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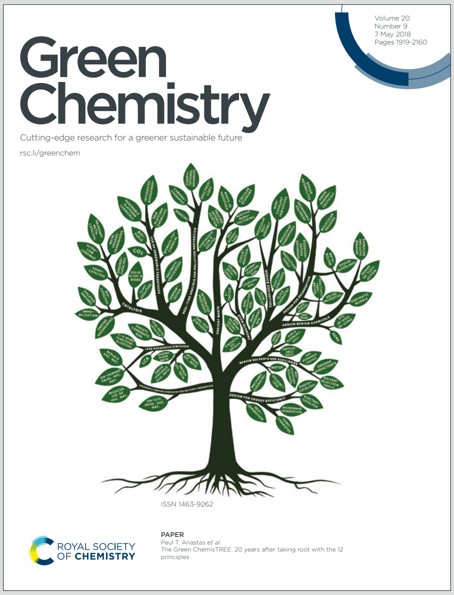

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Efficient Palladium Catalysis for the Upgrading of Itaconic and Levulinic Acid to 2-Pyrrolidones followed by their Vinylation into value-added Monomers

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The production of monomers from bio-based platform chemicals shows great potential to reduce the chemical industry's demand for fossil resources. We herein present a two-step approach, which yields N-vinyl-2-pyrrolidone monomers from bio-based carboxylic acids, such as itaconic and levulinic acid. A highly active, heterogeneous palladium catalyst facilitating the reductive amidation of itaconic acid (TOF = 950 $mol_{Pyr}\cdot mol_{Pd\_surface}^{-1}\cdot h^{-1}$) as well as the reductive amination of levulinic acid (TOF = 4000 $mol_{Pyr}\cdot mol_{Pd\_surface}^{-1}\cdot h^{-1}$) was designed. Especially the reductive amidation of itaconic acid to 3- and 4-methyl-2-pyrrolidone was found to be structure sensitive. A clear trend between Pd particle size and catalyst activity could be shown by the synthesis of Pd/C catalysts with varying Pd particle sizes. The vinylation of the synthesized methyl-2-pyrrolidones with acetylene was tested using common industrial conditions (10-18 bar acetylene, 150 °C, KOH catalyst, no solvent). Similar to the industrial vinylation of 2-pyrrolidone, good yields of up to 80% N-Vinyl-methyl-2-pyrrolidone were received. Therefore, and due to the excellent maximum yield of methyl-2-pyrrolidones in reductive amidation (95 mol.%), the envisioned process can be a promising drop-in technology, directly replacing fossil resources in the production of an established monomer class.

Introduction

Due to technological advances in recent years, several bio-derived platform chemicals are nowadays produced in a multi-ton scale.[1] However, the conversion of highly oxygenated platform chemicals into useful building blocks or fuels remains challenging, given the decade-long use of and experience with oil-derived chemicals.[2] On the other hand, the plethora of functional groups occurring in bio-based platform chemicals might be valorized in the efficient synthesis of a broad range of valuable chemicals.[3]

Several carboxylic acids are suggested to be promising platform chemicals derivable in bio-refineries.[4] Their reduction to valuable chemicals such as diols is well researched, but selective transformations remain challenging, as mixtures of alcohols, ethers and esters are usually formed.[5] Another reported approach to utilize the acid functionality is the reductive transformation with primary amines and hydrogen to produce pyrrolidones.[6] Especially the reductive amination of levulinic acid (LA) to 5-methyl-2-pyrrolidone has attracted widespread scientific attention. Several catalytic systems have been developed for this purpose in recent years.[7] Consequently, three general steps required for pyrrolidone synthesis from LA have been identified: (1) condensation of the carbonyl group of LA with an amine to form an imine intermediate, (2) hydrogenation of the imine to γ-amino-pentanoic acid and (3) intramolecular lactamization to generate 5-methyl-2-pyrrolidones. Metal-complexes of Ir[8], Ru[9] and In[10] were developed and used with a clear focus on the synthesis of N-alkyl- and N-aryl-pyrrolidones functioning as pharmaceutical intermediates. Nanoparticle catalysts (Ir[11], Au[12], Pt[13], Pd[14], Ru[15]) supported on metal-oxides (TiO_2, ZrO_2, Al_2O_3) were also shown to be suitable for the reductive amination of LA. With temperatures between 80-150 °C, H_2 pressures of up to 5 MPa and 12-24 h reaction time, N-substituted 5-methyl-pyrrolidones were synthesized in good yields. With ammonia as nitrogen source, yields were usually lower as compared to amines with alkyl or aryl groups. Even catalyst free systems proved feasible with HCOOH as reduction agent and primary amines as N-source. However, the non-catalytic conversion with ammonia to N-unsubstituted pyrrolidones is not mentioned in literature.[16]

In contrast to LA, dicarboxylic acids, such as itaconic and succinic acid, cannot undergo reductive amination as they lack the necessary carbonyl group. When reacted with amines at elevated temperatures, they form amides, diamides and imides. The reduction of amides, in turn, is a major challenge in heterogeneous catalysis and usually requires high temperatures and pressures.[17] Recently, amide reduction

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under relatively mild reaction conditions with heterogeneous catalysts was shown. However, the use of large quantities of precious metal, dry organic solvents, molecular sieve and long reaction times were inevitable.[18] Due to the vulnerability of these systems to water and presumably also ammonia, they can hardly be applied to the direct conversion of dicarboxylic acids, which are often derived by fermentation in aqueous media. Nevertheless, a few studies report the successful conversion of dicarboxylic acids to pyrrolidones over heterogeneous catalysts. White et al. investigated the production of N-methyl-2-pyrrolidone (NMP) from succinate containing fermentation broth.[19] N-methyl-succinimide was isolated from the fermentation broth via reactive distillation with methanol and ammonia and consecutively reduced over a commercial rhodium catalyst, yielding 90% NMP at 220 °C and 50 bar H_2. The direct conversion of succinic acid only yielded 42 mol.% NMP or 39 mol.% 2-pyrrolidone, respectively.

While the production of N-alkylated pyrrolidones takes prevalence in recent literature, a plethora of functionalized alternatives is attainable through the variation of the amine feedstock. In this context, we recently reported the catalytic conversion of biogenic diacids with ethanolamine and hydrogen to yield N-(2-hydroxyethyl)-2-pyrrolidone (HEP).[20] The product, in turn, was dehydrated in a continuous gas phase reaction over sodium-doped silica to yield N-vinyl-2-pyrrolidone (NVP), which is an industry known monomer. While a plethora of applications for the corresponding polymer (PVP) may give economic merit to this production strategy, intermediate HEP yields remain limited (75 mol.%) due to lacking chemo-selectivity of the employed Ru/C catalyst. In contrast, the synthesis of N-unsubstituted 3- and 4-methylpyrrolidones from itaconic acid and ammonia over the same catalyst reached up to 90 mol.% yield.[21] Including a sequential Reppe vinylation with gaseous acetylene, which has been proven on the industrial scale for 2-pyrrolidone[22] only, this opens an additional pathway to bio derived NVP monomers. Given the established Ru/C catalyst, the mentioned conversions of diacids with amines and hydrogen (herein termed reductive amidations), can be achieved in aqueous solution and with low catalyst loading ($<0.2\ \mathrm{mol_{Metal}} \cdot \mathrm{mol_{substrate}}^{-1}$). However, high temperatures (150-200 °C) and pressures (150 bar) are still required, which motivates the search for alternative catalytic systems.

We herein present the reductive transformation of itaconic and levulinic acid with ammonia, leading to 3- and 4- or 5-methyl-2-pyrrolidones respectively, which are subsequently vinylated with acetylene, yielding methyl-substituted N-vinyl-pyrrolidone monomers. Special emphasis is laid on the influence of catalytic properties on the conversion of itaconic acid to pyrrolidones. In this context, the use of tailored Pd/C catalysts allows for a reduction in hydrogen pressure from 150 bar to 50 bar without lowering the pyrrolidone yield as compared to the previous Ru/C benchmark.[21] Overall, NVP-like monomers were produced in good yields (72 mol.% over two steps) from bio-based carboxylic acids with water as the sole byproduct (**Scheme 1**). With the easy-to-make catalyst, short reaction time and relatively moderate reaction conditions, the two-step process offers great potential as a Green Chemistry value chain.

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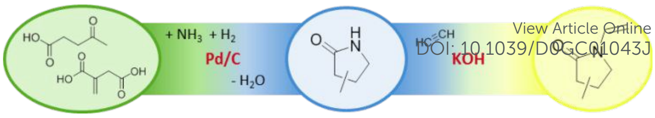

Scheme 1: Conversion of bio-based itaconic and levulinic acid into methyl substituted 2-pyrrolidones and consecutive vinylation with acetylene to yield vinylpyrrolidone monomers.

Experimental

Catalytic materials and Chemicals

Carbon supported catalysts (Pd/C, Rh/C and Ru/C) for the initial screening were kindly provided by Heraeus. The catalysts were received as wet solids and dried at 60 °C in a vacuum oven for 24 hours. Catalysts 4, 8 and 9 were provided in an oxidized form and were therefore additionally heated at a rate of 5 K/min under hydrogen flow to 300 °C, where they remained for 2 hours to ensure complete reduction of the metal species. Oxidic support materials SiO_2 (SS61138) and Al_2O_3 (SA6275) were kindly provided by Saint Gobain NorPro.

Synthesis of oxidized carbon support

For the synthesis of oxidized activated carbon, 15 g Norit A Supra (Acros Organics) were dispersed in 250 ml 10 M HNO_3 solution and refluxed for 4 hours under vigorous stirring. Thereafter, the oxidized Norit A Supra was filtered and washed with deionized water until neutral pH (≈ 1.5 l). Finally, the oxidized carbon was dried in a vacuum oven at 60 °C for 24 h.

Synthesis of Catalysts

For the synthesis of Pd catalysts with a $PdCl_4^{2-}$ precursor, 250 mg of $PdCl_2$ (abcr, 60% Pd) were dispersed in 10 mL of deionized water. Concentrated hydrochloric acid (≥37 wt.%, Honeywell) was added until the metal salt was completely dissolved (usually 15 mL). Subsequently, the support was added to the solution and the mixture was stirred at room temperature for 3 hours. Thereafter, the solvent was slowly removed using a rotary evaporator (60 mbar, 50 °C water bath) and dried at 60 °C in a vacuum oven for 16 hours. The catalysts were then reduced under hydrogen flow at 350 °C unless otherwise stated (heating rate 5 K/min).

Catalyst Characterization

TEM images were taken on a FEI Tecnai F20 operated in HAADF-STEM mode. For the determination of palladium particle size distributions, several hundreds of particles per catalyst were evaluated by application of the ImageJ software to the recordings. Several positions on the sample were included for the evaluation to guarantee statistical soundness of the obtained particle size data.

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X-ray photoemission spectra (XPS) were recorded on a Thermo Scientific K-Alpha spectrometer equipped with a monochromatic small-spot X-ray source and a 180° double focusing hemispherical analyser with a 128-channel delay line detector. Spectra were obtained using an aluminium anode (AlKα = 1486.6 eV) operated at 72 W and a spot size of 400 µm. Survey scans were measured at constant pass energy of 200 eV, and high-resolution scans of the separate regions were measured at 50 eV pass energy. The background pressure of the ultrahigh vacuum (UHV) chamber was $<2 \times 10^{-8}$ mbar. The samples were measured in a powder sample holder without the use of sticky tape. Sample charging was compensated for by the use of an electron flood gun, and binding energy (BE) calibration was done by setting the C 1s peak of sp^2 carbon to BE(C 1s) = 284.5 eV. Samples were transferred and handled in ambient air prior to entering the XPS apparatus.

Chemicals

Itaconic acid (≥99%) and levulinic acid (≥99%) were purchased from Sigma Aldrich. Ammoniumhydroxide solution (25 wt.%) was purchased from Honeywell. All chemicals were used without further purification.

Hydrogenation Reactions with Ammonia

Reductive transformation reactions were conducted with hydrogen as reducing agent in 50 mL Hastelloy autoclaves. In a typical experiment 1.5 g itaconic acid was dissolved in 1.5 g ammoniumhydroxide solution and 0.5 g water. 2.5 wt.% of catalyst (37.5 mg) were added before sealing the autoclave. Ambient air was purged from the autoclave by 3 cycles of pressurization (10 bar of H_2) and relaxation. Subsequently, H_2 was added up to the desired pressure value. The so-prepared autoclave was placed in a pre-heated heating jacket, leading to the onset of reaction. The reacting mixture was stirred with a magnetic stirring bar at 750 rpm. After a chosen reaction time, the autoclave was removed from the heating jacket and cooled down. The autoclave was depressurized and opened. Solids were removed from the product solution by filtration with a polyamide syringe filter before running HPLC analysis on an Organic Acid Resin column (CS – Chromatography Services) with diluted phosphoric acid as mobile phase and a refractive index detector. Conversion and yield are calculated from concentrations determined via HPLC through the assumption of mass conservation within the autoclave.

The following definitions are applied for the productivity (P) and the turnover frequency (TOF):

$$P = \frac{n_{product}}{n_{Metal} \cdot t_{reaction}} \qquad \textbf{(1)}$$

$$TOF = \frac{n_{product}}{n_{Metal\,(surface)} \cdot t_{reaction}} \qquad \textbf{(2)}$$

The number and surface area of palladium atoms was calculated using CO-pulse titration and palladium mass (ICP-OES).

Vinylation of Methylpyrrolidones

Vinylation of the produced methylpyrrolidones was conducted with gaseous acetylene in 50 mL Hastelloy autoclaves. High pressure acetylene was used according to the procedure described by Schüth et. al.[23] Thus, a 500 mL stainless steel autoclave was half filled with 3 Å molecular sieve and 100 mL acetone. 1.5 bar of acetylene (99.99%, Westfalen) was continuously added to the autoclave while the autoclave was cooled in an acetone dry ice bath. By increasing the temperature to room temperature, an acetylene pressure of up to 20 bar is attained in the autoclave which can be used as a reservoir for high pressure reactions. In a typical experiment, 3 g of methylpyrrolidone was mixed with 84.9 mg KOH (5 mol%) in a 50 mL Hastelloy autoclave. The autoclave was sealed and heated to 55 °C while applying vacuum (0.05 mbar) to remove water from the mixture. After purging 15 times with 1.5 bar acetylene, the pressure was increased to 15 bar and the autoclave was heated to 150 °C in a heating jacket. The reaction mixture was stirred at 500 rpm. After a chosen reaction time, the autoclave was quenched. The autoclave was depressurized, opened and the product solution was analyzed by gas chromatography (50 m CP-Wax-57 CB, ID-0.25 mm + DF-0.20 µm). Conversion and yield were calculated from concentrations determined via GC.

Results and Discussion

Reductive Amidation of Itaconic acid

The previously reported ruthenium catalyst (**Figure 1**, blue) requires high hydrogen pressures for a high activity in the conversion of itaconic acid to 3- and 4-methyl-2-pyrrolidone (3/4MP). In industrial scale, this significantly increases investment costs for a potential process and causes high energy consumption for hydrogen compression. Therefore, several commercial Pd, Rh and Ru catalysts were screened (**Figure 1**). As expected, the Ru catalyst remains the most active catalyst under the previously optimized conditions. The high activity of ruthenium catalysts for the reduction of imides can be explained by the ability to activate hydrogen as well as the C=O-bond that must be cleaved.[24] The drawback relates to high hydrogen pressure necessary, for an efficient use of Ru catalysts.[21]

While Pt/C and Rh/C are barely active, some commercial palladium catalysts enabled productivities of up to 110 $\text{mol}_{\text{Pyr}} \cdot \text{mol}_{\text{Pd}}^{-1} \cdot \text{h}^{-1}$ and product yields of more than 30 mol.% after 2 h reaction time. Furthermore, we observed strong variations in activity between different Pd/C catalysts. It can be concluded that the catalyst structure has a large influence on the activity. Besides the activity, also the ratio of the two isomeric products formed is strongly dependent on the catalytically active metal. We previously reported a 3MP/4MP ratio of 1.6 for ruthenium catalysts.[21] Rhodium and platinum favor the production of 3MP even more and have a ratio of 2.0-2.2, while all tested palladium catalysts yield an isomer ratio of 0.9-1.0. Moreover, the 3MP/4MP ratio seems to be unaffected by changing reaction conditions, as is shown

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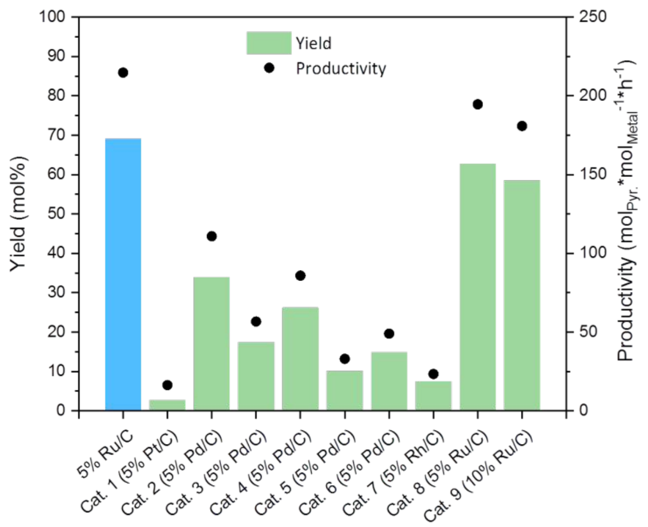

Figure 1: Catalyst screening with several commercial carbon-supported hydrogenation catalysts. Conditions that were optimized for Ru/C (blue bar) in a previous publication were applied (200 °C, 150 bar H_2, 2 h, 750 RPM, 1.5 g itaconic acid, 1.5 g 25 wt.% NH_4OH solution, 0.5 g H_2O, 37.5 mg catalyst).

in the screening results of **Table 1**. Herein, the influence of several process parameters on the catalytic activity was investigated with the most active Pd catalyst from the initial screening (Catalyst 2). The catalyst shows a low sensitivity towards hydrogen pressure (**Table 1**, entry 1-3). The productivity decreases by only 20% if the pressure is lowered from 150 bar to 50 bar. The small influence of hydrogen pressure on the activity can be assigned to the outstanding ability of palladium to activate hydrogen. As a result, the hydrogenation can be performed at lower pressures.

Since palladium cannot activate C=O-bonds as well as Ru[24], it was assumed that higher temperatures are required to accelerate the reaction. Indeed, the temperature has a great influence on the activity as the productivity of the catalyst increases by one order of magnitude for a temperature rise from 180 °C to 220 °C (**Table 1**, entry 4 and 5). That leads to a pyrrolidone yield of 46% at 220 °C and 50 bar after 2 h reaction time. The hydrogen pressure can be reduced further while maintaining viable reaction rates (**Table 1**, entry 6 and 7), but at 10 bar the amount of hydrogen present in the autoclave is too low to achieve high yields. The addition of higher amounts of catalyst leads to an increased pyrrolidone yield of 79% (entry 8). The parameter screening shows that palladium catalysts possess a low pressure sensitivity which is in good agreement with literature as palladium is known to activate hydrogen well.[25] Since palladium cannot activate C=O-bonds effectively, higher temperatures are necessary. At 220 °C and 50 bar, a maximum productivity of 149 $mol_{Pyr}\cdot mol_{Pd}^{-1}\cdot h^{-1}$ for the conversion of itaconic acid to 3- and 4-methyl-2-pyrrolidone was achieved with commercial Pd/C catalysts.

Table 1: Variation of reaction conditions with catalyst 2 (temperature, H_2 pressure, Pd amount). Reaction conditions: 1.5 g itaconic acid, 1.5 g NH_4OH-solution, 0.5 g H_2O.

Entry	T [°C]	p [bar]	Pd [mol%]	Productivity [$mol_{pyr.}\cdot mol_{Pd}^{-1}\cdot h^{-1}$]	Y [%]	3MP/4MP [ratio]
1	200	150	0.15	110.8	33.9	0.92
2	200	100	0.15	90.3	27.8	0.86
3	200	50	0.15	87.8	26.8	0.91
4	180	50	0.15	14.7	4.5	0.92
5	220	50	0.15	149.2	45.7	0.90
6	220	30	0.15	119.3	36.8	0.90
7	220	10	0.15	20.5	6.2	0.92
8	220	50	0.45	96.6	79.2	0.89

Table 2: Influence of support material choice on the activity of Pd catalysts. Reaction conditions: 220 °C, 50 bar H_2, 2 h, 1.5 g itaconic acid, 1.5 g NH_4OH solution, 0.5 g H_2O.

Entry	Catalyst	PZC	$d_{avg.}$ (STEM)	X [%]	Y [%]	Productivity [$mol_{pyr.}\cdot mol_{Pd}^{-1}\cdot h^{-1}$]
1	5% Pd/SiO_2	5.5	3.57	5.9	3.5	11.4
2	5% Pd/Al_2O_3	7.9	3.10	8.0	7.4	24.2
3	5% Pd/C	10.4	2.40	35.7	23.7	77.6
4	5% Pd/C(ox.)	2.2	1.99	71.9	64.8	212.3

To understand the reasons for the varying catalytic activity, a series of different Pd catalysts was synthesized. Palladium may be supported on different carrier materials potentially influencing the catalytic activity (**Table 2**). In this context, the support material may influence the reaction directly through its participation in adsorption/desorption processes, or indirectly via changes to the electronic state of Pd induced by metal-support interaction. Furthermore, the role of support surface functionalities in the adsorption and stabilization especially of charged metal precursors from aqueous solution has been extensively discussed in literature.[26] As exemplified by Regalbuto et al. in the revised physical adsorption model, impregnation pH and support material PZC (point of zero charge) are sufficient for the initial differentiation of favorable and unfavorable impregnation scenarios. In the case at hand, a negatively charged Pd complex ($[PdCl_4]^{2-}$) is employed in a strongly acidic aqueous solution. Thus, high support PZC (preferentially 7-11) should favor a positively charged surface state and thus lead to optimal precursor-support interaction. Accordingly, it was found that final catalyst activity increases with support PZC in the order SiO_2 (5.9) < Al_2O_3 (7.4) < carbon (10.4) (**Table 2**). As expected, the discussed activity trend coincides with changes in Pd particle size, as a strong precursor-support interaction translates into lower mobility of Pd species during thermal treatment.

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It must be stated, however, that support PZC is not the only characteristic by which precursor-support interactions can be judged. In the current case, activated carbon materials exhibit a specific surface area, which is an order of magnitude above that of the oxide supports. Consequently, the carbon material may exhibit a higher specific density of adsorption sites (sites/g^{-1}) in addition to a more optimal PZC. This is further underlined by the effect of carbon functionalization with HNO_3: While the oxidized carbon support exhibits a PZC, which is suboptimal for the interaction with $[PdCl_4]^{2-}$, it also possesses a significantly increased density of oxygen functionalities and thus potential adsorption sites. Consequently, the nature of precursor-support interactions is changed, leading to a facilitated reduction process (see TPR data, **Figure S3**) and a reduced average Pd particle size after thermal treatment (see **Figure S1**). While electronic effects of metal-support interaction seem not to influence the reactivity of the catalyst (XPS data, **Table S3**), smaller particles lead to an increased amount of surface Pd, the supposed active site for hydrogenation.

Due to the evidence for Pd particle size as descriptor of catalytic activity in reductive amidation, further efforts targeted the tailoring of Pd dispersion on C(ox.). Therefore, the impregnated Pd/C(ox.) catalyst was reduced at different temperatures. Catalysts reduced at higher temperatures should have larger Pd particles, due to enhanced surface mobility and coalescence. STEM analyses confirmed this expectation (**Figure S2**). A linear growth of the average particle size with increasing reduction temperature was found. The so-prepared catalysts were then tested in the reductive amidation of itaconic acid under the previously optimized reaction conditions. A clear correlation between particle size (HAADF-STEM) and catalytic activity was found (**Figure 2**). In detail, reducing the particle size led to a successive increase in conversion and pyrrolidone yield, with the exception of the catalyst reduced at 250 °C. The latter was less active than its counterparts reduced at 300-400 °C, despite showing the smallest particles size in STEM analysis. Thus, the highest activity was found for the catalyst reduced at 300 °C. The productivity reached 256.5 $mol_{Pyr} \cdot mol_{Pd}^{-1} \cdot h^{-1}$ and thus clearly outperformed the best commercial material (catalyst 2 - 149.2 $mol_{Pyr} \cdot mol_{Pd}^{-1} \cdot h^{-1}$). A high yield of 78 mol% 3- and 4-methyl-2-pyrrolidone was reached after just 2 hours reaction time.

Given the reduced yield with the 250 °C sample, the number of active sites does not seem to be the sole descriptor of catalytic activity for Pd/C_ox. Therefore, turnover frequencies (TOF) were calculated for the five catalysts distinguished by STEM particle size. The number of active sites determined by CO-pulse titration and total metal content (ICP-OES, **Table S1**) agrees well with the particle size trend established by electron microscopy. Combination with low conversion experiments (reaction time of 30 minutes) yielded TOFs characterizing the intrinsic activity of the active sites (**Figure 2**). Particles with an average size around 2 nm (1.77 – 2.24 nm) showed comparable levels of activity per active site (TOF ≈ 950 $mol_{Pyr} \cdot mol_{Pd\_surface}^{-1} \cdot h^{-1}$), while smaller as well as bigger Pd particles were less active. Thus, reductive amidation on Pd/C_ox was shown to be structure sensitive.

XPS analysis of the five Pd catalysts, reduced at different temperatures, was conducted to investigate whether the electronic properties of Pd are influenced, too. With increasing reduction temperature and thereby increasing Pd particle size, the Pd particles possess a more metallic character (**Figure 3**) as indicated by an enhanced presence of Pd^0 species at a binding energy of BE(Pd $3d_{5/2}$) = 335.2±0.1 eV. Smaller particles reveal a higher degree of oxidation as indicated by the relative enhancement of $Pd^{\delta+}$ (BE(Pd $3d_{5/2}$) = 336.0±0.1 eV) and Pd^{ox} species (BE(Pd $3d_{5/2}$) = 337.5±0.1 eV) as well as the absence of the Pd^0 component for the smallest particle size sample (reduced at 250 °C).[27] Since the catalysts were measured ex-situ, surface oxidation of the Pd particles in ambient air is possible. This would also explain the low amount of metallic Pd

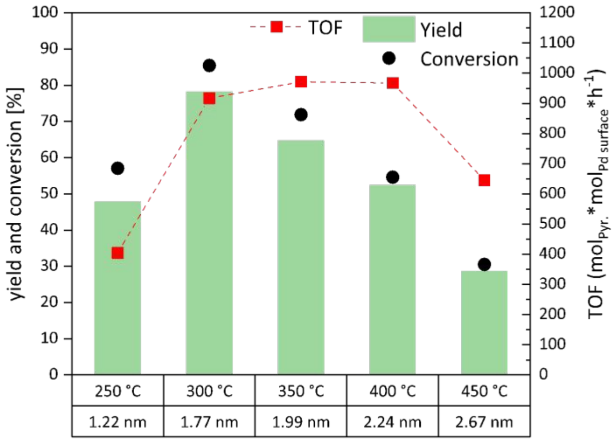

Figure 2: Activity in the reductive amidation of itaconic acid of Pd/C(ox.) reduced at Temperatures from 250 - 450 °C. Average particle size is displayed below the reduction temperature. Reaction conditions: 220 °C, 50 bar H_2, 2 h, 750 RPM, 1.5 g itaconic acid, 1.5 g 25 wt.% NH_4OH solution, 0.5 g H_2O, 37.5 mg catalyst. TOFs were calculated at 30 min reaction time (conversion <20%).

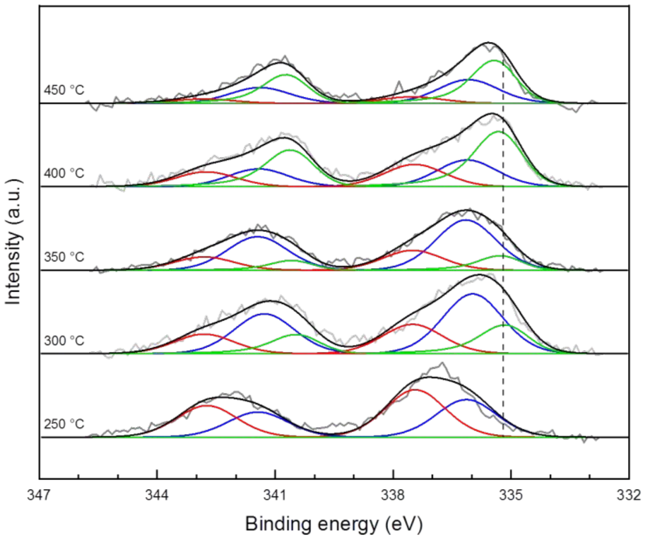

Figure 3: Pd^{3d} Area of the 5 wt.% Pd/C(ox.)_Cl catalysts reduced at 5 different temperatures in a range from 250 to 450 °C. The Pd^{3d} peak were convoluted into Pd^0, $Pd^{\delta+}$ and $Pd_{ox.}$. The relative areas can be found in Table S3.

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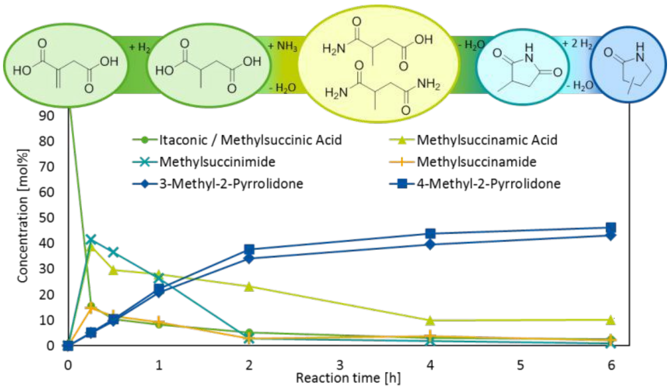

Figure 4: Concentration-time profile of the reductive amidation of itaconic acid with Pd/C(ox.)_Cl_300 as catalyst. Reaction conditions: 220 °C, 50 bar H_2, 2 h, 750 RPM, 1.5 g itaconic acid, 1.5 g 25 wt.% NH_4OH solution, 0.5 g H_2O, 37.5 mg catalyst.

in catalysts with small particles, as they tend to passivate when brought into contact with atmospheric oxygen.

Previous research[21] indicated that reductive amidation of itaconic acid with ammonia on Ru/C proceeds *via* amide formation, cyclization and finally hydrogenation. As is shown in **Figure 4**, the recorded concentration-time profile for Pd/C(ox.)_300 is similar to that previously reported. After a quick reduction of itaconic acid to methylsuccinic acid, three intermediates are formed: namely the respective monoamides (3-/4-methylsuccinamic acid), diamide (methylsuccinamide) and imide (methylsuccinimide). While these reactions are fast and proceed without the need of a catalyst, the final reduction of either of the carbonyl groups of methylsuccinimide leading to the formation of 3- and 4-methyl-2-pyrrolidone constitutes the rate-determining step. Thus, the highest imide levels are observed after 20 minutes, where pyrrolidone formation proceeds on the timescale of several hours. Consequently, it is the adsorption and reduction of the imide intermediate on the Pd surface that preferentially occurs on particles of intermediate size.

Reductive Amination of Levulinic Acid

Several heterogeneously catalyzed reaction systems for the conversion of levulinic acid into 5-methyl-2-pyrrolidones (5MP) have been reported to date and supported palladium catalysts are widely applied in hydrogenation reactions. However, successful examples of Pd catalysis in reductive amination of LA are scarce in literature[28], with a Pd/ZrO_2 catalyst being the sole heterogeneous example.[14] We therefore tested our Pd-catalysts in the reductive amination of LA with ammonia as nitrogen source and hydrogen as reduction agent. Since reductive aminations usually can be performed under milder conditions than reductive amidations, the catalysts were tested at 200 °C, 50 bar H_2 and 1 h reaction time (**Table 3**, entry 1-5).

For the reductive amination of LA, no direct trend regarding the reduction temperature or Pd particle size is observed. However, the catalysts reduced at 250-350 °C facilitate a higher activity than the catalysts reduced at higher temperatures. Yields of over 95% were achieved in a comparably short reaction period, resulting in productivities of more than 600 $mol_{Pyr}\cdot mol_{Pd}^{-1}\cdot h^{-1}$. Also, the catalyst, which was reduced at 250 °C and showed a comparably low activity in the reductive amidation of itaconic acid, reaches very high yields. With this catalyst the reaction temperature was varied (**Table 3**, entry 5-8). The temperature had a severe influence on the reaction rate with a maximum at 180 °C. Very high 5MP yields of around 95% were achieved at 180 and 200 °C in just 1 h reaction time. And even at 140 °C, 20% yield was reached, which shows the distinctly lower activation energy of the reductive amination compared to reductive amidation. The concentration-time profile of levulinic acid conversion at 180 °C (**Figure 5**) reveals a fast conversion of LA into 5MP within 1 hour. After that the concentration of 5MP remains constant. The TOF (calculated at 15 min reaction time) of the catalyst is 4000 $mol_{Pyr}\cdot mol_{Pd\_surface}^{-1}\cdot h^{-1}$ – four times as high as for the reductive amidation of itaconic acid.

Catalyst Recycling

To investigate whether the catalysts can be reused after the reaction, recycling experiments were conducted. Therefore, the reaction was stopped after 1 hour reaction time (<50% yield), the catalyst was filtered off, washed several times with water and finally dried in a vacuum oven at 60 °C. The recycled catalyst shows a decline in activity by 50% and in a third run no product is observed (**Figure S6**). To understand the deactivation, the used catalyst was analyzed. TEM images of

Table 3: Variation of reaction conditions (temperature, H_2 pressure, Pd amount). Reaction conditions: 1.5 g levulinic acid, 1.5 g NH_4OH-solution, 0.5 g H_2O.

Entry	Catalyst	Temperature [°C]	Yield [%]	Productivity [$mol_{Pyr}\cdot mol_{Pd}^{-1}\cdot h^{-1}$]
1	5Pd/C(ox.)_450	200	88.7	588.7
2	5Pd/C(ox.)_400	200	88.7	584.5
3	5Pd/C(ox.)_350	200	96.3	639.4
4	5Pd/C(ox.)_300	200	95.0	620.3
5	5Pd/C(ox.)_250	200	95.5	642.0
6	5Pd/C(ox.)_250	180	93.7	623.7
7	5Pd/C(ox.)_250	160	66.7	442.7
8	5Pd/C(ox.)_250	140	20.2	134.7

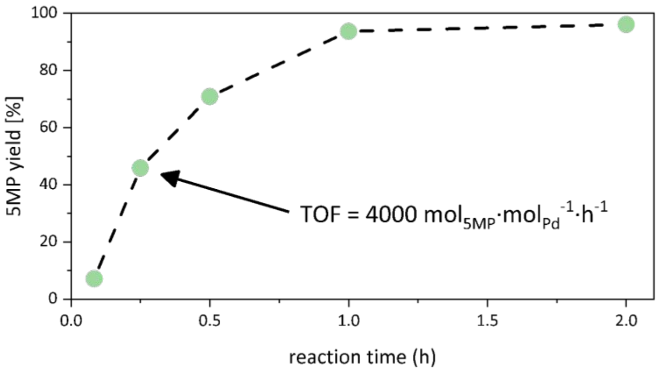

Figure 5: Concentration- time profile for the reductive amination of levulinic acid with 5% Pd/C(ox.)_250 at 180 °C and 50 bar H_2.

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the used catalyst show a few bigger agglomerates of Pd on the supporting material (**Figure S7**). However, the average Pd particle size stays unchanged. ICP-OES measurements of the used catalyst indicate that the palladium content remains constant (**Table S1**). Nitrogen physisorption measurements (**Table S1**) indicate that the specific surface area and pore volume of the catalyst decreases by 50%. Also, in CO pulse titration almost no adsorption of CO is observed (**Table S1**). As STEM confirms that Pd particles are still present and particle size is almost unchanged and ICP-OES confirms that Pd content decreased only slightly, the diffusion to the Pd particles must be hindered. A plausible reason for the decreased activity is a collapse of the pore structure of the carbon support during the reaction that leads to a blockage of the pores and hindering the substrate to access the Pd particles. XPS results of the fresh and used catalyst show an oxidation of palladium particles (**Figure S8**; **Table S3**). The oxidation state of palladium shifts from mainly $Pd^{\delta+}$ in the fresh catalyst to Pd^{ox} in the used catalyst. However, surface oxidation of the palladium particles from contact with atmospheric oxygen or water is possible since the catalyst was washed and dried in ambient air.

Vinylation of Methylpyrrolidones

Since the main application of commercial 2-pyrrolidone is the conversion into N-vinylpyrrolidone, the possibility to vinylate methyl-substituted 2-pyrrolidones under literatureconditions was investigated. Therefore, several reaction parameters for the conversion of commercial 2-pyrrolidone with acetylene and potassium hydroxide to NVP (**Table 4**, entry 1-6) were screened. Industrially, 2-pyrrolidone is converted into NVP by the reaction with high pressure acetylene (10-26 bar) at 130-160 °C. The vinylation is catalyzed by a 2-pyrrolidone-potassium salt, which forms by dissolving 5 mol% potassium hydroxide in 2-pyrrolidone and removing the formed water by evaporation in vacuo.[22,29] Similar conditions for the conversion of 2-pyrrolidone were tested in our setup. The NVP yield increases with increasing catalyst concentration (entries 1-3). When the acetylene pressure is increased, the reaction time can be decreased drastically (compare entries 3 and 5). The reaction rate can also be accelerated by increasing the temperature, but the selectivity suffers slightly (entries 4-6). The highest yield of 80% was achieved at 170 °C, 18 bar and with 5 mol% KOH.

Table 4: Vinylation of commercial 2-pyrrolidone (2P), bio-based 3/4-methyl-2-pyrrolidone (3/4MP) and bio-based 5-methyl-2-pyrrolidone (5MP) with pressurized acetylene in 50 ml autoclaves.

Entry	Substrate	T [°C]	p [bar]	t [h]	KOH [mol%]	X [%]	Y [%]
1	2P	150	12	3	1.25	37.5	32.4
2	2P	150	12	3	2.5	58.6	53.3
3	2P	150	12	3	5	99.1	65.2
4	2P	130	18	1	5	17.1	16.1
5	2P	150	18	1	5	60.4	59.6
6	2P	170	18	1	5	90.4	79.7
7	3/4MP	150	18	1.5	5	100.0	81.8 (69.6)
8	3/4MP	160	15	1.33	5	100.0	66.2
9	3/4MP	160	15	1	5	77.5	68.2 (61.7)
10	5MP	150	18	1	5	27.9	20.6
11	5MP	170	15	1	5	62.5	59.2
12	5MP	150	18	2	5	57.5	51.1 (29.1)
13	5MP	150	20	2	5	100	63.1 (52.7)

The conversion of 5-methylpyrrolidone and mixtures of 3- and 4-methylpyrrolidone to the corresponding monomers was tested under similar conditions (**Table 4**, entry 7-13). 3/4MP can be converted in high yields of up to 80 mol.% at 150 °C, 18 bar acetylene and 5 mol% KOH (entry 7). Scaling up the vinylation to 10 g substrate leads to yields between 65 and 70 mol.% (entries 8-9). The product was isolated (62 mol.%) via distillation (25-27 °C; 0.02 mbar) in high purities (>99 mol.%). When pure 5MP is used, lower reaction rates are observed (entry 10). Increasing the reaction time, temperature or acetylene pressure accelerates the reaction and leads to higher yields (entries 11-12). A maximum yield of 63 mol.% was achieved at 150 °C, 20 bar acetylene and 2 h reaction time (entry 13). 5-Methyl-N-vinyl-2-pyrrolidon was isolated (53 mol.%) via distillation (29-30 °C, 0.02 mbar) in high purities (>99 mol.%). The distillation bottom with unconverted substrate and the pyrrolidone-potassium-catalyst could be reused in the vinylation of another 5MP batch.

With these results we could show that bio-based methyl-substituted pyrrolidones can be vinylated into vinylpyrrolidone-monomers under industrial conditions with yields comparable to those in patent literature.[30] Hence, the reductive amidation/amination of biogenic carboxylic acids into 2-pyrrolidones enables a direct drop-in into the chemical value chain.

Green Chemistry

The direct amination and reduction of biogenic carboxylic acids with ammonia and molecular hydrogen to 2-pyrrolidones offers a great opportunity for green chemistry applications, as the product can be used as a direct drop-in for the industrial NVP production. Only a minimal amount of water is used as solvent to produce the methyl-2-pyrrolidones and water is also the sole co-product. Compared to our last publication[21], we could drastically reduce the required hydrogen pressure from 150 to 50 bar which does not only decrease investment costs but also energy demand for compression. At the same time our catalytic system is able to convert both itaconic and levulinic acid in yields >90% to the desired 2-pyrrolidones.

Conclusions

Palladium catalysts, synthesized via wet impregnation, were found to be highly active in the reductive amidation of itaconic acid with ammonia and molecular hydrogen to 3- and 4-methyl-2-pyrolidone. Compared to the former benchmark catalyst (commercial 5% Ru/C) the H_2 pressure could be reduced significantly from 150 to 50 bar together with an increase in activity (even with the reduced H_2 pressure). After

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optimization of the supporting material and activation procedure, an obvious trend between activity and Pd particle size could be identified. Pd nanoparticles with an average size of 1.8 – 2.2 nm supported on an oxidized carbon material were found to be most active (TOF ≈ 950 $\mathrm{mol_{Pyr}\cdot mol_{Pd\_surface}^{-1}\cdot h^{-1}}$) in the reductive amidation of itaconic acid. The synthesized group of catalysts is also highly active in the reductive amination of levulinic acid where productivities of more than 4000 $\mathrm{mol_{Pyr}\cdot mol_{Pd}^{-1}\cdot h^{-1}}$ and 5-methyl-2-pyrrolidone yields of >95% were achieved. The methyl-2-pyrrolidones were successfully vinylated with acetylene under industrial conditions with yields up to 80%. The overall yield of the two-step process from itaconic acid to vinylpyrrolidone monomers is 72%. Only the recycling of the catalyst remains challenging as the oxidized carbon material seems to break down during the reaction, as surface area and pore volume decrease drastically. Therefore, more stable supports will be investigated in future works.

Conflicts of interest

There are no conflicts to declare.

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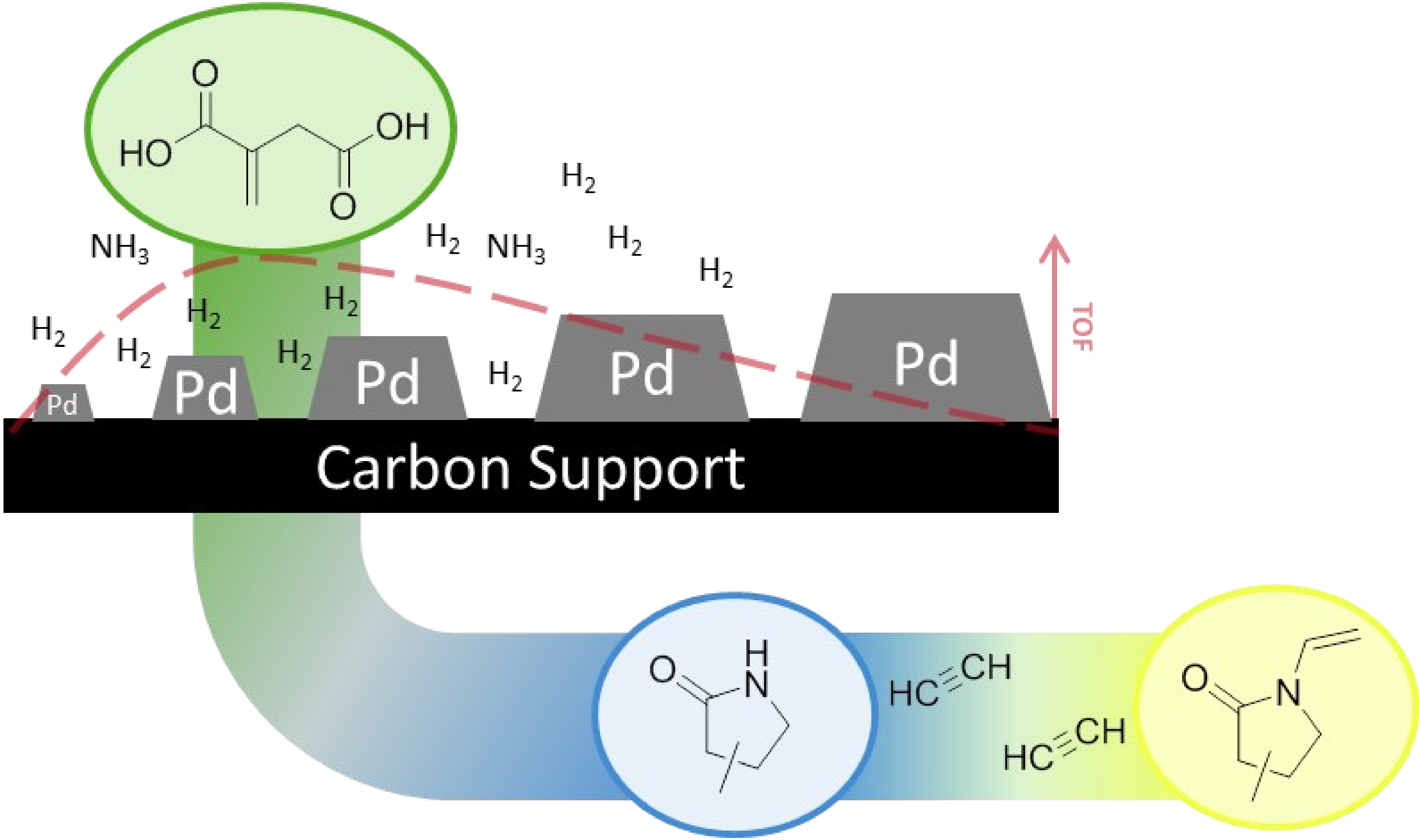
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