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Authors: Guillermo Nicolau, Giulia Tarantino, and Ceri Hammond

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Acceptorless alcohol dehydrogenation catalysed by Pd/C

Guillermo Nicolau, Giulia Tarantino and Ceri Hammond*[a]

Abstract: Although the selective oxidation of alcohols to carbonyl compounds is a critical reaction, it is often plagued by several challenges related to sustainability. Here, we demonstrate the continuous, acceptorless dehydrogenation of alcohols to carbonyl compounds over heterogeneous catalysts in the absence of oxidants, bases or acceptor molecules. In addition to improving selectivity and atom efficiency, the absence of an acceptor results in the co-production of molecular H_2, a clean energy source, and permits dehydrogenation to proceed at >98% selectivity at turnover frequencies values amongst the highest in the literature. Moreover, excellent durability is observed during continuous operation over 48 h, reaching space-time-yields of 0.683 $g_{(product)}$ mL^{-1} h^{-1}, better than the state of the art by over two orders of magnitude. Alongside these breakthroughs, we also identify the basic kinetic parameters of the reaction, allowing some of the elementary reaction steps to be identified.

Introduction

The synthesis of carbonyl compounds *via* alcohol oxidation is one of the most important chemical reactions in organic synthesis, due to the key role played by ketones and aldehydes as building block or intermediates for a wide range of value-added compounds, including fine chemicals and polymers.[1] However, despite the importance of this process for synthetic applications, alcohol oxidation is often performed by use of stoichiometric equivalents of high molecular weight oxidising agents.[2] Evidently, use of such oxidants dramatically affects the sustainability of these process, through the co-production of stoichiometric amounts of waste, and by decreased atom efficiency. Accordingly, much effort has been placed on increasing the sustainability of this reaction over the last decade. One approach involves the development of catalysts capable of converting alcohols to the corresponding carbonyl compounds using molecular O_2 as a benign oxidant, *i.e.* removing the need for inorganic and/or high molecular weight oxidants (oxidative dehydrogenation).[3] Another approach that has received far less attention is the development of catalysts capable of catalysing alcohol dehydrogenation under inert conditions, producing H_2 as by-product.[4,5] Although far less explored, this last route (acceptorless dehydrogenation) is especially desirable for a series of reasons, the most notable of which include the parallel production of H_2, highly valuable as a sustainable source of energy,[6] and increased selectivity towards the desired carbonyl compound, which is often readily overoxidised to the undesired carboxylic acid in the presence of O_2.[3c] Moreover, Gunanathan *et. al.* have recently demonstrated that acceptorless dehydrogenation can also be used as a starting point to achieve a broader range of organic reactions, following further reaction of the generated carbonyl compounds with nucleophiles, such as amines and terminal alkenes (so-called one pot synthesis *via* acceptorless dehydrogenative coupling).[4c]

Due to the potential of this approach, several attempts to develop catalysts capable of mediating the reaction have been made. Much focus has been placed upon homogeneous catalysts. However, these typically require several additives to be used (thus decreasing atom efficiency), or require the use of scare metals and/or expensive ligand complexes for high performance to be achieved. Amongst potential heterogeneous catalysts, supported noble metal nanoparticles (Cu, Ag, Au) exhibit high levels of performance, with the best catalytic performance being achieved by Ag nanoparticles supported on hydrotalcite, which achieves a turnover frequency (TOF) of around 2000 h^{-1}.[5c] Although displaying lower activities (TOF < 200 h^{-1}), examples of supported Ni,[5i,5m] Co,[5h] Pt,[5j] Re[5f] and Ru[5a,5b] catalysts have also been reported in the literature. Nevertheless, despite these previous breakthroughs, alcohol dehydrogenation over heterogeneous catalysts still suffers from several major drawbacks, including low intrinsic activity (*i.e.* low TOFs) and a lack of information on their long term stability. Moreover, the reactors employed for this reaction to date generally prohibit time on line measurement of the H_2 produced during the chemical reaction, and therefore do not allow detailed kinetic studies of the chemical process to be made, thus preventing a detailed reaction mechanism from being identified. Finally, the viability of this reaction to operate in a continuous manner has yet to be studied, despite it being an essential requirement for intensification purposes. Combined, these disadvantages limit the favourability and sustainability of this method, and make the rational improvement of catalytic activity extremely challenging. Hence, several challenges remain to be tackled.

Herein, we demonstrate the continuous, acceptorless dehydrogenation of alcohols over 5 wt. % Pd supported on activated carbon (henceforth, Pd/C), a readily available heterogeneous catalyst known to be active for H_2 production from formic acid. We show this commercial catalyst is able to quantitatively convert alcohols, such as 1-phenylethanol, to the corresponding carbonyl compound with > 98 % selectivity under optimised reaction conditions, whilst concurrently releasing molecular H_2 at a 1:1 molar ratio. The TOF values of the catalyst reach up to 1475 h^{-1}, amongst the highest in the literature. Moreover, under continuous operational conditions, the catalyst exhibits a space-time-yield (STY, amount of product produced per volume of reactor per unit time) two orders of magnitude higher than the best catalyst previously reported in the literature (Ag supported on hydrotalcite),[5c] and is active for over 48 hours on stream. We also report a novel type of reactor able to allow time on line collection and measurements of the H_2 produced during reaction. By use of this reactor, detailed kinetic investigation of the model reaction (1-phenylethanol dehydrogenation to acetophenone) is achieved, providing hitherto inaccessible insights into the reaction mechanism(s) of the reaction.

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[a] G. Nicolau, Dr. G. Tarantino, Dr. C. Hammond
Cardiff Catalysis Institute
Cardiff University
Main Building, Park Place
Cardiff, CF10 3AT (UK)
E-mail: hammondc4@cardiff.ac.uk
Homepage: http://blogs.cardiff.ac.uk/hammond/

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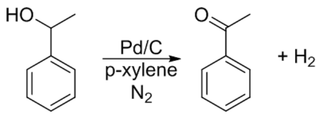
Results and Discussion

Preliminary kinetic measurements.

Building on our previous work of formic acid dehydrogenation, in which commercial palladium on carbon (Pd/C from Sigma Aldrich, 5% wt.% Pd) exhibited the best catalytic performances for H_2 generation, we identified Pd/C to also be a suitable choice of catalyst for the acceptorless dehydrogenation of 1-phenylethanol to acetophenone. Kinetic studies were first carried out using Pd/C as catalyst in N_2 atmosphere, at conditions comparable to various reports in the literature. Preliminary time on line analysis, performed at a Pd:substrate ratio of 1:80 (1.25 mol % of Pd), showed that after 3 hours of reaction, over 90 % of the substrate was converted into the desired product. Notably, an acetophenone selectivity > 95 % was observed throughout the reaction period, indicating that the dehydrogenation of 1-phenylethanol can efficiently be catalysed by Pd/C in N_2.



Scheme 1. General reaction scheme for 1-phenylethanol dehydrogenation to acetophenone over Pd/C in N_2.

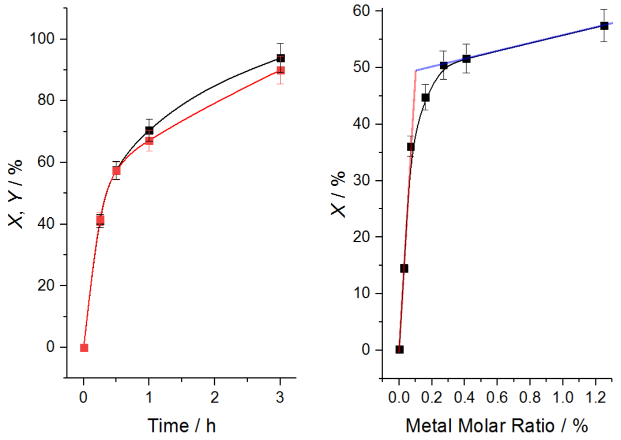


Figure 1. Left. Conversion (*X*) of 1-phenylethanol, and yield (*Y*) of acetophenone over time. **Right.** Initial (0.5 h) conversion (*X*) of 1-phenylethanol as a function of metal molar ratio (moles Pd / moles 1-phenylethanol x 100). Reaction conditions: 20 mL of a solution 0.2 M of 1-phenylethanol in *p*-xylene, 120°C. Reaction carried out under N_2 flow of 10 mL/min. (Left) 1.25 mol % Pd/Substrate molar ratio. (Right) Various amounts of Pd/C (5 wt. %) in the range 0-1.25 mol %, reaction time 0.5 hours.

Interestingly constructing an Arrhenius plot by measuring the initial rate of reaction (k) between 100-120 ˚C resulted in an activation energy of only 31 kJ/mol being observed (ESI Figure S1). Considering that the cleavage of a C(sp^3)-H bond should be involved in the reaction mechanism, the extremely low barrier obtained indicates contribution from other factors, particularly mass transfer. Therefore, further studies were performed to ensure that the amount of catalyst employed was low enough to carry out the reaction under the kinetic regime. Accordingly, the amount of Pd, relative to phenylethanol (mole %) was varied from to 0 to 1.25 mol % (Figure 1 (Right)). As can be seen, although a linear relationship between initial conversion (at 0.5 h) and the quantity of Pd exists at low metal molar ratios, deviation from linearity occurs above 0.1 mole % Pd. Thus, to maintain kinetic integrity, 0.08 mol % was chosen as the amount of catalyst for all further catalytic reactions. Additional optimisation experiments were also performed (ESI Figure S2), suggesting that stirring at rates above 250 rpm was also essential to avoid mass transfer limitations.

To ensure that the reaction is truly heterogeneously catalysed, *i.e.* that no contribution to the reaction rate derives from homogeneous species leached into the reaction mixture, a "hot filtration" experiment was performed By filtering the catalyst from the solution during the reaction, and analysing the residual activity of the supernatant solution following removal of the catalyst (ESI Figure S3). Following filtration of the solid catalyst, no further changes to the solution (1-phenylethanol conversion and acetophenone yield) were observed, indicating termination of the reaction by removal of the catalyst and, hence, demonstrating that the reaction is heterogeneously catalysed.

Acceptorless alcohol dehydrogenation is particularly beneficial due to the co-production of H_2, which is a valuablue by-product. Therefore, accurate analysis of the gas produced throughout 1-phenylethanol dehydrogenation is essential both to perform thorough kinetic and mechanistic studies of alcohol dehydrogenation, and confirm the formation of H_2 as reaction product, and confirm that the reaction is truly acceptorless. However, under typical literature conditions *i.e.* in conventional borosilicate batch reactors, technical challenges prevent accurate collection and quantification of the gas produced during the reaction. To overcome these problems, and, therefore, to allow accurate analysis of the gaseous products, a novel reactor was developed, by coupling a stainless steel reactor body with a pressurised collection vessel with a tolerance of 8 bar (ESI Figure S4). Equipped with this set up, the volume and composition of the gas formed during reaction was periodically monitored at three different temperatures, in a range 110-130 ˚C. In all cases, the amount of gas collected during the first 10 minutes of reaction was in good agreement to the theoretical amount of gas that should be produced based on the moles of 1-phenylethanol converted (Table 1). This confirms that appropriate time on line measurements can be achieved by measuring the gas evolution during the reaction. In addition to this, analysis of the liquid phase at the end of the reaction also allows substrate conversion and product yields to also be determined for all liquid products.

Table 1. Catalytic performances of Pd/C at different temperatures.[a]

T. (ºC) [a]	*X* (%)[b]	*Y* (%)[c]	*S* (%)[d]	*C Bal.* (%)[e]	*Theor. vol.* (mL)[f]	*Coll. vol.* (mL)[g]
130	29.6	28.8	97.6	99.4	26.1	25
120	23.6	23.6	> 98	100	22.0	20
110	15.4	15.4	> 98	100	14.4	15

[a] Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, static N_2 atmosphere, 10 mins. [b] Conversion of 1-phenylethanol. [c] Yield of acetophenone. [d] Selectivity for acetophenone. [e] Carbon balance. [f] Theoretical volume of gas. [g] Collected volume of gas.

In addition to allowing the kinetic parameters to be verified from both gaseous and the liquid phases, this approach also permits the acceptorless nature of the dehydrogenation reaction to be confirmed. To do so, the gas produced during the dehydrogenation of 1-phenylethanol was collected over a reaction time of 1 hour (43 mL of gas collected) and analysed *via* mass spectrometry (Table 2). As can be seen, compositional analysis of the collected gas indicated 24.4 mol % of H_2 to be present into the gas mixture. To ensure that the produced H_2 derives from dehydrogenation of the substrate, a control experiment was performed, conducting the reaction under typical reaction conditions, but without the substrate. As expected, only trace amounts of H_2 were detected (0.08 mol %), indicating 1-phenylethanol to be the source of H_2.

The relatively high molar percentage of H_2 detected in the gas phase, in addition to the good catalytic performances exhibited by the catalyst, strongly indicates that acceptorless alcohol dehydrogenation can be efficiently catalysed by Pd/C in N_2 atmosphere. Notably, the employment of an inert gas dramatically reduces the over-oxidation problems typically observed during aerobic alcohol oxidation,[3c] leading to higher selectivity values for the carbonyl compounds. However, performing the reaction for prolonged periods (18 hours) under optimised reaction conditions resulted in a drop in selectivity from 97.6 to 69.0 %, thus, suggesting the presence of side reactions at elevated levels of conversion and low masses of catalyst. In parallel to the drop of selectivity, the amount of substrate converted at extended periods was lower than anticipated based on the initial rate of reaction (from 29.6 % conversion at 0.16 hours to only 51.0 % at 2.5 hours). This result is in agreement to previous reports suggesting the reversibility of the process,[7] *i.e.* regeneration of the substrate following the hydrogenation of acetophenone.

Table 2. Gas composition analysis for 1-phenylethanol dehydrogenation with and without 1-phenylethanol.[a]

Gas Composition (mol %)	N_2	H_2	O_2
General reaction	74.12	24.73	1.15
Without 1-phenylethanol[b]	99.20	0.08	0.72

[a] Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, static N_2 atmosphere, 1 hour. [b] no 1-phenylethanol.

To study the negative effect of H_2 accumulation on the reaction, experiments were first performed in order to investigate the role played by gas flow *i.e.* static N_2 atmosphere was replaced with N_2 flow (Table 3), to remove H_2 from the reaction mixture following its formation. Notably, performing the reaction under N_2 flow (10 mL/min) dramatically affected the reaction, increasing 1-phenylethanol conversion and acetophenone yield, and boosting acetophenone selectivity to 98.4 %, strongly indicating that excessive quantities of H_2 impact selectivity, especially at high conversion.

Table 3. Effect of N_2 flow on 1-phenylethanol dehydrogenation catalysed by Pd/C.[a]

Time (h)	*X* (%)[b]	*Y* (%)[c]	*S* (%)[d]	*C Bal.* (%)[e]
0.16	29.6	28.8	97.6	100
2.5	51.0	40.8	80.0	100
18	85.2	58.8	69.0	100
2.5 [f]	72.7	71.5	98.4	100

[a] Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, static N_2 atmosphere, 130 °C. [b] Conversion of 1-phenylethanol. [c] Yield of acetophenone. [d] Selectivity for acetophenone. [e] Carbon balance calculated including also the amounts of observed by-products (styrene and ethylbenzene). [f] Reaction performed in N_2 flow (10 mL/min).

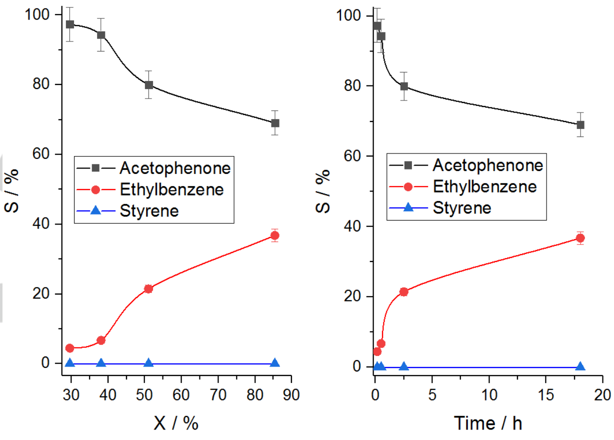
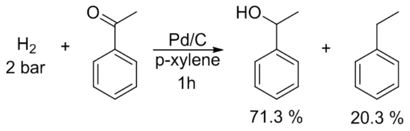
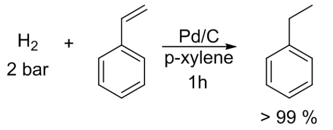


Figure 2. Left. Selectivity (*S*) for; i) acetophenone (squares), ii) ethylbenzene (circles), and styrene (triangles) as a function of 1-phenylethanol conversion (*X*). **Right**. Time on line profile of selectivity for i) acetophenone (squares), ii) ethylbenzene (circles), and iii) styrene (triangles). Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 20 mL of a solution 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, static N_2 atmosphere, 130 °C.

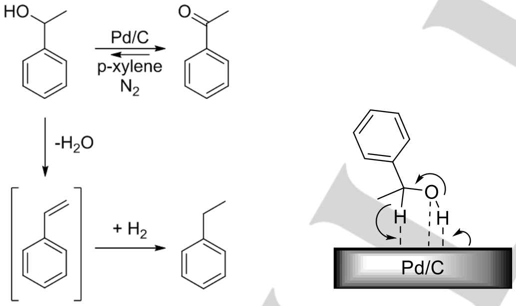
Analysis of the liquid phase after reaction was also performed, in order to allow the by-products produced at high conversion to be identified. In addition to confirming the absence of benzoic acid, this analysis revealed that under static N_2 atmosphere, the quantity of acetophenone lost at high conversion was comparable to the amount of ethylbenzene formed (Figure 2). The presence of ethylbenzene is in agreement to reactant stability studies, performed by conducting the hydrogenation of acetophenone and styrene in an autoclave filled with H_2 (2 bar) and Pd/C as catalyst (Scheme 2). Following 1 hour of acetophenone hydrogenation, a 1-phenylethanol yield of 71.3 %, and ethylbenzene yield of 20.3 %, was detected. This indicates that at high quantities of H_2, the reverse hydrogenation, accompanied by the formation of 1-phenylethanol occurs. Although no styrene was found into the reaction mixture (Scheme 2), it may still be involved in the reaction mechanism as an intermediate with a short lifetime, *i.e.* this compound may be formed from the dehydration of 1-phenylethanol, which rapidly undergoes hydrogenation to ethylbenzene. Therefore, stability studies using styrene as substrate were also performed. During these, quantitative conversion of styrene into ethylbenzene was reached in only one hour of reaction (Scheme 3). Notably, the formation of ethylbenzene may also arise from direct hydrogenolysis of 1-phenylethanol and/or acetophenone catalysed by the Pd-containing catalyst.[8] These side reactions indicate the detrimental effect that excessive quantities of H_2 exert on the reaction. Hence, working under conditions that remove H_2 from the reactor, and/or working at low conversion conditions, is beneficial for the overall reaction selectivity. Based on these observations, all further kinetic studies were performed at short reaction times and lower conversion levels, to limit the contribution of the side reactions to the kinetic parameters and catalyst optimisation studies. Moreover, experiments were performed under static conditions to continue to permit measurement of the gaseous phase of the reaction.



Scheme 2. Acetophenone hydrogenation catalysed by Pd/C. Autoclave reactor (Parr® 5500) with 100 mL glass liner. Reaction conditions: 20 mL of a 0.2 M solution of acetophenone in toluene and 0.08 mol % of Pd/substrate molar ratio, 130 ˚C. Reaction performed with 2 bars of H_2.



Scheme 3. Styrene hydrogenation catalysed by Pd/C. Autoclave reactor (Parr® 5500) with 100 mL glass liner. Reaction conditions: 20 mL of a solution 0.2 M of styrene in toluene and 0.08 mol % of Pd/substrate molar ratio, 130 ˚C. Reaction performed with 2 bars of H_2.



Scheme 4. Proposed reaction pathway and proposed intermediate species for 1-phenylethanol dehydrogenation over Pd/C.

Having identified the optimal kinetic regime of the reaction, and ensuring a negligible contribution of side reactions to the reaction network, an accurate Arrhenius plot was obtained by measuring the initial rate of the reaction (k) in the linearity range true kinetic conditions, an activation energy of 98.8 kJ/mol was determined, in better agreement to the nature of the reaction (Figure 3). Extending the Arrhenius analysis over a larger range of temperature demonstrates the barrier is consistent over a temperature range of 90-130 ˚C.

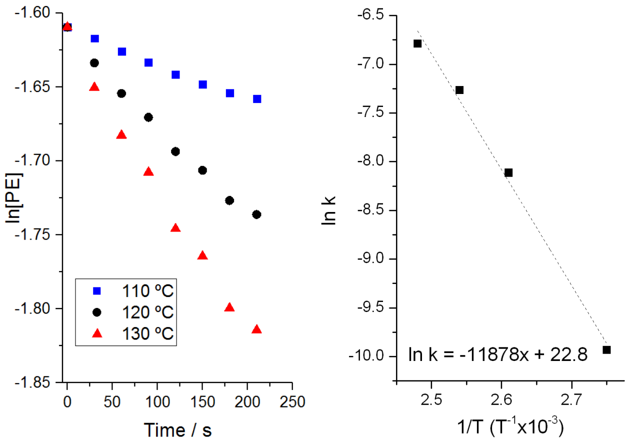


Figure 3. Left. ln of [1-phenyletanol] over time at different temperatures (110-130°C). **Right.** Arrhenius plot obtained in a temperature range of 90-130°C. Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 20 mL of a solution 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, static N_2 atmosphere.

Following these kinetic insights, more detailed attention was paid to the mechanism of the reaction, since very little is known about acceptorless dehydrogenation chemistry, especially over heterogeneous catalysts. In order to identify the nature of the reaction intermediate, a Hammett correlation was obtained, using substituted benzyl alcohols as substrates, due to the greater commercial availability of substituted benzylic alcohols. As can be seen (Figure 4 (Left)), the acceptorless dehydrogenation of benzyl alcohol and its *p*-substituted analogues, 4-methylbenzyl alcohol and 4-chlorobenzyl alcohol, indicates that electron donating substituents ($\sigma < 1$), such as -CH_3, lead to increased activity. On the other hand, electron withdrawing groups ($\sigma > 1$), such as -Cl, exhibit a negative impact on the reaction rate. The negative slope of the Hammett plot strongly indicates the formation of a positively charged reaction intermediate, suggesting the formation of a carbo-cationic intermediate during the reaction.

Additional mechanistic insights on the reaction mechanism was obtained by deuteration of the benzylic H-atoms of the substrate (KIE). As can be seen (Figure 4 (Right)), a lower reaction rate (k) was observed when benzylic C-D bonds are present over C-H bonds. Since KIEs greater than 1 usually indicate that cleavage of that bond is involved in the rate determining step of the reaction, this indicates that cleavage of the benzylic C-H/D bond may be rate limiting. However, it is notable that the observed KIE is lower than that typically observed for reactions limited by the rate of C-H bond cleavage, although they are in line with the values observed for acceptorless dehydrogenation over homogeneous Pd complexes.[3d,3e] The relatively low KIE values observed in these systems could be due to second order effects – where the H/D substitution in question is not directly involved in the rate limiting step – or the involvement of the H/D atom in a different rate limiting step, such as elimination of the H/D atom from the Pd surface to regenerate the active site. Nevertheless, the negative Hammett correlation, coupled with a KIE > 1, indicates that the acceptorless dehydrogenation reaction possesses some similarities to classical beta-hydride elimination mechanisms, often observed during aerobic alcohol oxidation.[9]

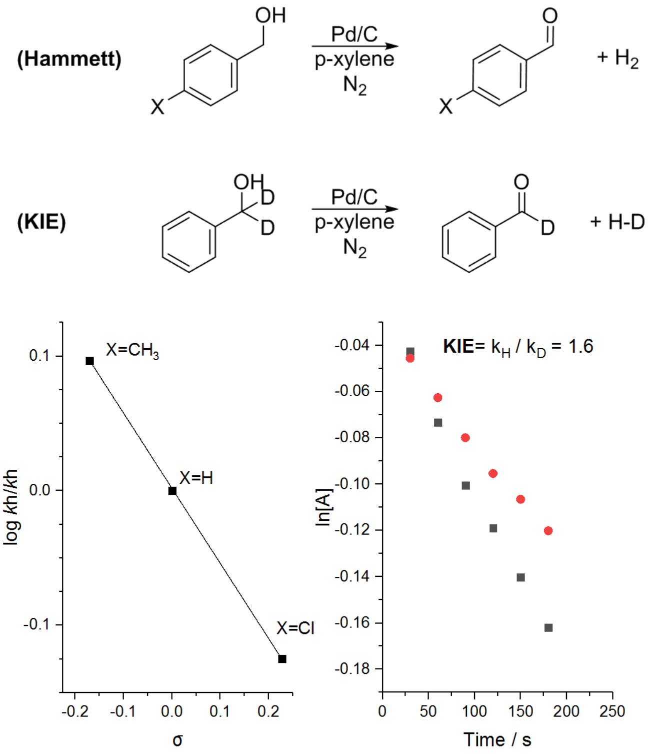


Figure 4. Left. Hammett plot obtained from substituted benzyl alcohol dehydrogenation to acetophenone over Pd/C. **Right.** Reaction rate for benzyl alcohol (squares) and α,α-deuterated benzyl alcohol (circles). Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 20 mL of a solution 0.2 M of substrate in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, 0.16 hours, 130 ºC, static N_2 atmosphere.

Following mechanistic and kinetic evaluation of the system, preliminary catalyst optimisation studies were performed by examining the effect of the oxidation state of the metal (Pd) on the reaction rate. To do so, the catalyst was subjected to a series of heat treatments in reducing atmosphere (5% H_2 in Ar), or oxidising conditions (air). Notably, although treatments in H_2 at 400 °C did not affect the C support, analogous treatment in air at 400 °C led to decomposition of the support (ESI Figure S5-6). Therefore, the optimal temperatures were found to be 400 °C for the H_2 treatment and 300 °C for the air treatment. As shown in Figure 5, although treating the catalyst in air for 2 hours at 300°C was beneficial for the catalytic performance of Pd/C (from 29.5 % conversion to 33.1 % following air treatment), a loss in selectivity for acetophenone occurred (from 97.3 % to 87.6 %). An opposite effect was observed calcining the catalyst under reducing atmosphere, as lower conversion values were achieved but higher acetophone selectivity observed (> 98 %). However, we note these differences may also be (partially) related to the natural conversion *vs.* selectivity relationship of the reaction (Figure 2, Left).

To correlate the observed trends in selectivity and activity as a function of pre-treatment, and hence with differences in Pd speciation and material composition and structure, selected catalysts were characterised *via* X-Ray Diffraction (XRD), X-ray Photoelectron Spectroscopy (XPS), Transmission Electron Microscopy (TEM) and Brunauer-Emmett-Teller (BET) analysis.

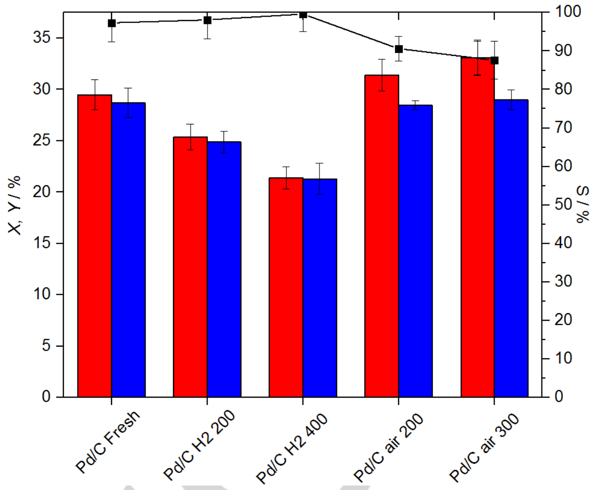


Figure 5. Conversion (*X*) of 1-phenylethanol (red bars), yield (*Y*) of acetophenone (blue bars) and selectivity (*S*) for acetophenone (black squares) for: a) fresh Pd/C (*i.e.* not treated), Pd/C heated in 5 % H_2 in Ar for 2 hours (ramp rate 10 °C/min) b) at 300 °C, c) at 400 °C, and Pd/C heated under air for 2 hours (ramp rate 10 °C/min) d) at 200 °C, and e) at 300 °C. Reaction conditions: stainless steel reactor body with 100 mL pressurised round bottom flask. 20 mL of a solution 0.2 M of 1-phenylethanol in *p*-xylene, 0.08 mol % of Pd/substrate molar ratio, 130 ºC, static N_2 atmosphere, 0.25 hours.

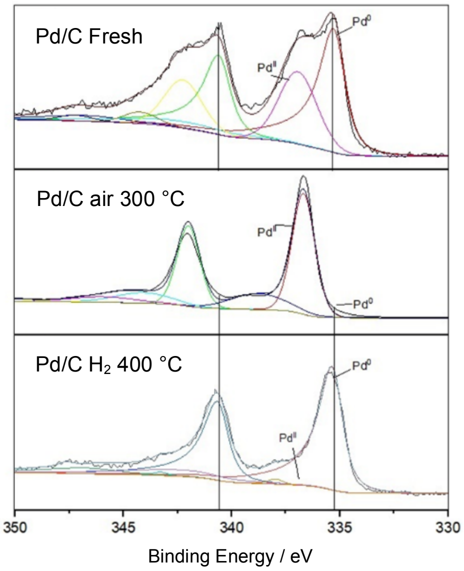


Figure 6. XPS analysis for: a) fresh Pd/C (*i.e.* not treated), b) Pd/C heated at 300 °C under air for 2 hours (ramp rate 10 °C/min), and c) Pd/C heated at 400 °C in 5 % H_2 in Ar for 2 hours (ramp rate 10 °C/min).

To analyse the Pd speciation, XPS analysis was performed. As expected, although a mix of oxidation states was found in the untreated Pd/C catalyst (37.1 % Pd^{II}, 62.9 % Pd^0), a predominance of Pd^{II} was found on Pd/C heated in air at 300 °C (73.9 % Pd^{II}, 26.1 % Pd^0) whilst mostly Pd^0 was found on Pd/C heated in H_2 at 400 °C (1.7 % Pd^{II}, 98.3 % Pd^0). Interestingly, although large differences in Pd speciation were observed in this series of catalysts, each of these materials exhibits high activity for acceptorless 1-phenylethanol dehydrogenation. This may be due to both oxidation states being active for this reaction, and/or interconversion between Pd^{II} and Pd^0 readily occurring during

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the reaction itself. More detailed comparison of the initial rates of each reaction, achieved by monitoring the gas evolution with time, shows that lower initial rates (k) are observed for catalysts possessing higher initial percentages of Pd^0 (Table 4), indicating that Pd^0 may catalyse 1-phenylethanol dehydrogenation to a lower degree than Pd^{II}. This is in contrast to the dehydrogenation of formic acid over the same catalyst, where metallic Pd^0 has routinely been proposed to be the most active form of Pd.[10] Notably, XRD analysis is in good agreement to the XPS analysis (ESI Figure S5), showing different distribution between metallic Pd and Pd oxide to be present on these catalysts, in analogy with the results displayed in Table 4.

Table 4. Correlation between amount of Pd^0 and initial rate for 1-phenylethanol dehydrogenation over Pd/C fresh (*i.e.* non-treated), and following different heat treatments.

Catalyst	%Pd^0 [a]	k x 10^{-3} (s) [b]
Pd/C Fresh	62.9	1.09
Pd/C H_2 200 °C	78.1	0.90
Pd/C H_2 400 °C	98.3	0.82
Pd/C air 200 °C	49.1	1.13
Pd/C air 300 °C	26.1	1.14

[a] Relative percentage of Pd^0 on the overall Pd, measured *via* deconvolution of XPS spectra [b] Initial reaction rate (ESI Figure S7)

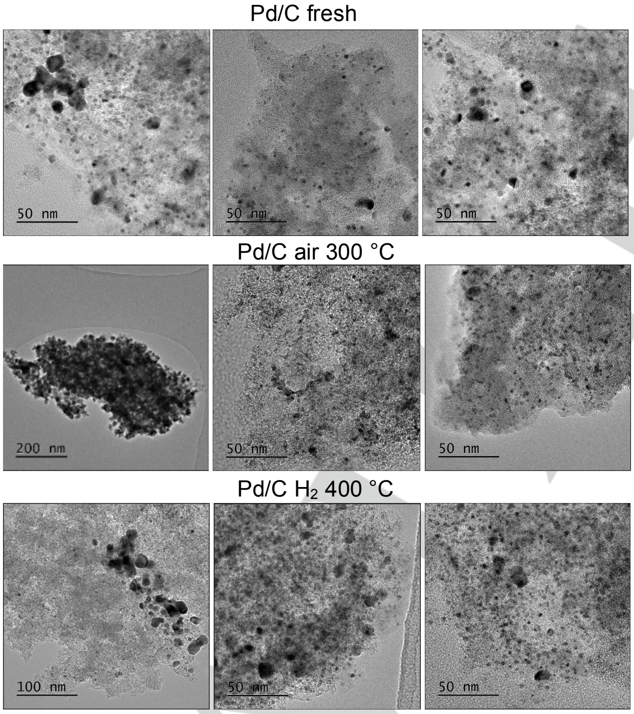

Figure 7. TEM images for: a) fresh Pd/C (*i.e.* not treated), b) Pd/C heated at 300 °C under air for 2 hours (ramp rate 10 °C/min), and c) Pd/C heated at 400 °C in 5 % H_2 in Ar for 2 hours (ramp rate 10 °C/min).

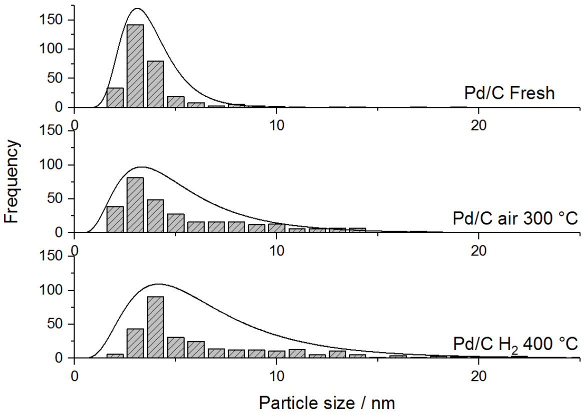

Figure 8. Particles size distribution for: a) fresh Pd/C (*i.e.* not treated), b) Pd/C heated at 300 °C under air for 2 hours (ramp rate 10 °C/min), and c) Pd/C heated at 400 °C in 5 % H_2 in Ar for 2 hours (ramp rate 10 °C/min).

In addition to oxidation state, variation in activity may also arise from several other parameters related to the material surface and structure, as well as variations of the Pd particle size. In fact, heat treatment often affects the particles size distribution of supported nanoparticles, due to agglomeration (sintering) of the particles.[3c] Accordingly, TEM analysis was also performed on this series of catalysts. As can be seen (Figures 7,8), the untreated catalyst possesses a relatively narrow distribution of Pd nanoparticles with a mean size of 3.5 nm, an increase in the Pd particle size distribution was found for both heattreated samples. However, although there is a net agglomeration of Pd in both heat treated catalysts, the extent of agglomeration is comparable in both H_2 and air atmospheres, and is unlikely to explain the different kinetic capabilities of these samples.

To further investigate structural changes potentially occurring on the surface of the catalyst, BET analysis was also performed. However, no major variation to the catalyst surface area occurs following the heat treatments (ESI Table S1), with all catalytic materials possessing surface areas of approximately 900 m^2 g^{-1}, regardless of the choice of heat treatment.

Alongside activity and selectivity, the durability of a heterogeneous catalyst also plays a key role in its potential applicability. In order to perform an accurate investigation of the durability of the material, and hence, gain preliminary understanding of the scalability of the process, the catalytic performance of Pd/C was studied under continuous flow conditions using a Plug Flow Reactor (PFR), under otherwise analogous conditions to the batch experiments. When employed in continuous mode, Pd/C displayed good activity for 1-phenylethanol dehydrogenation with acetophenone selectivity > 80 % (Figure 9 and ESI Figure S8) observed. Although some losses in activity are observed over the first 24 h on stream, the system reaches steady state conditions thereafter, indicating the longer term durability of Pd/C for continuous operations. XPS analysis of the catalyst after 48 h on stream indicates that the relative content of Pd^0 increases from 62.9 % (fresh sample) to 88.6 % during this period of operation, indicating that reduction of Pd occurs *in situ*. This may be the reason for the initial loss of activity over the first 24 h, prior to steady state being achieved, since Pd^0 has been shown to be less intrinsically active than Pd^{II}

(Table 4). However, we note that several other phenomena, such as poisoning, pore fouling and active site reorganisation, may also contribute to the initial drop of activity. However, these studies indicate that long term dehydrogenation is clearly feasible, even in the absence of acceptors and bases, and that the reaction is accompanied by the continuous production of high purity H_2. Notably, this preliminary result yields a maximum space-time-yield (STY) of 0.683 $g_{(product)}$ mL^{-1} h^{-1} being achieved, which is over two orders of magnitude higher than the ones calculated for the best catalysts reported in the literature (Ag/hydrotalcite) to date, indicating the high viability of Pd/C as a heterogeneous catalyst for alcohol dehydrogenation. In addition to 1-phenylethanol and substituted benzyl alcohols, preliminary studies on the general applicability of the system were made by substituting 1-phenylethanol for a smaller, non-aromatic substrate, 2-butanol. Interestingly, Pd/C was also able to continuously perform 2-butanol dehydrogenation to 2-butanone in the continuous regime, albeit at slightly higher temperature (200 °C). Alongside 1-phenylethanol and the substituted benzylic alcohols, this substrate further indicates the general suitability of Pd/C-catalysed dehydrogenation in continuous operational mode.

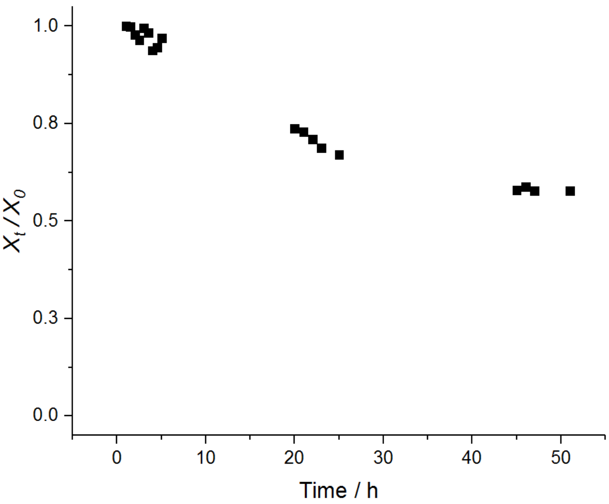

Figure 9. Continuous 1-phenylethanol dehydrogenation reactions in PFR. Relative performance for Pd/C-catalysed 1-phenylethanol dehydrogenation (X_t/X_0) over time on stream. For details see Experimental Section.

Table 4. Comparitive performance of Pd/C and Ag/hydrotalcite.

Catalyst	Substrate	STY ($g_{(product)}$ mL^{-1} h^{-1})[a]
Ag/hydrotalcite[5c]	1-phenylethanol	2.2×10^{-3}[b]
Pd/C	1-phenylethanol	0.683
Pd/C	2-butanol[c]	0.010

[a] STYs calculated at maximum conversion as grams of reactant converted per mL (reactor volume), per hour. Volume of catalyst bed used as the reactor volume [b] Only the liquid volume was used as the reactor volume. [c] Reaction condition identical to the ones used for 1-phenylethanol, albeit at 200 °C.

Conclusions

Commercially available 5 wt. % Pd/C is demonstrated to be a suitable catalyst for the acceptorless dehydrogenation of alcohols, such as 1-phenylethanol, in inert atmosphere (N_2). In addition to displaying STY values over two orders of magnitude higher than the ones found in literature, the acceptorless nature of the reaction results in the co-production of molecular H_2. The intrinsic activity of the catalyst (TOF) was found to be amongst the highest in the literature, reaching a maximum of 1475 h^{-1}. Full kinetic analysis of all the reaction products and kinetic parameters, including the gaseous product, was achieved following design of a novel batch reactor. Accurate kinetic analyses were performed, and an activation energy of 98.8 kJ/mol was found, alongside a negative Hammett correlation and a Kinetic Isotope Effect > 1, indicating that the reaction possesses mechanistic similarities to beta-hydride elimination aerobic oxidation mechanisms. Preliminary structure-activity relationships, performed with kinetics, XPS, XRD, TEM and BET, reveal Pd/C calcined in air at 300 °C to be the optimal catalyst for acceptorless dehydrogenation. Experiments in the continuous regime also the durability of the catalyst over 48 hours on stream, resulting in space-time-yields up to 0.683 $g_{(product)}$ mL^{-1} h^{-1}, over two orders of magnitude higher than the ones found in literature up to date. Alongside its high TOF, the extremely high space-time-yield of the system clearly demonstrate the favourability of the system for acceptorless dehydrogenation.

Experimental Section

All substrates were obtained from commercial sources and used without purification. Fresh Pd/C (5 wt. %) was obtained from Sigma Aldrich® and used without further modifications.

Heat treatments: All heat treatments were performed in a tube furnace. In a typical heat treatment, Pd/C was loaded into a calcination boat and subjected to heat treatment at temperatures varying between 200 – 400 ˚C at a ramp rate of 10 ˚C/min under flowing air. For reduction, an identical procedure was performed albeit under 5% H_2 in Ar.

Experimental procedure for 1-phenylethanol dehydrogenation in batch using a borosilicate glass flask: Pd/C-catalysed dehydrogenation reactions were performed at a range of temperatures between 100-120 °C using a three neck 100 mL round bottom flask. The flask was charged at room temperature with 20 mL of a solution of 1-phenylethanol in *p*-xylene (0.2 M) and various amounts of Pd/C (5 Pd wt. % from Sigma Aldrich®) in the range 0-1.25 mol % Pd/1-phenylethanol molar ratio (0-106.8 mg of Pd/C). The round bottom flask was equipped with a condenser and glass cap adaptors and connected to a N_2 line. The N_2 flow was controlled using a mass flow controller. For all reactions, the flask was purged with a N_2 flow of 50 mL/min for 6 min. The flow was then decreased to 10 mL/min of N_2 and the flask was introduced in the oil bath and pre heated at the desired temperature. The reaction was then initiated by switching on the magnetic stirring (750 rpm). After the reaction, the flask was cooled down to room temperature, the catalyst was recovered by filtration and each sample was prepared by adding 100 μL of reaction solution to 900 μL of a solution of biphenyl in toluene (0.01 M), which acts as external standard. The samples were analysed by a Gas Chromatograph (GC) (Agilent 7820) equipped with a 25 m CP-Wax 52 CB capillary column and a Flame Ionisation Detector (FID), with He as carrier gas (5 mL min^{-1}). The concentrations of acetophenone and 1-phenylethanol were obtained by previous GC calibration with the respective standards.

Experimental procedure for 1-phenylethanol dehydrogenation in batch using a stainless steel reactor body with a pressurised connection vessel (ESI Figure S4): Pd/C-catalysed dehydrogenation reactions were performed at a range of internal temperatures between

110-130 °C using a one neck 100 mL Ace round-bottom pressure flask with an Ace-Thred 15 PTFE front-seal plug. The flask was charged at room temperature with 20 mL of a solution of 1-phenylethanol in p-xylene (0.2 M) and 7.2 mg of 5 wt. % Pd/C (0.08 mol % Pd). The flask was connected to a stainless steel body reactor, placed into an oil bath, connected to a burette and to a N_2 line with a mass flow control (see ESI Figure S4). For all reactions, the flask was purged with a flow of 50 mL/min of N_2 for 10 min at room temperature. When H_2 measurement was required, the flow was then stopped for the reaction to be carried out under static N_2 atmosphere. For experiments with N_2 flow, the reaction was carried out using a N_2 flow rate of 10 mL/min. The flask was introduced into the oil bath and pre heated at the desired temperature for 15 min. The reaction was then initiated by switching on the magnetic stirring (750 rpm). For kinetic studies, the gas produced during the reactions was collected in the burette allowing the quantification of the H_2 produced. Aliquots of gas sample were then collected and analysed by Mass Spectrometry (MS). Analysis of the liquid samples was performed analogously to the procedure described in the previous section (General procedure for 1-phenylethanol dehydrogenation in batch using a borosilicate glass flask). Theoretical gas volumes was calculated from the ideal gas equation (PV=nRT) considering n=moles of acetophone produced, T = 22 ºC, P=1 atm.

Hot filtration: During the first part of the hot filtration experiment, a general reaction with the solid catalyst, as described earlier was initiated. After 5 min of reaction, the reaction mixture was withdrawn, and the solid catalyst was removed by filtration. The filtered reaction mixture was then added into another flask equipped with a magnetic stirrer, purged with a flow of 50 mL/min of N_2 for 10 min at room temperature and heated again. The reaction was then continued by switching on the magnetic stirring, this time in the absence of the solid catalyst (dotted line Figure S2). After an appropriate length of time, the reaction solution was then analysed again to determine any differences in substrate conversion or product yield in the absence of the solid catalyst.

General procedure for 1-phenylethanol dehydrogenation in Plug Flow Reactor (PFR): Continuous 1-phenylethanol dehydrogenation reactions were performed in a home-made, tubular, stainless steel, PFR. Reactant delivery (0.19 M of a solution 1-phenylethanol in toluene) was performed by an HPLC pump. The catalyst, 5 wt. % Pd/C (0.08 g) was placed in between two plugs of quartz wool and densely packed into a 1/4 inch stainless steel tube (3.8 mm ID), and a frit (0.5 mm) was placed at the end of the bed to avoid any loss of material. A contact time of 0.45 min was employed. The reactor temperature was controlled by immersion in an oil bath, and the pressure was controlled by means of a backpressure regulator. Aliquots of the reaction solutions were taken periodically from a sampling valve placed after the backpressure regulator, and were analysed in the same manner as the batch reactions.

Gas Chromatography: For liquid sample analysis, a GC (Agilent 7820) equipped with a 25 m CP-Wax 52 CB column and an FID (at 250 °C), was employed, using He (5 mL/min) as carrier gas. Quantification of the analytes was carried out against biphenyl as external standard. For all samples the following temperature programme was used: Hold at 40 °C for 5 minutes, ramp at 20 °C/min to 210 °C and hold at 210 °C for 5 minutes.

Mass Spectrometry (MS): Gas samples were analysed by a mass spectrometer (Hiden Analytical Quadrupole Gas Analyzer (QGA)) equipped with an inert quartz capillary with a consumption rate of 16 mL/min and Faraday electron multiplier detector capable of detecting concentrations between 0.1 ppm to 100 %. QGA Professional Software was used to quantify the partial pressures as a function of the M/Z ratio.

Powder X-Ray Diffraction (pXRD): pXRD patterns were recorded on a PANalytical X'Pert PRO X-ray diffractometer, with a Cu Kα radiation source (40 kV and 30 mA) and Ni filter. Diffraction patterns were recorded between 5-80° 2θ at a step size of 0.0167° (time/step = 150 s, total time = 1.5 h).

N_2 physisorption analysis: The surface area of the catalysts was measured using N_2 physisorption. Each sample was evacuated for 3 hours at 120 °C using a Quantachrome Quadrasorb SI instrument. Following evacuation, surface area analysis was performed and subsequently calculated using BET theory over the range P/P0 = 0-1.

Transmission Electron Microscopy (TEM): Samples for examination by TEM were prepared by dispersing the catalyst powders in high purity ethanol using ultra-sonication. 40 µl of the suspension was dropped on to a holey carbon film supported by a 300 mesh copper TEM grid before the solvent was evaporated. The samples for TEM were then examined using a JEOL JEM 2100 TEM model operating at 200 kV.

X-Ray Photoelectron Spectroscopy (XPS): XPS analysis was performed on a Thermo Scientific K-Alpha+ spectrometer. Samples were analysed using a monochromatic Al X-ray source operating at 72 W (6 mA x 12 kV), with the signal averaged over an oval-shaped area of approximately 600 x 400 microns. Data was recorded at pass energies of 150 eV for survey scans and 40 eV for high resolution scan with a 1 eV and 0.1 eV step size respectively. Charge neutralisation of the sample was achieved using a combination of both low energy electrons and argon ions (less than 1 eV) which gave a C(1s) binding energy of 284.8 eV. All spectra were analysed using CasaXPS (v2.3.17 PR1.1) using Scofield sensitivity factors and an energy exponent of -0.6.

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Keywords: alcohol oxidation • dehydrogenation • hydrogen storage • heterogeneous catalysis • nanoparticles

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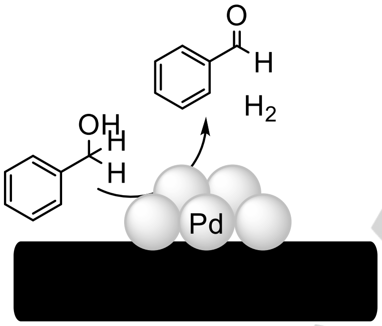

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Acceptorless alcohol dehydrogenation catalysed by Pd/C

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