been known to promote oxidation reactions due to the formation of peroxocarbonate type species,²⁶ and in fact palladium peroxocarbonate complexes have been reported.²⁷ As mentioned previously, Sigman and co-workers utilised acetic acid 35 to improve the catalytic turnover for their [Pd(IrPr)(OAc)₂(H₂O)] catalyst.¹¹ The addition of acetic acid is believed to help prevent catalyst decomposition by increasing the rate of catalyst re-oxidation and also by reducing the rate of alcohol oxidation; which consequently reduces the concentration of Pd(0) species. 40 Indeed, Waymouth and co-workers showed in their studies with neocuproine cationic complexes, that a lack of acid led to unwanted catalyst decomposition due to slow reoxidation of the catalyst.¹⁰

In order to further elucidate the potential role of CO₂ as an

45 acidic promoter, we decided to test the effect of adding acetic acid to our catalyst system (Figure 10).

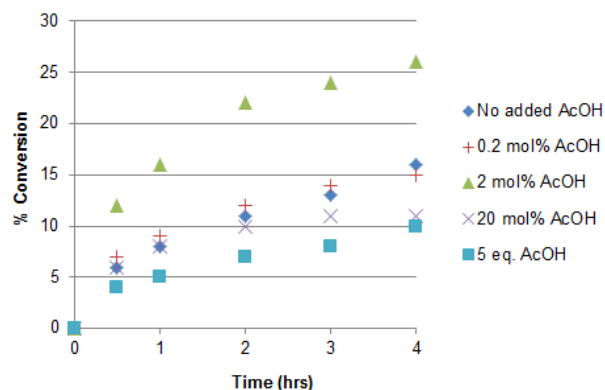


Figure 10: Effect of the addition of acetic acid to the oxidation of 2-octanol with 0.01 mol% (HSA)Pd(OAc)₂ in toluene at 100°C.

50 In our studies we found that addition of small amounts of acetic acid did improve the rate of the reaction, however at higher acid concentrations, this led to significant decrease in rate. This is likely due to the additional acid hindering the initial deprotonation of the alcohol (as seen in the mechanism in Figure 55 4). Similar concentration effects were also observed by Sigman.^{11b} Analogous to what we observed with CO₂, the addition of acetic acid only increased the *initial* TOF, and after 24 hours the conversions with and without the addition of 2 mol% acetic acid are identical (31%). The dramatic differences that we 60 observed with 8% O₂ gas mixtures (Figure 5) could be due to a combination of factors. However, the fact that at low catalyst loadings we only see a benefit on the initial rate, would suggest that a significant factor in the results shown in Figure 5 is due to the ability of CO₂ to improve O₂ solubility and mass transport. 65 This is a significant advantage as it allows optimal catalyst performance to be obtained under safer, dilute O₂ conditions.

3. Conclusions

We have shown that the (HSA)Pd(OAc)₂ system is an effective 70 catalyst for the oxidation of a range of secondary aliphatic alcohols. The crystal structures of Pd(HCA)(DMF) and Pd(HSA)(DMF) may help to explain the high catalytic activity of this particular system. The performance of the (HSA)Pd(OAc)₂ catalyst compares favourably with previous 75 Pd(II) catalyst systems, and it is possible to obtain high yields with aliphatic alcohols with loadings as low as 0.2 mol%. An attractive feature of this system is that all the components are commercially available and the catalyst is formed *in situ*. We also demonstrated that utilising O₂/CO₂ gas mixtures can be 80 advantageous, enabling excellent performance with lower concentrations of O₂. CO₂ has a promotional effect on the initial rate in the same way as acetic acid, but we believe a major benefit of CO₂ is that it improves O₂ solubility and mass transport in the liquid phase. We can obtain good yields with comparatively low 85 loadings of catalyst, nonetheless it is clear that the system still deactivates, presumably *via* the well documented pathway of

Pd(0) aggregation. Studies are ongoing in an attempt to stabilise and/or prevent such decomposition pathways in order to develop catalysts that can deliver high TON.

4. Experimental

All chemicals were obtained from Sigma Aldrich and used as received. Tetrabutylammonium acetate ($[\text{NBu}_4][\text{OAc}]$) (>99%, electrochemical grade), palladium acetate (99.9+% grade) were used. O_2/N_2 (8:92) and O_2/CO_2 (8:92) high pressure premixed gas cylinders (β standard grade), and high pressure air cylinder were obtained from BOC gases.

Catalyst stock solutions were prepared as followed: $\text{Pd}(\text{OAc})_2$ (0.055g, 0.4875 mmol), 8-hydroxyquinolinesulfonic acid, (0.060g, 0.4875 mmol) and tetrabutylammonium acetate (1.475g, 4.875 mmol) were dissolved in toluene in a 25 mL volumetric flask. The flask was stirred vigorously until the solution was homogenous.

General conditions for catalyst testing: To a 16 mL Hastelloy C-276 reactor was added 2 mL of catalyst stock solution and 3.9 mmol of alcohol substrate. Biphenyl was added as an internal standard. The reactor vessel was sealed, charged with appropriate premixed gas mixture and heated on a metal heating block on a temperature controlled hotplate. The reaction was stirred at 750 rpm for the appropriate time before the reactor was cooled, slowly depressurised and a sample of the reaction mixture was filtered through a silica plug to remove any solids. Analysis of catalytic reactions was carried out by gas chromatography, using an Agilent 6890N series gas chromatograph. Product yields were determined using biphenyl as an internal standard. Reactions with **1a**, **1b**, **1d** and **1i** were analysed using an Agilent J&W HP-5, (30 m, 0.32 mm, 0.25 μm) silica column, under the following conditions: initial column temperature, 40 $^\circ\text{C}$; initial hold time, 0 min; rate of temperature ramp 1, 4 $^\circ\text{C}/\text{min}$; next temperature, 100 $^\circ\text{C}$; hold time, 0 min; rate of temperature ramp 2, 30 $^\circ\text{C}/\text{min}$, final temperature 320 $^\circ\text{C}$; hold time, 15 min; injection temperature, 250 $^\circ\text{C}$; detection temperature, 250 $^\circ\text{C}$. The effluent was combusted in a H_2/air flame and detected using an FID. The remaining substrates were analysed using a 30 m \times 0.32 mm ID SOLGEL-WAX 0.5UM (SGE Analytical Science) column under the following conditions: initial column temperature, 50 $^\circ\text{C}$; initial hold time, 1 min, next temperature, 200 $^\circ\text{C}$; hold time, 0 min; rate of temperature ramp 1, 25 $^\circ\text{C}/\text{min}$, final temperature 230 $^\circ\text{C}$; hold time, 18 min; rate of temperature ramp 2, 3 $^\circ\text{C}/\text{min}$; injection temperature, 250 $^\circ\text{C}$; detection temperature, 250 $^\circ\text{C}$. The effluent was combusted in an H_2/air flame and detected using a flame ionisation detector (FID).

Crystals were grown using the vapour diffusion method. The ligand (HSA or HCA) and $\text{Pd}(\text{OAc})_2$ were dissolved in the minimum amount of DMF and diethyl ether was used as the diffusion solvent. The samples were then placed in a freezer.

Single-crystal X-ray diffraction analyses of $\text{Pd}(\text{HCA})(\text{DMF})$ were performed using a Bruker APEXII CCD diffractometer mounted at the window of a Bruker FR591 rotating anode (Mo $K\alpha$, $\lambda = 0.71073 \text{ \AA}$) and equipped with an Oxford Cryosystems Cryostream device. Data were processed using the Collect package.²⁸

The X-ray data of $\text{Pd}(\text{HSA})(\text{DMF})$ were collected on Rigaku AFC12 goniometer equipped with an enhanced sensitivity (HG)

Saturn724+ detector mounted at the window of an *FR-E+ SuperBright* (Mo $K\alpha$, $\lambda = 0.71073 \text{ \AA}$) rotating anode generator with HF *Varimax* optics (100 μm focus), and processed with CrystalClear²⁹ software package.

Unit cell parameters were refined against all data. For $\text{Pd}(\text{HCA})(\text{DMF})$ an empirical absorption correction was carried out using SADABS,³⁰ whereas for $\text{Pd}(\text{HSA})(\text{DMF})$ CrystalClear software was used. Both crystal structures were solved by direct methods and refined on F_o^2 by full-matrix least-squares refinements using programs of the SHELX-97/SHELX-2014 family.³¹ All non-hydrogen atoms were refined with anisotropic displacement parameters. All hydrogen atoms located on carbon atoms were placed at calculated positions and refined using a riding model on their parent atoms with isotropic displacement parameters based on the equivalent isotropic displacement parameter ($U_{\text{iso}}(\text{H}) = 1.2 U_{\text{eq}}(\text{aromatic})$ and $U_{\text{iso}}(\text{H}) = 1.5 U_{\text{eq}}(\text{CH}_3)$) of the parent atom.

Crystal data for $\text{Pd}(\text{HCA})(\text{DMF})$: $\text{C}_{13}\text{H}_{12}\text{N}_2\text{O}_4\text{Pd}$, $M_r = 366.65$, yellow plate, $0.16 \times 0.06 \times 0.02 \text{ mm}^3$, Orthorhombic, $Pna2_1$, $a = 10.9190(7)$, $b = 23.8725(14)$, $c = 4.8372(3) \text{ \AA}$, $\alpha = \beta = \gamma = 90^\circ$, $V = 1260.88(13) \text{ \AA}^3$, $Z = 4$, $D_c = 1.931 \text{ g cm}^{-3}$, $\mu = 1.487 \text{ mm}^{-1}$, $T = 120 \text{ K}$, 8455 collected reflections, 2621 unique reflections ($R_{\text{int}} = 0.0559$), 2242 reflections with $F^2 > 2\sigma$, hkl ranges: $-14 \leq h \leq 14$, $-27 \leq k \leq 30$, $-6 \leq l \leq 6$, data completeness to $\theta_{\text{max}} = 27.47^\circ = 99.6\%$, $R(F^2 > 2\sigma) = 0.0486$, $wR2 = 0.0985$, $\text{GoF} = 1.087$. The final model was refined as inversion twin (Flack Parameter = 0.14(10)). CCDC: 988167

Crystal data for $\text{Pd}(\text{HSA})(\text{DMF})$: $\text{C}_{12}\text{H}_{12}\text{N}_2\text{O}_5\text{PdS}$, $M_r = 402.70$, yellow needle, $0.20 \times 0.02 \times 0.02 \text{ mm}^3$, Monoclinic, $P2_1/c$, $a = 19.681(3)$, $b = 7.1866(8)$, $c = 20.443(3) \text{ \AA}$, $\beta = 107.332(2)^\circ$, $V = 2760.2(6) \text{ \AA}^3$, $Z = 8$, $D_c = 1.938 \text{ g cm}^{-3}$, $\mu = 1.518 \text{ mm}^{-1}$, $T = 100 \text{ K}$, 34176 collected reflections, 6318 unique reflections ($R_{\text{int}} = 0.0453$), 5831 reflections with $F^2 > 2\sigma$, hkl ranges: $-25 \leq h \leq 25$, $-8 \leq k \leq 9$, $-26 \leq l \leq 26$, data completeness to $\theta_{\text{max}} = 27.48^\circ = 99.7\%$, $R(F^2 > 2\sigma) = 0.0409$, $wR2 = 0.1027$, $\text{GoF} = 1.072$. CCDC: 988168.

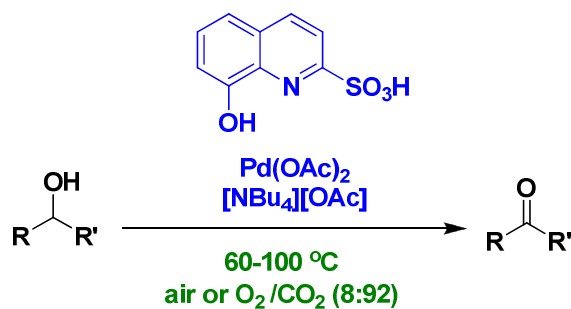
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N,O-ligated Pd(II) complexes show considerable promise for the oxidation of challenging secondary aliphatic alcohols. The crystal structures of the highly active complexes containing the 8-hydroxyquinoline-2-carboxylic acid (HCA) and 8-hydroxyquinoline-2-sulfonic acid (HSA) ligands have been obtained. The (HSA)Pd(OAc)₂ system can effectively oxidise a range of secondary alcohols, including unactivated alcohols, within 4-6 h using loadings of 0.5 mol%, while lower loadings (0.2 mol%) can be employed with extended reaction times. The influence of reaction conditions on catalyst degradation was also examined in these studies.