Acceptorless Alcohol Dehydrogenation Catalysed by Pd/C

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Although the selective oxidation of alcohols to carbonyl compounds is a critical reaction, it is often plagued by several challenges related to sustainability. Here, the continuous, acceptorless dehydrogenation of alcohols to carbonyl compounds over heterogeneous catalysts was demonstrated, in the absence of oxidants, bases or acceptor molecules. In addition to improving selectivity and atom efficiency, the absence of an acceptor resulted in the co-production of molecular H_2, a clean energy source, and permitted dehydrogenation to proceed at >98 % selectivity at turnover frequency values amongst the highest in the literature. Moreover, excellent durability was 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, the basic kinetic parameters of the reaction were also determined, allowing some of the elementary reaction steps to be identified.

Introduction

The synthesis of carbonyl compounds through alcohol oxidation is one of the most important chemical reactions in organic synthesis, owing to the key role played by ketones and aldehydes as building blocks 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, the use of such oxidants dramatically affects the sustainability of these processes, through the co-production of stoichiometric amounts of waste, and by decreased atom efficiency. Accordingly, much effort has been devoted to 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 by using molecular O_2 as a benign oxidant, that is, 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 a byproduct.[4, 5] Although far less explored, this last route (acceptorless dehydrogenation) is especially desirable for a number of reasons, the most notable of which include the parallel production of H_2, highly valuable as a sustainable source of energy,[6] and the increased selectivity towards the desired carbonyl compound, which is often readily over-oxidised to the undesired carboxylic

acid in the presence of O_2.[3c] Moreover, Gunanathan and Milstein have demonstrated recently 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 through acceptorless dehydrogenative coupling).[4c]

Owing to the potential of this approach, several attempts have been made to develop catalysts capable of mediating the reaction. Much focus has been placed upon homogeneous catalysts. However, these typically require the use of several additives (thus decreasing atom efficiency), or the use of scarce 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 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, m] Co,[5h] Pt,[5j] Re[5f] and Ru[5a, b] 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 identification of a detailed reaction mechanism. Finally, the viability of this reaction to operate in a continuous manner has yet to be studied although this is an essential requirement for intensification purposes. Combined, these disadvantages limit the favourability and sustainability of this method and make the rational improvement of catalytic activi-

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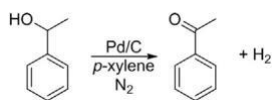http ://blogs.cardiff.ac.uk/hammond/

ty 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 that this commercial catalyst can convert alcohols such as 1-phenylethanol quantitatively to the corresponding carbonyl compound with >98 % selectivity under optimised reaction conditions and concurrently release molecular H_2 at a 1:1 molar ratio. The TOF values of the catalyst reach 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 litera-ture (Ag supported on hydrotalcite)[5c] and is active for over 48 h on stream. We also report a novel type of reactor that allows time-on-line collection and measurements of the H_2 produced during reaction. By using this reactor, detailed kinet-ic investigation of the model reaction (1-phenylethanol dehy-drogenation to acetophenone) is achieved, providing hitherto inaccessible insights into the reaction mechanism(s).

Results and Discussion

Preliminary kinetic measurements

Building on our previous work on formic acid dehydrogena-tion, in which commercial palladium on carbon (Pd/C from Sigma–Aldrich, 5 wt % Pd) exhibited the best catalytic perform-ances for H_2 generation, we also identified Pd/C as a suitable choice of catalyst for the acceptorless dehydrogenation of 1-phenylethanol to acetophenone. Kinetic studies were first per-formed with Pd/C as catalyst in a N_2 atmosphere, under condi-tions comparable to those described in various reports in the literature. Preliminary time-on-line analysis, performed at a Pd/ substrate ratio of 1:80 (1.25 mol % Pd), showed that after 3 h reaction, over 90 % of the substrate was converted into the de-sired product. Notably, an acetophenone selectivity of >95 % was observed throughout the reaction period, indicating that the dehydrogenation of 1-phenylethanol can be catalysed effi-ciently by Pd/C in N_2 (Scheme 1).

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

Interestingly, the Arrhenius plot constructed by measuring the initial rate of reaction (k) between 100 and 120 8C gave an activation energy of only 31 kJ mol^{-1} (Figure S1 in the Support-ing Information). Considering that the cleavage of a $C(sp^3)$ H bond should be involved in the reaction mechanism, the ex-

tremely low barrier obtained indicates contributions from other factors, particularly mass transfer. Therefore, further stud-ies were performed to ensure that the amount of catalyst em-ployed was low enough to perform the reaction under the ki-netic regime. Accordingly, the amount of Pd relative to phenyl-ethanol (mol %) was varied from to 0 to 1.25 mol % (Figure 1, right). 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 mol % Pd. Thus, to maintain kinetic integrity, 0.08 mol % was chosen as the amount of catalyst for all further catalytic reactions. Addi-tional optimisation experiments were also performed (Fig-ure S2 in the Supporting Information), suggesting that stirring at rates above 250 rpm was also essential to avoid mass-trans-fer limitations.
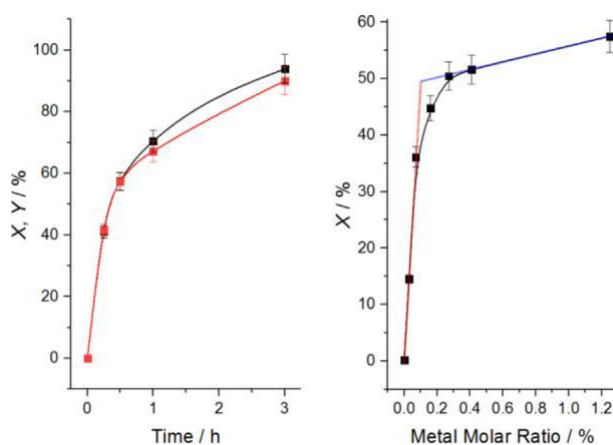
Figure 1. Left: Conversion (X) of 1-phenylethanol, and yield (Y) of acetophe-none over time. Right : Initial (0.5 h) X of 1-phenylethanol as a function of metal molar ratio (moles Pd/moles 1-phenylethanol 0 100). Reaction condi-tions : solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m), 120 8C. Reac-tion performed under N_2 flow of 10 mL min^{-1}. 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 h.

To ensure that the reaction was truly heterogeneously cata-lysed, that is, that no contribution to the reaction rate derived from homogeneous species leached into the reaction mixture, we performed a "hot filtration" experiment, for which the cata-lyst was filtered from the solution during the reaction, and the residual activity of the supernatant solution following removal of the catalyst was analysed (Figure S3 in the Supporting Infor-mation). Following filtration of the solid catalyst, no further changes to the solution (1-phenylethanol conversion and ace-tophenone 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 benefi-cial because of the co-production of H_2, which is a valuable by-product. Therefore, accurate analysis of the gas produced throughout 1-phenylethanol dehydrogenation is essential for performing thorough kinetic and mechanistic studies of alco-hol dehydrogenation, confirming the formation of H_2 as the re-action product, and verifying that the reaction is truly accept-

orless. However, under typical literature conditions, that is, 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 (Figure S4 in the Supporting Information). Equipped with this setup, the volume and composition of the gas formed during reaction was monitored periodically at three different temperatures, in the range 110–130 $°$C. In all cases, the amount of gas collected during the first 10 min of reaction was in good agreement with 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, analysis of the liquid phase at the end of the reaction also allows the determination of substrate conversion and product yields for all liquid products.

Table 1. Catalytic performances of Pd/C at different temperatures.[a]						
$T_{[a]}$ [$°$C]	$X_{[b]}$ [%]	$Y_{[c]}$ [%]	$S_{[d]}$ [%]	$CB_{[e]}$ [%]	$V_{theor.}^{[f]}$ [mL]	$V_{coll.}^{[g]}$ [mL]
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 1-phenylethanol in p-xylene, 0.08 mol % Pd/substrate molar ratio, static N_2 atmosphere, 10 min. [b] Conversion of 1-phenylethanol. [c] Yield of acetophenone. [d] Selectivity for acetophe-none. [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 the gaseous and liquid phases, this approach also permits the acceptorless nature of the dehydrogenation reaction to be confirmed. To this end, the gas produced during the dehydrogenation of 1-phenylethanol was collected over a reaction time of 1 h (43 mL gas collected) and analysed by MS (Table 2). Compositional analysis of the collected gas indicated 24.4 mol % H_2 present in the gas mixture. To ensure that the produced H_2 is derived from dehydrogenation of the substrate,

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 1-phenylethanol in p-xylene, 0.08 mol % Pd/substrate molar ratio, static N_2 atmosphere, 1 h. [b] No 1-phenyletha-nol.

we performed a control experiment in which the reaction was conducted under typical reaction conditions but without the substrate. As expected, only trace amounts of H_2 were detect-ed (0.08 mol %), indicating 1-phenylethanol to be the source of the H_2.

The relatively high molar percentage of H_2 detected in the gas phase, in addition to the good catalytic performances ex-hibited by the catalyst, strongly indicates that acceptorless al-cohol dehydrogenation can be catalysed efficiently by Pd/C in a N_2 atmosphere. Notably, the employment of an inert gas dra-matically reduces the over-oxidation problems typically ob-served during aerobic alcohol oxidation,[3c] leading to higher selectivity values for the carbonyl compounds. However, per-forming the reaction for prolonged periods (18 h) under opti-mised reaction conditions resulted in a drop in selectivity from 97.6 to 69.0 %, suggesting the presence of side reactions at elevated levels of conversion and low masses of catalyst. In parallel with this drop in selectivity, the amount of substrate converted at extended periods was lower than anticipated from the initial rate of reaction (from 29.6 % conversion at 0.16 h to only 51.0 % at 2.5 h). This result is in agreement with previous reports suggesting the reversibility of the process,[7] that is, regeneration of the substrate following the hydrogena-tion of acetophenone.

To study the negative effect of H_2 accumulation on the reac-tion, we first performed experiments to investigate the role played by gas flow, that is, the static N_2 atmosphere was re-placed with N_2 flow (Table 3) to remove H_2 from the reaction mixture following its formation. Performing the reaction under N_2 flow (10 mL min^{-1}) affected the reaction dramatically, in-creasing 1-phenylethanol conversion and acetophenone yield and boosting acetophenone selectivity to 98.4 %, strongly indi-cating that excessive quantities of H_2 impact the selectivity, es-pecially at high conversion.

Analysis of the liquid phase after reaction was also per-formed to allow the identification of byproducts produced at high conversion. In addition to confirming the absence of ben-zoic acid, this analysis revealed that under static N_2 atmos-phere, 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 with

Table 3. Effect of N_2 flow on 1-phenylethanol dehydrogenation catalysed by Pd/C.[a]				
t [h]	$X_{[b]}$ [%]	$Y_{[c]}$ [%]	$S_{[d]}$ [%]	$CB_{[e]}$ [%]
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 pressur-ised round-bottom flask, 0.2 m 1-phenylethanol in p-xylene, 0.08 mol % Pd/substrate molar ratio, static N_2 atmosphere, 130 $°$C. [b] Conversion of 1-phenylethanol. [c] Yield of acetophenone. [d] Selectivity for acetophe-none. [e] Carbon balance calculated including also the amounts of ob-served byproducts (styrene and ethylbenzene). [f] Reaction performed in N_2 flow (10 mL min^{-1}).
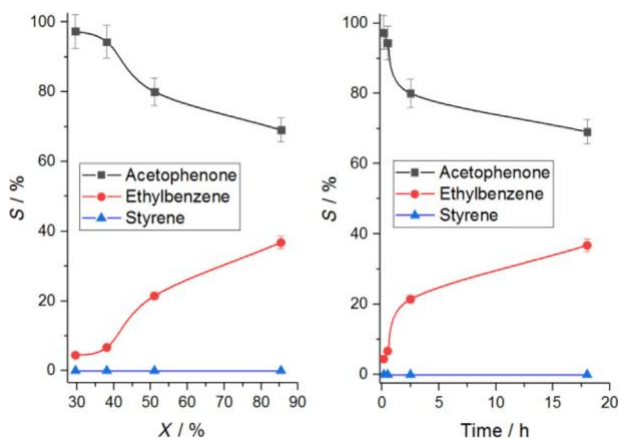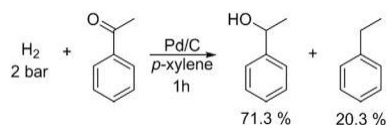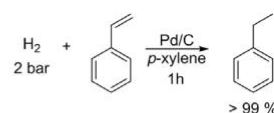
Figure 2. Left: Selectivity (S) for acetophenone (squares), ethylbenzene (circles), and styrene (triangles) as a function of 1-phenylethanol conversion (X). Right : Time-on-line profile of selectivity for acetophenone (squares), ethylbenzene (circles), and styrene (triangles). Reaction conditions: stainless-steel reactor body with 100 mL pressurised round-bottom flask. solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m), 0.08 mol % Pd/substrate molar ratio, static N_2 atmosphere, 130 8C.

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 acetophenone hydrogenation for 1 h, yields of 71.3 % 1-phenylethanol and 20.3 % ethylbenzene were detected. This indicates that at high quantities of H_2, the reverse hydrogenation occurs,
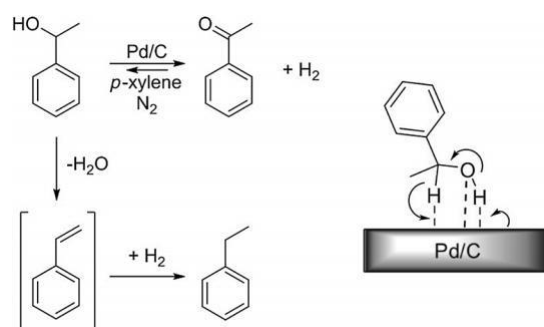

Scheme 2. Acetophenone hydrogenation catalysed by Pd/C. Autoclave reac-tor (Parr 5500) with 100 mL glass liner. Reaction conditions : solution of ace-tophenone in toluene (20 mL, 0.2 m), 0.08 mol % Pd/substrate molar ratio, 130 8C. Reaction performed with H_2 (2 bar).

accompanied by the formation of 1-phenylethanol. Although no styrene was found in the reaction mixture (Scheme 2), it may still be involved in the reaction mechanism as an inter-mediate with a short lifetime; that is, this compound may be formed from the dehydration of 1-phenylethanol, which rapid-ly undergoes hydrogenation to ethylbenzene. Therefore, stabil-ity studies were also performed with styrene as a substrate. During these experiments, quantitative conversion of styrene into ethylbenzene was reached in only 1 h 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 exerted on the re-action by excessive quantities of H_2. 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. On the basis of these observations, all further kinetic studies were performed at short reaction times and lower con-

Scheme 3. Styrene hydrogenation catalysed by Pd/C. Autoclave reactor (Parr 5500) with 100 mL glass liner. Reaction conditions: solution of styrene in toluene (20 mL, 0.2 m), 0.08 mol % Pd/substrate molar ratio, 130 8C. Reac-tion performed with H_2 (2 bar).

version levels, to limit the contribution of the side reactions (Scheme 4) 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 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 ensured 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 linear-range true kinetic conditions, and an activation energy of 98.8 kJ mol [1] was determined, in better agreement with the nature of the reaction (Figure 3). Extending the Arrhenius anal-
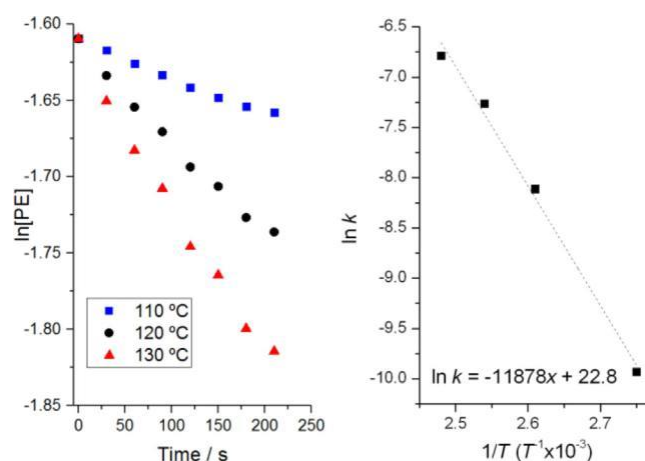

Figure 3. Left: ln [1-phenyletanol] over time at different temperatures (110–130 8C). Right : Arrhenius plot obtained in temperature range 90–130 8C. Re-action conditions: stainless-steel reactor body with 100 mL pressurised round-bottom flask. solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m), 0.08 mol % Pd/substrate molar ratio, static N_2 atmosphere.

ysis over a larger range of temperatures demonstrates the bar-rier is consistent over the temperature range 90–130 °C.

Following these kinetic insights, more attention was paid to the mechanism of the reaction because very little is known about acceptorless dehydrogenation chemistry, especially over heterogeneous catalysts. To identify the nature of the reaction intermediate, we obtained a Hammett correlation by using substituted benzyl alcohols as substrates, owing to the greater commercial availability of substituted benzylic alcohols. It is seen from Figure 4 (left) that the acceptorless dehydrogenation of benzyl alcohol and its p-substituted analogues, 4-methyl-benzyl alcohol and 4-chlorobenzyl alcohol, indicates that elec-tron-donating substituents (σ <1) such as CH_3 lead to in-creased activity. In contrast, electron-withdrawing groups (σ >1) such as Cl have a negative impact on the reaction rate. The negative slope of the Hammett plot strongly indi-cates the formation of a positively charged reaction intermedi-ate, suggesting the formation of a carbo-cationic intermediate during the reaction.

Additional mechanistic insights into the reaction mechanism were obtained by deuteration of the benzylic H-atoms of the substrate (kinetic isotope effect, KIE). As seen in Figure 4 (right), a lower reaction rate (k) is observed if benzylic C D bonds are present over C H bonds. Because KIEs greater than 1 usually indicate that cleavage of that bond is involved in the rate-de-termining 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 ob-served for reactions limited by the rate of C H bond cleavage, although they are in line with the values observed for accept-orless dehydrogenation over homogeneous Pd complexes.[3d,e] The relatively low KIE values observed in these systems could be attributed to second-order effects, in which the H/D substi-tution 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 nega-tive Hammett correlation, coupled with KIE >1, indicates that the acceptorless dehydrogenation reaction possesses some similarities to the classical beta-hydride elimination mecha-nisms often observed during aerobic alcohol oxidation.[9]

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. The catalyst was subjected to a series of heat treatments in a reducing atmosphere (5 % H_2 in Ar) or in 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 (Figures S5 and S6 in the Supporting Information). Therefore, the optimal tem-peratures 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 h 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 aceto-phenone occurred (from 97.3 to 87.6 %). An opposite effect was observed upon calcining the catalyst under a reducing at-mosphere, for which lower conversion but higher acetophe-none selectivity was observed (>98 %). However, we note these differences may also be (partially) related to the natural
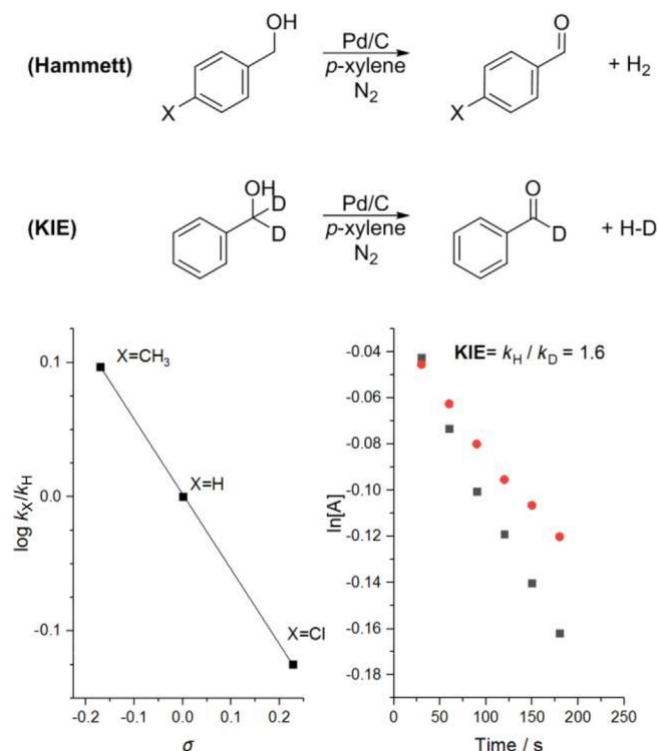

Figure 4. Left: Hammett plot obtained from substituted benzyl alcohol de-hydrogenation to acetophenone over Pd/C. Right : Reaction rate for benzyl alcohol (squares) and a,a-deuterated benzyl alcohol (circles). Reaction condi-tions : stainless-steel reactor body with 100 mL pressurised round bottom flask. solution of substrate in p-xylene (20 mL, 0.2 m), 0.08 mol % Pd/sub-strate molar ratio, 0.16 h, 130 °C, static N_2 atmosphere.
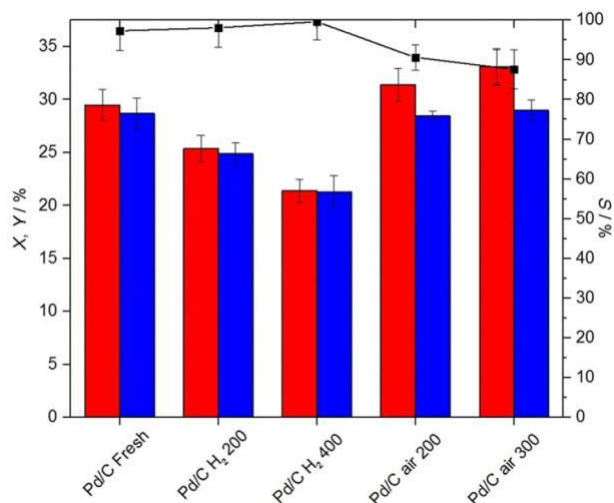

Figure 5. Conversion (X) of 1-phenylethanol (red bars), yield (Y) of acetophe-none (blue bars) and selectivity (S) for acetophenone (black squares) for a) fresh Pd/C (i.e., not treated), b, c) Pd/C heated in 5 % H_2 in Ar for 2 h (ramp rate 10 °C min [1]) at 300 °C (b) and at 400 °C (c), and d, e) Pd/C heated under air for 2 h (ramp rate 10 °C min [1]) at 200 °C (d) and at 300 °C (e). Reac-tion conditions : stainless-steel reactor body with 100 mL pressurised round-bottom flask. solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m), 0.08 mol % Pd/substrate molar ratio, 130 °C, static N_2 atmosphere, 0.25 h.
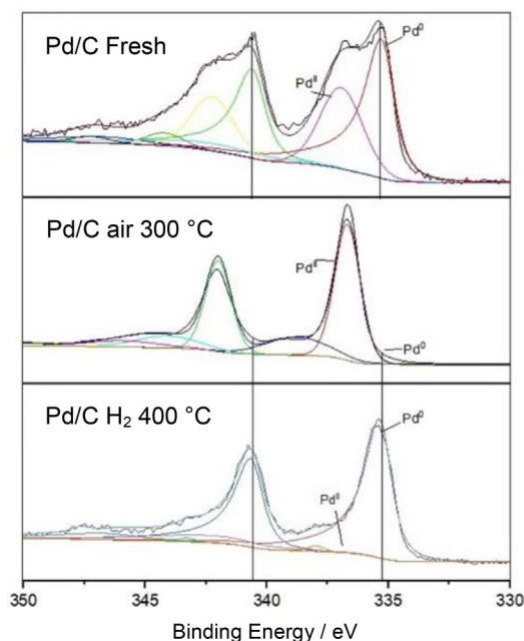
Figure 6. XPS analysis for a) fresh Pd/C (i.e., not treated), b) Pd/C heated at 300°C under air for 2 h (ramp rate 10 °C min^{-1}), and c) Pd/C heated at 400 °C in 5 % H$_2$ in Ar for 2 h (ramp rate 10 °C min^{-1}).

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

Catalyst	Pd$^{0[a]}$ [%]	k 0 10$^{3[b]}$ [s]
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 by deconvolu-tion of XPS spectra. [b] Initial reaction rate (Figure S7 in the Supporting Information).

conversion-versus-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, we charac-terised selected catalysts by XRD, X-ray photoelectron spec-troscopy (XPS), TEM, and Brunauer–Emmett–Teller (BET) analy-sis.

To analyse the Pd speciation, we performed XPS analysis (Figure 6). 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 in Pd/C heated in air at 300 °C (73.9 % Pd^{II}, 26.1 % Pd^0), whereas mostly Pd^0 was found in Pd/C heated in H$_2$ at 400 °C (1.7 % Pd^{II}, 98.3 % Pd^0). Interestingly, al-though large differences in Pd speciation were observed in this series of catalysts, each of these materials exhibits high ac-tivity for acceptorless 1-phenylethanol dehydrogenation. This may be because both oxidation states are active for this reac-tion, and/or because of interconversion between Pd^{II} and Pd^0 occurring readily during the reaction itself. More detailed com-parison of the initial rates of each reaction, achieved by moni-toring the gas evolution over time, shows that lower initial rates (k) are observed for catalysts possessing higher initial per-centages 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 with the dehydrogenation of formic acid over the same catalyst, for which metallic Pd^0 has routinely been proposed to be the most active form of Pd.[10] Notably, XRD analysis is in good agreement with the XPS analysis (Fig-ure S5 in the Supporting Information), showing a different dis-tribution between metallic Pd and Pd oxide to be present on these catalysts, in analogy with the results displayed in Table 4.

In addition to oxidation state, variation in activity may also arise from several other parameters related to the material sur-face and structure, as well as variations in the Pd particle size. In fact, heat treatment often affects the particles size distribu-tion of supported nanoparticles owing to agglomeration (sin-tering) of the particles.[3c] Accordingly, TEM analysis was also performed on this series of catalysts. As seen in Figures 7 and 8, the untreated catalyst possesses a relatively narrow distribu-tion of Pd nanoparticles with a mean size of 3.5 nm, and an in-crease in Pd particle size distribution is found for both heat-treated samples. However, although there is a net agglomera-tion of Pd in both heat-treated catalysts, the extent of agglom-eration is comparable in both H$_2$ and air atmospheres and is unlikely to explain the different kinetic capabilities of these samples.
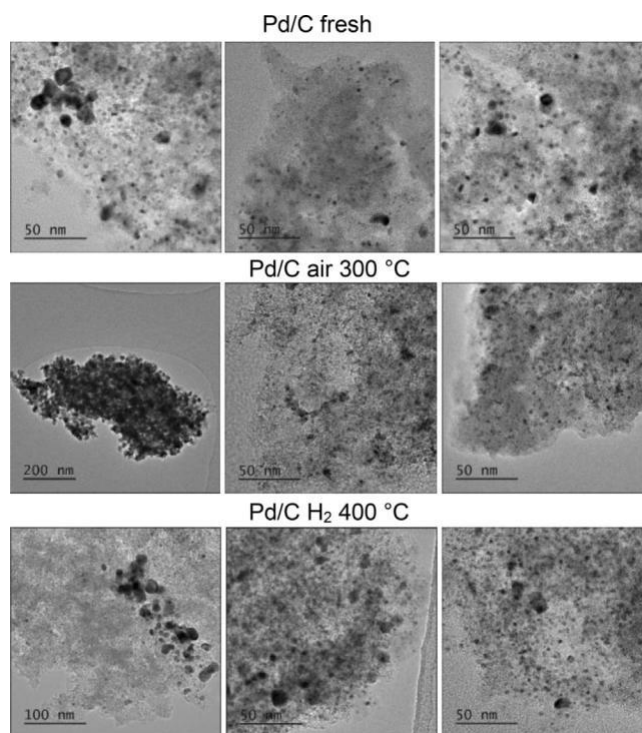

Figure 7. TEM images for a) fresh Pd/C (i.e. , not treated), b) Pd/C heated at 300°C under air for 2 h (ramp rate 10 °C min^{-1}), and c) Pd/C heated at 400 °C in 5 % H$_2$ in Ar for 2 h (ramp rate 10 °C min^{-1}).
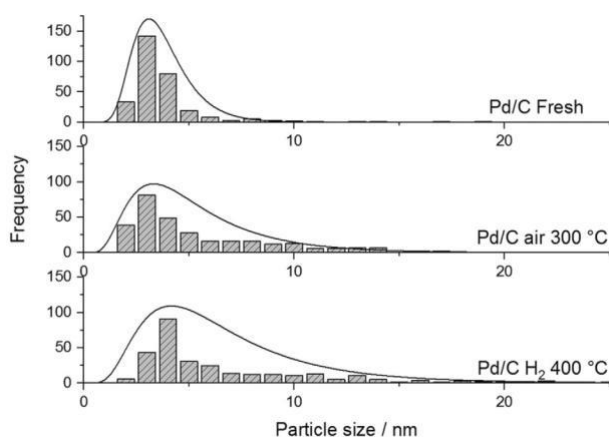
Figure 8. Particle size distribution for a) fresh Pd/C (i.e., not treated), b) Pd/C heated at 300 °C under air for 2 h (ramp rate 10 °C min[1]), and c) Pd/C heated at 400 °C in 5 % H_2 in Ar for 2 h (ramp rate 10 °C min[1]).

For further investigation of the structural changes potentially occurring on the surface of the catalyst, BET analysis was also performed. However, no major variation in the catalyst surface area occurs following the heat treatments (Table S1 in the Supporting Information), 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. To perform an accurate investigation of the durability of the material, and hence, gain a preliminary understanding of the scalability of the process, we studied the catalytic per-formance of Pd/C under continuous flow conditions using a plug-flow reactor (PFR), under conditions otherwise analogous to the batch experiments. Employed in continuous mode, Pd/C displayed good activity for 1-phenylethanol dehydrogenation with an observed acetophenone selectivity of over 80 % (Figure 9 and Figure S8 in the Supporting Information). Although some losses in activity are observed over the first
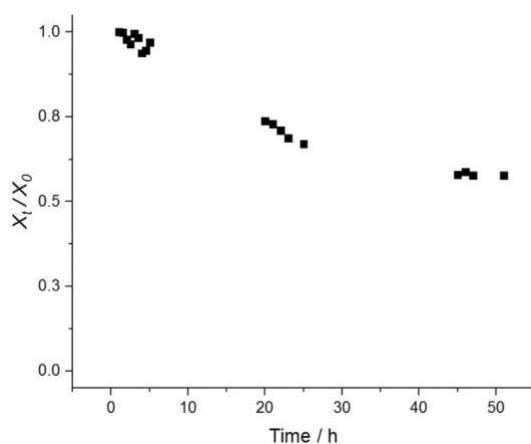

Figure 9. Continuous 1-phenylethanol dehydrogenation reactions in PFR. Relative performance for Pd/C-catalysed 1-phenylethanol dehydrogenation (X_t/X_0) over time on stream. For details see the Experimental Section.

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 oper-ation, suggesting in situ reduction of Pd. This may be the reason for the initial loss of activity over the first 24 h, prior to steady state being achieved because 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 in activity. Nevertheless, 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 STY of 0.683 $g_{(product)}$ mL^{1} h^{1}, which is over two orders of magnitude higher than the one calculated for the best catalyst reported in the literature (Ag/hydrotalcite) to date, indicating the high via-bility of Pd/C as a heterogeneous catalyst for alcohol dehydro-genation (Table 5). In addition to 1-phenylethanol and substi-tuted benzyl alcohols, preliminary studies on the general ap-plicability of the system were made by substituting 1-phenyle-thanol for a smaller, non-aromatic substrate, 2-butanol. Inter-estingly, Pd/C was also able to perform 2-butanol dehydrogenation to 2-butanone in the continuous regime, albeit at a slightly higher temperature (200 °C). Alongside 1-phenylethanol and the substituted benzylic alcohols, this sub-strate further indicates the general suitability of Pd/C-catalysed dehydrogenation in continuous operational mode.

Table 5. Comparative performance of Pd/C and Ag/hydrotalcite.		
Catalyst	Substrate	STY [$g_{(product)}$ mL^{1} h^{1}][a]
Ag/hydrotalcite[5c]	1-phenylethanol	2.2 0 10^{3}[b]
Pd/C	1-phenylethanol	0.683
Pd/C	2-butanol[c]	0.010

[a] STYs calculated at maximum conversion as g (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 conditions identical to those used for 1-phenylethanol, but at 200 °C.

Conclusions

Commercially available 5 wt % Pd/C has been 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 space-time yield values over two orders of magnitude higher than those found in the literature, the ac-ceptorless nature of the reaction results in the co-production of molecular H_2. The intrinsic activity of the catalyst (turnover frequency, 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[1] 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, obtained from kinetics, X-ray photoelectron spectroscopy, XRD, TEM and Brunauer–Emmett–Teller analyses, revealed Pd/C calcined in air at 300 °C to be the optimal catalyst for acceptorless dehydrogenation. Experiments in the continuous regime also showed the durability of the catalyst over 48 h 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 the literature to date. Alongside its high TOF, the extremely high space-time-yield of the system clearly demonstrates 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 and 400 °C at a ramp rate of 10 °C min[1] under flowing air. For reduction, an identical procedure was performed albeit under 5 % H_2 in Ar.

1-Phenylethanol dehydrogenation in batch mode using a borosilicate glass flask

Pd/C-catalysed dehydrogenation reactions were performed at a range of temperatures between 100 and 120 °C using a three-neck 100 mL round-bottom flask. The flask was charged at room temperature with a solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m) and various amounts of Pd/C in the range 0–1.25 mol % Pd/1-phenylethanol molar ratio (0–106.8 mg 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 by using a mass-flow controller. For all reactions, the flask was purged with a N_2 flow of 50 mL min[1] for 6 min. The flow was then decreased to 10 mL min[1] N_2, and the flask was placed in the oil bath and preheated to the desired temperature. The reaction was then initiated by switching on the magnetic stirring (750 rpm). After the reaction, the flask was cooled to room temperature, the catalyst was recovered by filtration, and each sample was prepared by adding the reaction solution (100 mL) to a solution of biphenyl in toluene (900 mL, 0.01 m), which acted as an external standard. The samples were analysed by 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.

1-Phenylethanol dehydrogenation in batch mode using a stainless-steel reactor body with a pressurised connection vessel

Pd/C-catalysed dehydrogenation reactions were performed at a range of internal temperatures between 110 and 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 a solution of 1-phenylethanol in p-xylene (20 mL, 0.2 m) and 5 wt % Pd/C (7.2 mg, 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 (Figure S4 in the Supporting Information). For all reactions, the flask was purged with a flow of N_2 (50 mL min[1]) for 10 min at room temperature. For H_2 measurement, the flow was stopped for the reaction to be performed under a static N_2 atmosphere. For experiments with N_2 flow, the reaction was performed with a N_2 flow rate of 10 mL min[1]. The flask was introduced into the oil bath and preheated 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 MS. Analysis of the liquid samples was performed analogously to the procedure described above (1-phenylethanol dehydrogenation in batch mode using a borosilicate glass flask). Theoretical gas volumes were calculated from the ideal gas equation (PV =nRT), in which R is the gas constant, n is the number of moles of acetophenone produced, T =22 °C, and 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 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[1] 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 in Figure S3 in the Supporting Information). After an appropriate length of time, the reaction solution was analysed again to determine any differences in substrate conversion or product yield in the absence of the solid catalyst.

1-Phenylethanol dehydrogenation in a PFR

Continuous 1-phenylethanol dehydrogenation reactions were performed in a home-made, tubular, stainless-steel PFR. Reactant delivery (0.19 m solution of 1-phenylethanol in toluene) was performed by an HPLC pump. The catalyst (5 wt % Pd/C; 0.08 g) was placed 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 prevent 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 back-pressure regulator. Aliquots of the reaction solutions were taken periodically from a sampling valve placed after the back-pressure regulator and were analysed in the same manner as for 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^{-1}) as the carrier gas. The analytes were quantified against biphenyl as external standard. For all samples the following temperature programme was used: hold at 40 °C for 5 min, ramp at 20 °C min^{-1} to 210 °C and hold at 210 °C for 5 min.

Mass spectrometry

Gas samples were analysed by MS [Hiden Analytical Quadrupole Gas Analyzer (QGA)] equipped with an inert quartz capillary with a consumption rate of 16 mL min^{-1} and Faraday electron multiplier detector capable of detecting concentrations from 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 patterns were recorded on a PANalytical X'Pert PRO XRD, with a CuK$_a$ radiation source (40 kV and 30 mA) and Ni filter. Diffraction patterns were recorded in the 2q range 5–80° at a step size of 0.0167° (time per step =150 s, total time =1.5 h).

N$_2$ physisorption

The surface area of the catalysts was measured by N$_2$ physisorption. Each sample was evacuated for 3 h at 120 °C by using a Quantachrome Quadrasorb SI instrument. Following evacuation, surface area analysis was performed, and the surface area was calculated by using the BET theory over the range P/P$_0$ =0–1.

Transmission electron microscopy

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

X-ray photoelectron spectroscopy

XPS analysis was performed on a Thermo Scientific K-Alpha + spectrometer. Samples were analysed by using a monochromatic Al X-ray source operating at 72 W (6 mA 0 12 kV), with the signal averaged over an oval-shaped area of approximately 600 0 400 mm. Data were recorded at pass energies of 150 eV for survey scans and 40 eV for the high-resolution scan with a 1 and 0.1 eV step size, respectively. Charge neutralisation of the sample was achieved by 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 by using CasaXPS (v2.3.17 PR1.1) with Scofield sensitivity factors and an energy exponent of 0.6.

Acknowledgements

Conflict of interest

The authors declare no conflict of interest.

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