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Article

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Dehydrogenation of Alcohols to Carboxylic Acid Catalyzed by in-situ Generated Facial Ruthenium-CPP Complex

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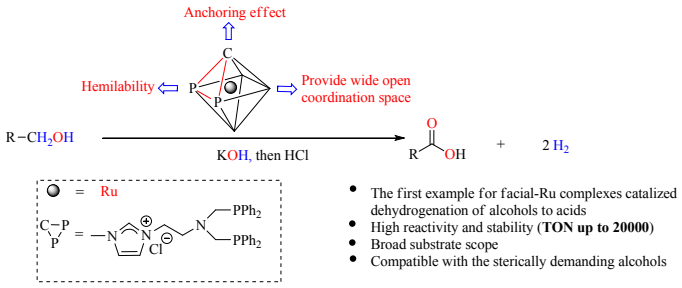


ABSTRACT: A selectively catalytic system for the dehydrogenation of primary alcohols to carboxylic acids using a facial ruthenium complex generated *in-situ* from the $[Ru(COD)Cl_2]_n$ and a hybrid NHC-phosphine-phosphine ligand (**CPP**) has been first reported. The facial coordination model was unveiled by NMR analysis of the reaction mixture. Such *fac*-ruthenium catalyst system exhibited high catalytic activity and stability, and a high turnover number of 20000 could be achieved with a catalyst loading as low as 0.002 mol%. The exceedingly high catalyst stability was tentatively

attributed to both the anchoring role of the NHC and the hemi-lability of the phosphine. The catalytic system also features a wide substrate scope. In particular, the facial coordination of **CPP** ligand was found to be beneficial for the sterically hindered alcohols, and the *ortho*-substituted benzylic alcohols and bulky adamantanyl-methanol as well as the cholesterol were all viable dehydrogenation substrates.

INTRODUCTION

The selective oxidation of primary alcohols to carboxylic acids is an important transformation in both academic research and industrial production.[1] Traditionally, either the stochiometric amount of toxic (in) organic oxidant[2] or the hydrogen acceptor reagents[3] are required to accomplish this transformation. However, the low atom efficiency and frequently generated heavy metal and organic wastes does not meet the requirements of atom economy and environment concerns. In recent years, acceptorless alcohol dehydrogenation system has emerged as a green alternative method, where without any oxidant or hydrogen acceptor is required and the only by-product is the molecule hydrogen which could be used as a fuel.[4-18]

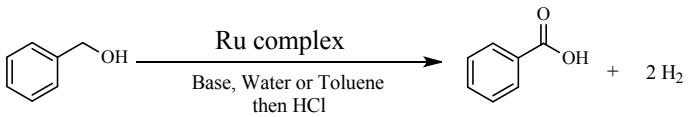
A wide range of efficient catalytic system based on Ru,[4-13] Rh,[14] Ir,[15] Fe,[16] Ni[17] and Mn[16,18] complexes have been investigated in such an acceptorless alcohol dehydrogenation reaction. Among them, the most studied catalyst precursors are the ruthenium-based complexes modified by different ligands. The first example of homogeneously catalyzed transformation of alcohols to carboxylic acids was reported

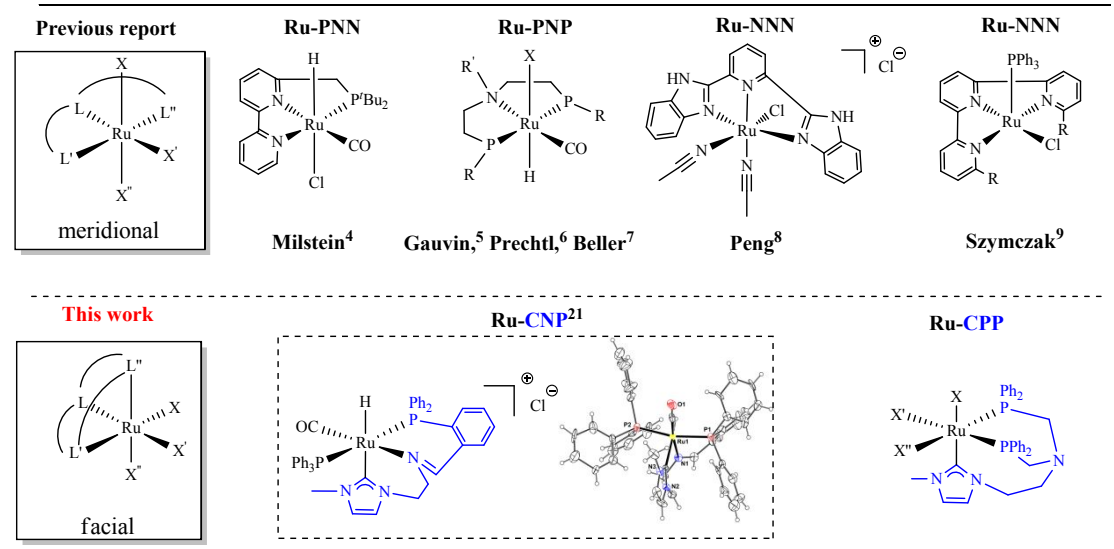
by Milstein et al. in 2013 by using the ruthenium complex with a PNN-type pincer ligand.[4a] Since then, several other ruthenium complexes containing PNP[5-7] and NNN[8,9] pincer ligands, have also been successfully used in this reaction (**Scheme 1**). These tridentate "pincer ligands" tend to coordinate in a meridional geometry around the metal center, and embrace a planar framework,[19] which crosscuts the coordination sphere around the metal center. Although such a meridional geometry offers an enhanced stability to the resulting pincer complexes, which exhibited good catalytic performance in the acceptorless alcohol dehydrogenation reaction, these *mer*-Ru complexes are too rigid to reflect hemi-lability which is beneficial for the catalytic reactivity due to the formation of two five-membered rings around the Ru center.

Recently, our group has developed two new hybrid *N*-heterocyclic carbene (NHC) phosphine ligands, one is pincer type **CNP** and the another is tripodal **CPP,** their structures are shown in Scheme 1. Due to their coordination sites are far away from each other by 4 to 5 bonds, these ligands tend to form a more flexible six-, seven- or even eight-membered ring upon coordination with the metal center. Such structural features may enforce them forming a facial configuration,[20,21] in which three chelating atoms occupy one face of the octahedron. The facial configuration for the RuH(CO)(PPh_3)(κ^3-CNP)]Cl complex (**Ru-CNP** for short) has already been ambiguously confirmed by its X-ray structure in our previous work.[21] In comparison with the previously reported meridional Ru complexes, these facial Ru complexes own both a more flexible framework backbone and an open wide coordination space around

the metal center. We envisioned that such *fac*-Ru/NHC complexes would exhibit the following advantages in the catalytic process: (1) the NHC moiety could anchor the metal center by robust bonding; (2) the hemilabile phosphine/amine moiety could stabilize the coordinatively unsaturated catalytic species; (3) the wide coordination space could provide more opportunity to accommodate the substrate. Most likely benefit from these advantages, the *fac*-Ru complexes showed excellent catalytic properties in our previous reported catalytic *N*-alkylation of aromatic amine[22] and the acceperless-dehydrogention of alcohol.[21] Encouragingly, the above-mentioned ***fac*-Ru-CNP** complex has successfully enabled the cross-coupling dehydrogenative cross-coupling of primary alcohols to form cross-esters, which is difficult to achieve and scarcely been reported in meridional Ru complex systems.[21] Following our continuing interest in the catalytic facial Ru complex, we herein demonstrate that they are also efficient catalysts for the acceptor-less dehydrogenation of alcohol to carboxylic acid. To the best of our knowledge, this is the first report of *fac*-ruthenium complexes in acceptorless alcohol dehydrogenation to carboxylic acid.

Scheme 1. The Representative Pincer Type Ligands Used in the Ru-catalyzed Dehydrogenation of Primary Alcohol to Acids





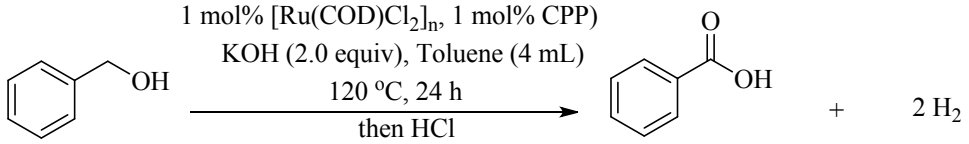
RESULTS AND DISCUSSION

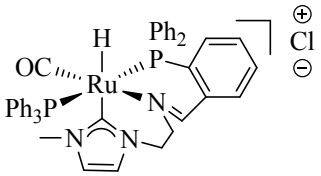
Initially, the benzyl alcohol was chosen as the substrate to evaluate the catalytic properties of the *fac*-Ru-complex in acceptorless dehydrogenation of alcohol to carboxylic acid. In our previous report,[21] we demonstrated that the ***fac*-Ru-CNP** complex is an excellent catalyst for dehydrogenation of alcohol to ester. The dehydrogenation of benzyl alcohol (1 mmol) catalyzed by 1 mol% ***fac*-Ru-CNP** in toluene at 110 ℃ for 24 h in the presence of 0.5 of equiv Cs_2CO_3 led to the selective formation of benzyl benzoate in 94% yield. We supposed that the increase of the basicity and the nucleophilicity of the base would be favorable to form the carboxylic acid. As expected, a significant amount of benzoic acid was detected when using 0.5 equiv of KOH instead of Cs_2CO_3 as the base. Increase the amount of KOH to 1.0 equiv rapidly increased the carboxylic acid to 69% yield. We were pleased to find that the 1

mol% of $[Ru(COD)Cl_2]_n$/**CPP** (**Ru-CPP** for short) as the catalyst was even much superior to the ***fac*-Ru-CNP,** affording the benzoic acid in 85% and 99% yield, in the presence of 1.0 equiv and 2.0 equiv KOH, respectively. Accordingly, the **Ru-CPP** was selected as the catalyst in the following experiment (**Table 1**).

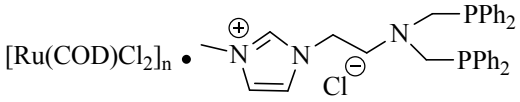
The controlled experiments showed that other hydroxide type bases, such as NaOH and CsOH were less efficient than KOH (**entries 2 and 3**). The ligand **CPP** play a key role in maintaining the catalyst activity, since the absence of it only led to a lower yield of 21%. Different kinds of solvents were also briefly investigated, and it was found that besides the toluene, the dioxane is also a proper solvent for this reaction. Considering the relatively low solubility of potassium carboxylate in toluene than that in dioxane, we have chosen the toluene as the optimal solvent (**Table 1**).

Table 1. Optimization of Reaction Conditions for the Dehydrogenation of Benzyl Alcohol to Carboxylic Acid[a]





Ru-CNP



Ru-CPP

Cs_2CO_3, 0.5 eq, trace
KOH, 0.5 eq, 4%
KOH, 1.0 eq, 69%
KOH, 2.0 eq, 72%

85%
>99%

Entry	Deviation from the standard condition	Yield (%)
1	No change	>99
2	NaOH instead of KOH	73
3	CsOH instead of KOH	65
4	in absence of **CPP**	21
5	DMF or DMSO instead of toluene	trace
6	Dioxane instead of toluene	97

[a] Standard conditions: 1.0 mol% of $[Ru(COD)Cl_2]_n$, 1 mol% of ligand **CPP**, benzyl alcohol (1 mmol) and 2.0 equiv KOH in toluene (4 mL) at 120 °C for 24 h under the nitrogen atmosphere. Yields were determined by GC.

The advantage of toluene as solvent is that it allows for the easy isolation of the product from the catalyst system.[10] The generated potassium carboxylate was easily precipitated due to the low solubility in toluene, which, after simple filtration, could be converted into the acids by acidifying with aqueous HCl. While, the filtrate containing the catalyst would be recycled. Then, we used the benzyl alcohol as the substrate to demonstrate the catalyst recyclability, after the produced potassium benzoate was isolated by filtration, and the remaining solution was subjected to the next catalytic cycle. The outcome showed that the catalyst in the filtrate could be recycled for 5 times, albeit with a remarkable decreased yield in the fifth cycle (see SI, **Figure S1**). In addition, to test the efficiency and the stability of this catalytic system, two large scale experiments were conducted with the substrate to catalyst ratio being 10000:1, and 50000:1, respectively. As shown in Figure 1, in the former case the conversion of benzyl alcohol increased gradually with the prolonged reaction time, even after six days. After six days, benzyl alcohol has been converted into carboxylic acid. It should be mentioned that a turnover number (TON) of 20000 for this Ru catalyst could be achieved by employing 0.002 mol% of catalyst after the reaction proceeded 3 days. This is so far the highest TON value for the Ru catalyzed dehydrogenation of primary alcohol to acid. All these results revealed that the **Ru-CPP** is a highly active and robust catalyst for the acceptorless dehydrogenation of alcohol to carboxylic acid.

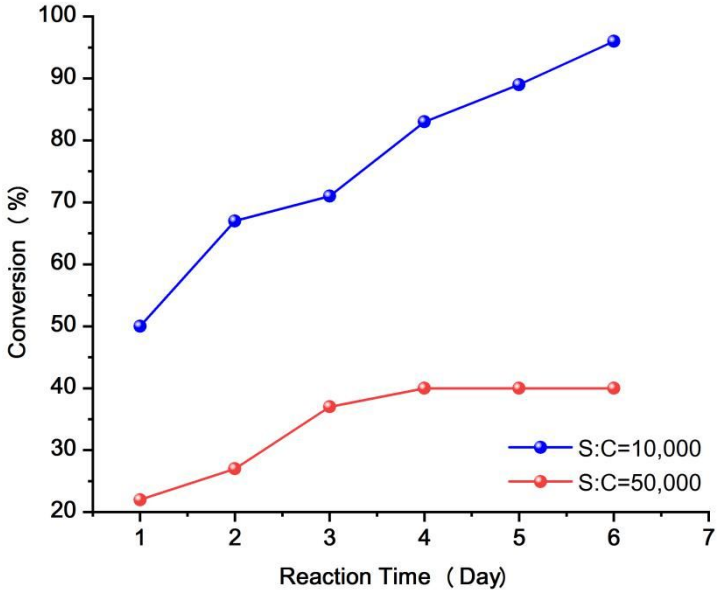
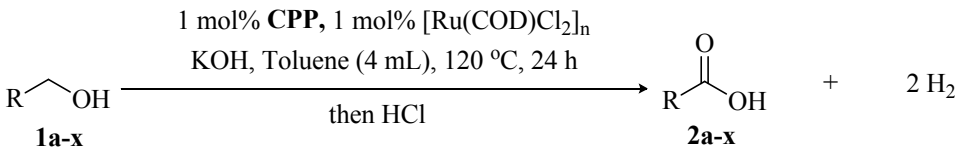


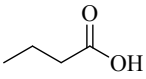
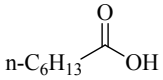
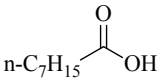
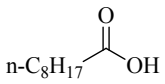
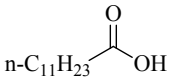
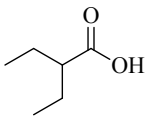
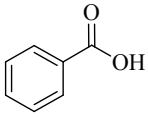
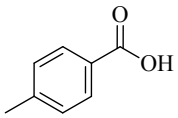
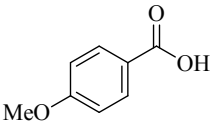
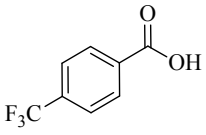
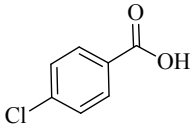
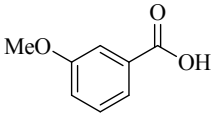
Figure 1. The Influence of Reaction Time on the Conversion.

After the establishment of the robust catalytic system: 1 mol% of **CPP**, 1 mol% of $[Ru(COD)Cl_2]_n$, and 2.0 equiv of KOH in toluene at 120 °C for 24 h under the nitrogen atmosphere, we next investigated the substrate scope in terms of alcohols. A wide range of alcohols including aliphatic, (hetero)aromatic alcohols were studied (**Table 2**). The catalytic system exhibited a wide substrate scope and all the tested alcohols could be smoothly converted into the carboxylic acids under the optimal condition in 25-99% isolated yields. In case of aliphatic alcohols, the yields of the reaction were generally high ranging from 55-98% (**Table 2, 2a-2f**). Various benzylic alcohol derivatives also reacted well in this system (**Table 2**, **2g-2x**). For the benzylic alcohols bearing a

substituent at the *meta*/*para* position of the aromatic ring, the yields were higher than 90%, regardless of the substituent is electron-rich or -poor (**Table 2**, **2h-2m**). It is worth mentioning that sterically demanding substrates, such as the adamantanyl-methanol and the *ortho*-substituted benzylic alcohols, could also undergo this transformation smoothly to afford corresponding carboxylic acids in good yields of 31-96% (**Table 2**, **2n-2s**). So far, only few examples of sterically demanding alcohols have been demonstrated in the dehydrogenation reaction.[4a,15b,18] Take the adamantanyl-methanol for example, there are only two catalytic systems being reported, which suffer from the either low reactivity[15b] or forcing reaction conditions.[23] These results showed that our designed ***fac*-Ru-CPP** catalyst was advantageous for the alcohol with large steric hindrance. However, for the aromatic alcohols bearing an electron-deficient group at *ortho*-position, the reaction outcome is often complicated, possibly due to the undesirable side-reactions. For example, when using 2-(2-nitrophenyl)ethan-1-ol as the dehydrogenation substrate, we unexpectedly obtained the indole as the major product in 35% GC yield (**Table 2**, **2t**). The reason might be that the nitro group serve as the hydrogen acceptor during the alcohol dehydrogenation process, and the resulted aldehyde and amino functional groups would then condense to give the indole.[24] Finally, the 2-naphthalenemethanol was easily converted into 2-naphthoic acid in 90% yield (**Table 2**, **2u**). Furthermore, heteroaryl alcohols, such as 3-thiophenylmethanol, 2-furanylmethanol and 3-pyridinylmethanol were also well tolerated, and generating the corresponding product in 25-92% yield (**Table 2**, **2v-x**).

Table 2. Dehydrogenation of Different Primary Alcohols to Carboxylic Acids[a]



			
2a, 79%	**2b 95%**	**2c 94%**	**2d 98%**
			
2e 90%	**2f 55%**	**2g 92%**	**2h 95%**
			
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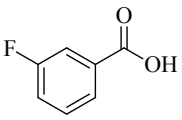
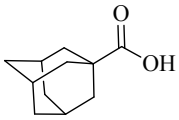
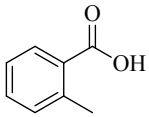
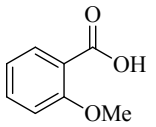
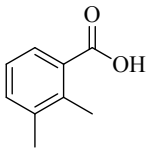
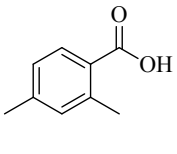
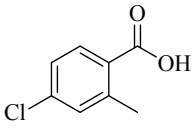
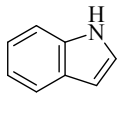
			
2m 94%	**2n 72%**	**2o 96%**	**2p 31%**
			
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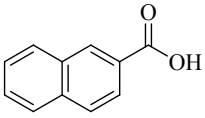
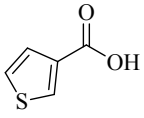
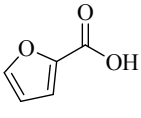
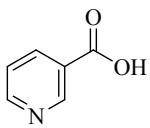
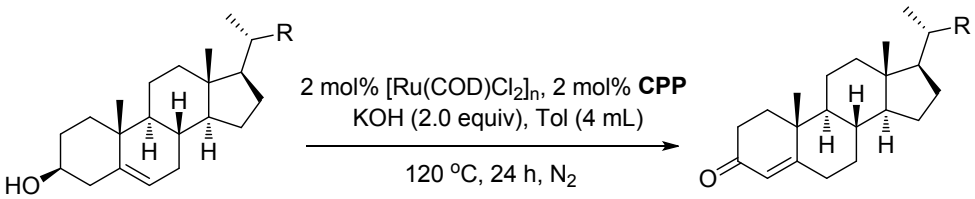
			
2u 90%	**2v 76%**	**2w 25%**	**2x 92%**

[a] Reaction conditions: $[Ru(COD)Cl_2]_n$ (1 mol%), ligand **CPP** (1 mol%), alcohol (1 mmol) and KOH (2.0 equiv) in toluene (4 mL) at 120 °C for 24 h under the nitrogen atmosphere; After of the reaction, the corresponding acid salts was converted to carboxylic acids by treatment with hydrochloric acid (4 mmol); the isolated yield.

As noted earlier, the facial Ru-complex may provide a wide-open coordination space

around the Ru center and hence is beneficial for the large molecules approaching. To further confirm this, we selected a more sterically hindered molecule cholesterol as the dehydrogenation substrate. To our pleasure, the facial-Ru catalytic system was proved to be capable of dehydrogenation of the cholesterol and followed by double bond isomerization to give cholest-4-en-3-one in 42% yield. The reason for the double bond isomerization of the dehydrogenative product might be the presence of a base in the system, since the base was believed to act a promoter in double bond isomerization to the thermodynamically more stable products.[25] The cholest-4-en-3-one is a potentially bioactive compounds[26] and often prepared from cholesterol under enzyme catalysis.[27] While the chemical oxidation of the cholesterol usually use the stochiometric amount of toxic oxidation reagents such as Martin,[28] $PhI(OAc)_2$,[29] *N*-chlorosuccinimide,[30] *etc*. We herein present the first example of dehydrogenative oxidation of cholesterol (**Scheme 2**).

Scheme 2. **Ru-CPP** Catalyzed Dehydrogenation of Cholesterol



1y, R = $-(CH_2)_3CH(CH_3)_2$ **2y**, 42% isolated yield

In order to get further information about the reaction mechanism, we performed the

following experiments. Firstly, in order to find out the oxygen source for the oxidation of primary alcohols to acids, we reacted the benzyl alcohol with the ^{18}O-labeled and nonlabelled potassium hydroxide, respectively, then analyzed the produced potassium benzoates using IR, ESI/MS and NMR. In the former case, a wave number of 1677 cm^{-1} was detected in IR spectrum, which is obviously lower than 1693 cm^{-1} for the potassium benzoate obtained from the nonlabelled KOH (**Table 3**). In addition, the electro-spray ionization/mass spectrum (ESI/MS) of the sample prepared from the ^{18}O labeled KOH display two major peaks at m/z = 125.04 and 123.04 and one minor peak at 121.03, while only one peak at m/z = 121.03 was observed for the latter case. The peaks at m/z = 123.04 and 125.04 correspond to the benzoic salts labeled with one and two ^{18}O atoms, respectively. The two ^{18}O atoms incorporation is presumed to arise from the Cannizzaro reaction of the intermediate benzaldehyde mediated by ^{18}O-labled KOH (**see SI**, **Figure S2-7**). Similarly, ^{13}C NMR spectrum showed three resonance signals for carboxylic group of potassium benzoate at 167.34, 167.32, 167.29 ppm in the former case, while in contrast, only one peak at 167.34 ppm was shown in the latter case (**see SI, Figure S2**). All of these results revealed that the oxygen atom incorporated into the carboxylic acids originate from potassium hydroxide.

Table 3. Comparative Data of the Benzoic Acids Prepared From $K^{18}OH$ and KOH

	$K^{18}OH$	KOH
IR(cm^{-1})	1677	1693

m/z	121.03, 123.04, 125.04	121.03
Chemical shift for ^{13}C NMR	167.34, 167.32, 167.29	167.34

Then, the evolution of H_2 gas was measured by reacting 1.0 mmol of benzyl alcohol in a Schlenk tube connected to a burette filled with water. A total volume of evolved dihydrogen gas was 44.5 mL, corresponding to approximately 1.9 mmol, which was calculated using the ideal gas law. The molar amount of which confirms that 2 equiv of dihydrogen is released during the dehydrogenation reaction (**Figure 2**). This is in line with Madsen's previous report.[10] It was shown from the H_2 evolution experiments that the rate of dehydrogenation of benzyl alcohol was fast and the reaction was completed within 7 h, but in view of the relatively low reactivity of the aliphatic acohols (**see SI, Table S1**), we prolonged the reaction time to 24 h when investigated the substrate scope (**see Table 2**).

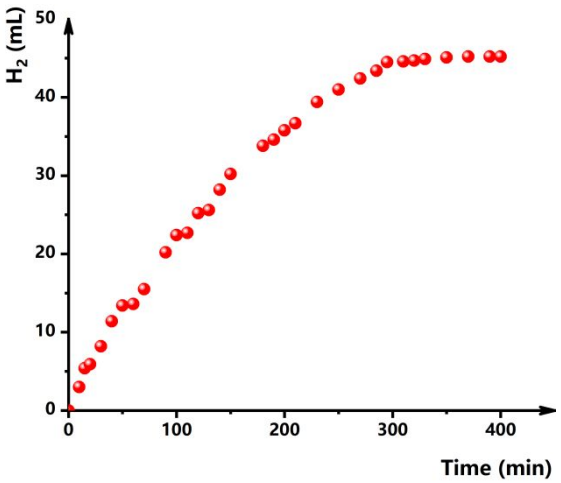
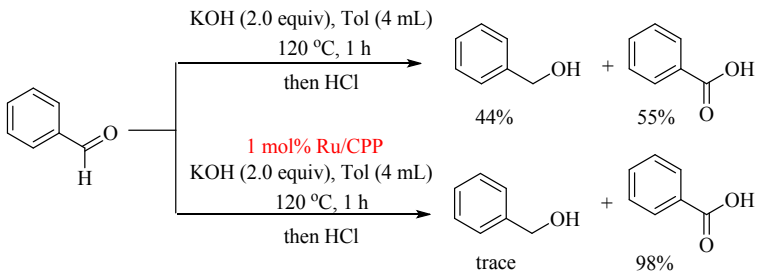


Figure 2. Evolution of Dihydrogen Over Time.

Reaction conditions: $[Ru(COD)Cl_2]_n$ (1 mol%), ligand **CPP** (1 mol%), benzyl alcohol (1 mmol) and KOH (2.0 equiv) in toluene (4 mL) at 120 °C for 7 h under the nitrogen atmosphere.

Considering the intermediate benzaldehyde could undergo a Cannizzaro reaction in the presence of KOH, two parallel experiments with and without the Ru-complex were conducted in toluene at 120 °C for 1 h, and after neutralization with aqueous HCl, the benzoic acid was obtained in 55% and 98% yields, respectively (**Scheme 3**). These results clearly demonstrated that both the Cannizzaro and the Ru-catalyzed dehydrogenation pathway are operating in case of the benzylic alcohol derivatives as substrates.[10]

Scheme 3. Cannizzaro and Dehydrogenation Reaction of Benzaldehyde



Then, we conducted a mercury poisoning experiment[31] under the standard reaction condition, by adding 500 equivalents of mercury with respect to $[Ru(COD)Cl_2]_n$. The dehydrogenation yield of benzyl alcohol in the presence of mercury resulted in 78% yield after 15 h, without significant decrease in activity. The result indicates that the ruthenium nanoparticles are not formed during the catalytic cycle. Furthermore, the

kinetic profile of hydrogen evolution did not exhibit **S** curve,[32] and without inductive time was observed, thus revealing that the reaction follows a homogenous catalytic pathway.

However, possibly due to the structural flexibility and fluxionality of the *fac*-**Ru-CPP** complex, the attempt to isolate it was not successful. We therefore studied the benzyl alcohol dehydrogenation process using the *in-situ* NMR experiments to get further information on the coordination behavior of the **CPP** ligand (**Figure 3**). Firstly, a deuterated toluene solution containing 0.5 mmol of benzyl alcohol, 10 mol% of **CPP**, 0.5 mmol of KOH and 10 mol% of $[Ru(COD)Cl_2]_n$ was heated to 120 ^oC under the nitrogen atmosphere for 1 h, then which was then submitted to ^1H NMR analysis, the spectrum displays two dd (doublet of doublets) peaks in the typical hydride region at −6.35 ppm and −6.75 ppm, both of them share with the same coupling constants ($^2J_{H-P}$ = 15.2 Hz and $^2J_{H-H}$ = 2.4 Hz). This observation serves as a key evidence pointing to the two facts: (1) A $[RuH_2]$ species is present in the catalytic system, which was coordinated with only one P atom of the ligand **CPP**; (2) In this species, the two hydrides and the P atom coordinates in a cis configuration to each other. This conclusion is in good agreement with our previously report.[22] Particularly, this typical $[RuH_2]$ species was only observed in the system with the presence of both the benzyl alcohol and KOH, and it disappeared after removal of either of them. Apart from $[RuH_2]$, there also exist a singlet at 9.6 ppm, a characteristic peak of the benzaldehyde, which probably produced from the dehydrogenation of the benzyl alcohol. These facts

indicated that the two hydrides most likely come from the benzyl alcohol via its coordination to **Ru-CPP** complex followed by a KOH promoted β-hydride elimination process.

The sample taken from the above-mentioned solution was also analyzed by ^{31}P NMR. Interestingly, no signal was shown in the typical range for free phosphine, which usually resonates at upfield in a negative value. The reason was probably due to the equilibrium between the intermediates **a** and **b** (**Figure 3**), which is so fast that, on the NMR time scale, no free phosphorus can be detected.[33] Indeed, the two doublets at 88 ppm and 71 ppm in ^{31}P NMR, which have the same coupling constant of 30 Hz (**Figure 3**), suggesting the presence of a Ru species with two P atoms arranged cis to each other around the Ru center.[34] In addition, no large P, P coupling was observed in ^{31}P NMR spectrum of the reaction mixture. These results revealed that ligand **CPP** most likely adopts a facial coordination in the catalytic Ru species, which is in line with the previous literature report by Venanzi, who demonstrated that a tripodal triphosphine was prone to adopt a facial coordination with Ruthenium.[35] In addition, two broad signals centered at 31 ppm and 23 ppm further supported a fast equilibrium among all the fluxional ruthenium species. The fluxionality of these ruthenium intermediates is probably attributed to the presence of a hemilabile P-donor, which could dissociate and coordinate in a hemilabile manner, thus both promoting for substrate binding and the product dissociation steps. Furthermore, the hemilabile phosphorous in the **CPP** ligand is constrained within close proximity of the Ru coordinating sphere due to the anchoring

effect of NHC moiety, which may benefit greatly to the catalyst stability. Therefore, the aforementioned high TON value for Ru catalyst could be obtained.

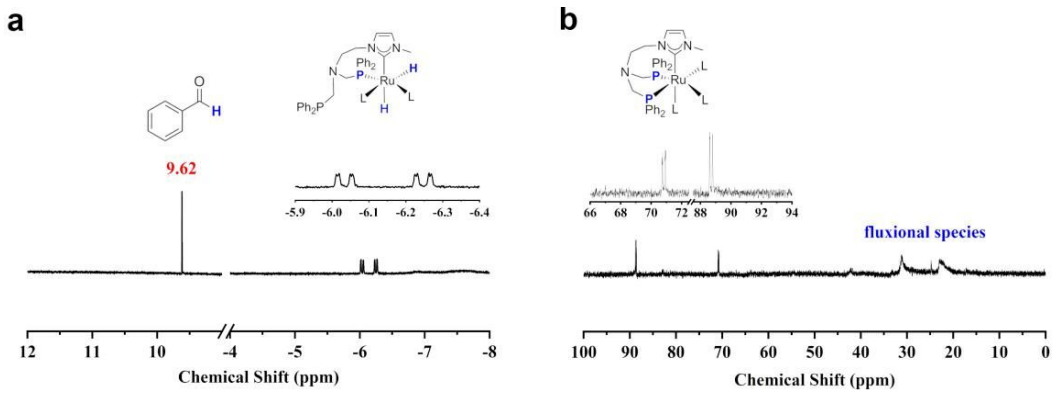
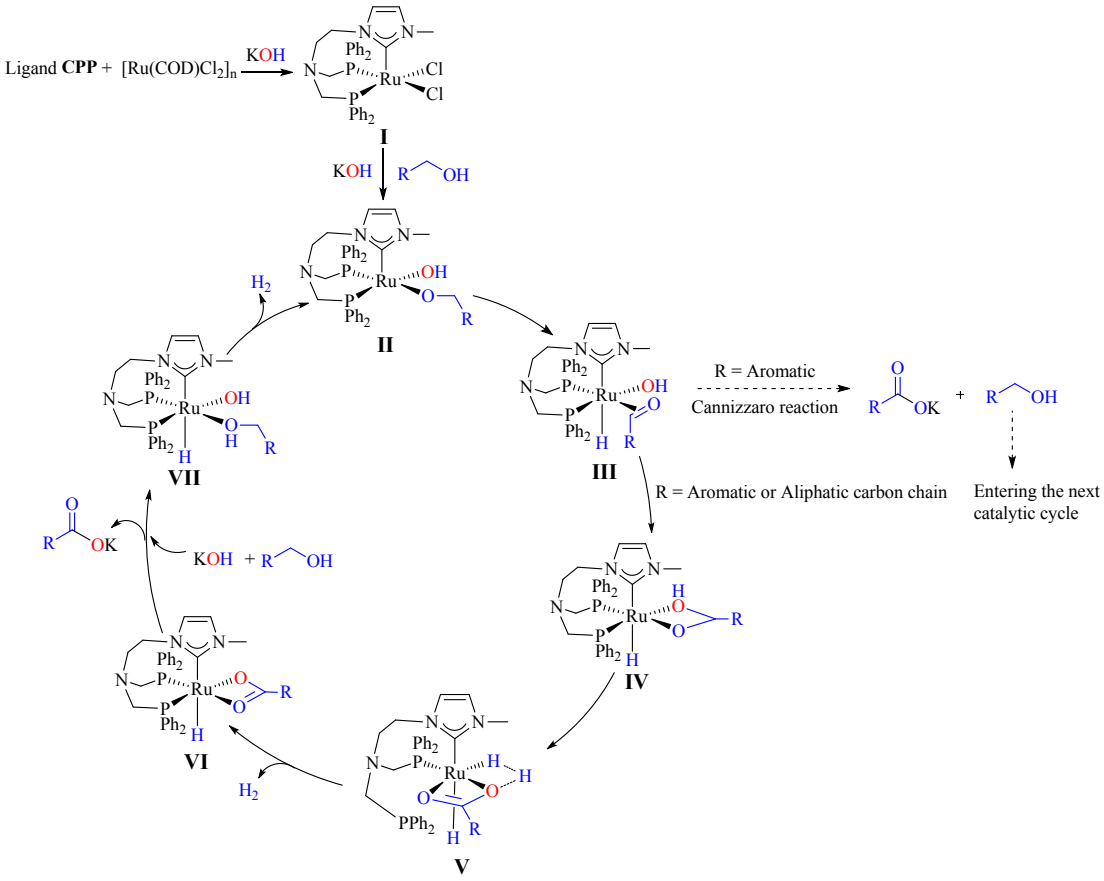


Figure 3. ^{1}H NMR (400 MHz, toluene-d_8) and ^{31}P NMR (162 MHz, toluene-d_8) Spectra Evidencing the Presence of RuH_2 (a) and the Facial Ru-complexes (b) in the Reaction Mixture.

On the basis of these results and the previous Madsen's report,[10] we proposed a possible mechanism for the reaction in Scheme 4. First, the ligand **CPP** replaces the cycloocta-1,5-diene when mixed with $[Ru(COD)Cl_2]_n$ to give the dichloride ruthenium precatalyst **I**, which then occurs the dissociation of chlorine and coordination of hydroxyl anion and the primary alcohol to generate **Ru-CCP** complex **II**. The catalytic cycle is initiated by β-hydride elimination of the alkoxyl ligand, which deliver the important Ru-H species **III** with concomitant formation of the aldehyde. At this stage, the resulting aldehyde may dissociate or coordinated with the Ru center in an equilibrium form. For the coordinated form, the cis hydroxide ligand readily undergoes a nucleophilic attack to the carbonyl group of the aldehyde, producing a ruthenium

intermediate **IV** bearing a hemiacetal ligand, where another β-hydride elimination take place to give a RuH_2 species **V**. In this step the hemilabile P atom is dissociated to provide the vacant site for β-hydride elimination. From the intermediate **V**, the first molecule of H_2 was released, simultaneously the free P atom dissociated in the previous step coordinated back to stabilize the newly formed Ru-H species **VI**. The product potassium carboxylate was generated from **VI** *via* the carboxylate group replacement by OH^-, accompanied by the coordination of another primary alcohol to give Ru-H species **VII**, upon which the second H_2 is liberated, thus close the catalytic circle with regeneration of the Ru complex **II**. It should be mentioned that in case of benzylic alcohols, the intermediate aromatic aldehyde dissociated from **III** can also be transformed into the carboxylic acid via the Cannizzaro reaction. Finally, the peak displayed at m/z = 747.1711 in the ESI/MS spectra of the catalytic system evidence the presence of the possible species II-V (the exact mass of them is 747.1717) (**see SI, Figure S3**), thus indicating the rationality of the proposed mechanism.

Scheme 4. Proposed Catalytic Cycle



CONCLUSIONS

In summary, a selectively catalytic dehydrogenation of primary alcohols to carboxylic acids by using a new type facial **Ru-CPP** catalyst was presented. This novel efficient system allows a simple and straightforward synthesis of carboxylic acids in good yields and the only by-product is the molecular hydrogen. The plausible mechanism was proposed on the basis of the controlled experiments and NMR studies. Benefit from the anchoring role of NHC, hemi-lability of phosphine, and the facial coordination of **CPP** ligand, the catalyst system featured a high catalytic activity and robust stability, as well

as a broad substrate scope.

EXPERIMENTAL SECTION

General Information: All reactions were carried out under nitrogen atmosphere unless otherwise stated. All solvents were dealt with standard purification method. All reagents were purchased from commercial suppliers and used as received, and moisture sensitive compounds were stored in glovebox. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded on the Bruker AVANCE III HD-400 MHz in $CDCl_3$, DMSO-d_6 or toluene-d_8. GC analysis was performed with Agilent 6890N (KB-1, 30 m × 0.32 mm × 0.25 μm) and Agilent 6890N-GC/MSD (GC-Mass). HR-MS was measured on SHIMADZU LCMS-IT-TOF mass spectrometer. **CPP** ligand and $[Ru(COD)Cl_2]_n$ were synthesized according to the reported method.[22]

Typical catalytic procedure: $[Ru(COD)Cl_2]_n$ (0.01 mmol Ru, 2.8 mg), ligand **CPP** (0.01 mmol, 5.6 mg) and KOH (2.0 mmol, 112 mg) were added into a dried reaction tube. After the tube was charged with N_2, benzyl alcohol (1 mmol, 108.1 mg) and toluene (4 mL) were added to it. The Schlenk tube was placed in a preheated heating mantle (T = 120 °C) for 24 h. At the end of the reaction, the mixture was cooled to room temperature, 2 M HCl (4 mL) and ethyl acetate (4 mL) were added to it, and then the mixture solution was extracted with ethyl acetate (5 ml×2), the combined organic phase was washed with saturated aqueous HCl (25 ml×2), dried over $MgSO_4$, filtered,

and purified by column chromatography to afford the desired product **2g** as a white solid in 92% yield (112 mg).

Physical Data of 2a−2y.

n-butanoic acid (2a).[4a] General procedure gave pale yellow oily liquid (70 mg, 79%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14 (s, 1H), 2.34 (t, J = 7.4 Hz, 2H), 1.75 – 1.59 (m, 2H), 0.97 (t, J = 7.4 Hz, 3H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 179.9, 35.9, 18.2, 13.6.

n-heptanoic acid (2b).[24] General procedure gave pale yellow oily liquid (124 mg, 95%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 11.97 (s, 1H), 2.18 (t, J = 7.4 Hz, 2H), 1.54 – 1.42 (m, 2H), 1.33 – 1.16 (m, 6H), 0.85 (t, J = 6.8 Hz, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 174.9, 34.1, 31.5, 28.7, 24.9, 22.4, 14.3.

n-octanoic acid (2c).[18] General procedure gave colorless oily liquid (135 mg, 94%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 11.99 (s, 1H), 2.18 (t, J = 7.4 Hz, 2H), 1.55 – 1.41 (m, 2H), 1.17 – 1.30 (m, 8H), 0.86 (t, J = 6.8 Hz, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 174.9, 34.1, 31.6, 28.9, 28.9, 24.9, 22.5, 14.4.

n-nonanoic acid (2d).[36] General procedure gave colorless oily liquid (155 mg, 98%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 11.96 (s, 1H), 2.18 (t, J = 7.4 Hz, 2H), 1.57 – 1.41 (m, 2H), 1.37 – 1.16 (m, 10H), 0.86 (t, J = 6.8 Hz, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 174.8, 34.1, 31.8, 29.2, 29.1, 29.0, 24.9, 22.6, 14.3.

n-dodecanoic acid (2e).[37] General procedure gave a white solid (180 mg, 90%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 11.96 (s, 1H), 2.18 (t, J = 7.4 Hz, 2H), 1.56 – 1.43 (m, 2H), 1.32 – 1.14 (m, 16H), 0.86 (t, J = 6.8 Hz, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 174.9, 34.1, 31.8, 29.5, 29.5, 29.4, 29.3, 29.2, 29.1, 24.9, 22.6, 14.3.

2-ethylbutyric acid (2f).[18] General procedure gave a oily liquid (64 mg, 55%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.09 (s, 1H), 2.27 – 2.14 (m, 1H), 1.68 – 1.59 (m, 2H), 1.57 – 1.49 (m, 2H), 0.93 (t, J = 7.4 Hz, 6H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 182.7, 48.9, 24.8, 11.7.

Benzoic acid (2g).[10] General procedure gave a white solid (112 mg, 92%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.98 (s, 1H), 7.96 (d, J = 7.0 Hz, 1H), 7.63 (t, J = 7.4 Hz, 1H), 7.51 (t, J = 7.6 Hz, 1H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.8, 133.3, 131.2, 129.7, 129.0.

4-methylbenzoic acid (2h).[24] General procedure gave a white solid (129 mg, 95%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.79 (s, 1H), 7.85 (d, J = 8.1 Hz, 2H), 7.31 (d, J = 8.0 Hz, 2H), 2.37 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.8, 143.5, 129.1, 129.6, 128.5, 21.6.

4-methoxybenzoic acid (2i).[27] General procedure gave a white solid (143 mg, 94%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.63 (s, 1H), 7.91 (d, J = 8.9 Hz, 2H), 7.02 (d, J = 8.9 Hz, 2H), 3.83 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.5, 163.3, 131.8, 123.4, 114.3, 55.9.

4-(trifluoromethyl)benzoic acid (2j).[15a] General procedure gave a white solid (165 mg, 87%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.49 (s, 1H), 8.15 (d, J = 8.1 Hz, 2H), 7.88 (d, J = 8.3 Hz, 2H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 166.7, 135.1, 132.9 (q, J = 31.9 Hz), 130.8, 126.1 (q, J = 3.7 Hz), 125.1 (q, J =274.7 Hz).

4-chlorobenzoicacid (2k).[14] General procedure gave a white solid (144 mg, 92%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.20 (s, 1H), 7.95 (d, J = 8.6 Hz, 2H), 7.58 (d, J = 8.5 Hz, 2H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 166.9, 138.3, 131.6, 130.1, 129.2.

3-methoxybenzoic acid (2l).[15a] General procedure gave a white solid (141 mg, 93%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.03 (s, 1H), 7.56 (d, J = 7.6 Hz, 1H), 7.47 (s, 1H), 7.43 (t, J = 7.9 Hz, 1H), 7.20 (d, J = 8.2 Hz, 1H), 3.82 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.6, 159.7, 132.6, 130.2, 122.0, 119.3, 114.3, 55.7.

3-fluorobenzoic acid (2m).[38] General procedure gave a white solid (132 mg, 94%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.31 (s, 1H), 7.80 (d, J = 7.6 Hz, 1H), 7.67 (d, J = 9.6 Hz, 1H), 7.55 – 7.60 (m, 1H), 7.53 – 7.46 (m, 1H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 166.7, 162.4 (d, J = 244.7 Hz), 133.7 (d, J = 7.2 Hz), 131.3 (d, J = 8.0 Hz), 125.9 (d, J = 2.8 Hz), 120.3 (d, J = 21.2 Hz), 116.2 (d, J = 22.6 Hz).

1-adamantane carboxylic acid (2n).[15b] General procedure gave a white solid (130 mg, 72%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 11.99 (s, 1H), 2.00 – 1.90 (m, 3H), 1.85 – 1.73 (m, 6H), 1.72 – 1.60 (m, 6H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 183.8, 40.5, 38.6, 36.4, 27.8.

2-methylbenzoic acid (2o).[14] General procedure gave a white solid (131 mg, 96%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.78 (s, 1H), 7.82 (d, J = 7.8 Hz, 1H), 7.44 (t, J = 7.5 Hz, 1H), 7.44 (t, J = 7.5 Hz, 2H), 2.53 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 169.1, 139.4, 132.1, 131.9, 130.9, 130.6, 126.2, 21.7.

2-methoxybenzoic acid (2p).[14] General procedure gave a white solid (47 mg, 31%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.57 (s, 1H), 7.61 (d, J = 5.8 Hz, 1H), 7.47 (t, J = 8.0 Hz, 1H), 7.09 (d, J = 8.1 Hz, 1H), 6.96 (t, J = 7.0 Hz, 1H), 3.78 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.8, 158.5, 133.5, 131.1, 121.7, 120.4, 112.8, 56.1.

2,3-dimethylbenzoic acid (2q).[39] General procedure gave a white solid (113 mg, 75%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.79 (s, 1H), 7.50 (d, J = 7.4 Hz, 1H), 7.28 (d, J = 7.4 Hz, 1H), 7.12 (t, J = 7.6 Hz, 1H), 2.35 (s, 3H), 2.24 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 170.2, 138.0, 136.7, 132.9, 132.5, 127.5, 125.6, 20.5, 16.7.

2,4-dimethylbenzoic acid (2r).[40] General procedure gave a white solid (110 mg, 73%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.62 (s, 1H), 7.72 (d, J = 7.8 Hz, 1H), 7.08 (d, J = 4.4 Hz, 1H), 7.05 (s, 1H), 2.46 (s, 3H), 2.28 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 168.9, 142.2, 139.7, 132.6, 130.9, 127.7, 126.9, 21.8, 21.3.

4-chloro-2-methylbenzoic acid (2s).[41] General procedure gave a white solid (116 mg, 68%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.00 (s, 1H), 7.83 (d, J = 8.4 Hz, 1H), 7.42 (s, 1H), 7.35 (d, J = 6.6 Hz, 1H), 2.52 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 134.7, 126.8, 123.1, 119.7, 118.8, 109.9, 101.6, 28.7.

Indole (2t).[30b] General procedure gave a white solid (41 mg, 35%) ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.08 (s, 1H), 7.58 (d, J = 7.6 Hz, 1H), 7.33 (d, J = 8.1 Hz, 1H), 7.16 – 7.10 (m, 2H), 7.05 (t, J = 7.0 Hz, 1H), 6.51 – 6.48 (m, 1H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 134.7, 126.8, 123.1, 120.9, 119.7, 118.8, 109.9, 101.6.

2-naphthalenecarboxylic acid (2u).[24] General procedure gave a white solid (155 mg, 90%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.11 (s, 1H), 8.63 (s, 1H), 8.13 (d, J = 7.9 Hz, 1H), 8.06 – 7.97 (m, 3H), 7.60 – 7.69 (m, 2H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 167.9, 135.4, 132.6, 130.9, 129.8, 128.8, 128.6, 128.5, 128.1, 127.3, 125.6.

Thiophene-3-carboxylic acid (2v).[18] General procedure gave a colourless needle crystal (97 mg, 76%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 12.73 (s, 1H), 8.27 (m, 1H), 7.66 – 7.58 (m, 1H), 7.50 – 7.41 (m, 1H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 164.1, 134.8, 133.8, 128.2, 127.7.

2-furancarboxylic acid (2w).[3d] General procedure gave a white solid (28 mg, 25%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.58 (s, 1H), 7.65 – 7.50 (m, 1H), 7.33 – 7.21 (m, 1H), 6.53 – 6.43 (m, 1H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 162.6, 146.4, 142.8, 119.1, 111.3.

3-pyridinecarboxylic acid (2x).[18] General procedure gave a colourless needle crystal (113 mg, 92%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 13.47 (s, 1H), 9.07 – 9.08 (m, 1H), 8.78 – 8.80 (m, 1H), 8.26 – 8.29 (m, 1H), 7.53 – 7.56 (m, 1H). ^{13}C NMR {^{1}H} (101 MHz, DMSO-d_6): δ 166.8, 153.8, 150.7, 137.4, 127.0, 124.3.

Cholest-4-en-3-one **(2y).**[26] General procedure gave pale yellow oily liquid (162 mg, 42%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.72 (s, 1H), 2.40 (ddd, *J* = 18.7, 15.4, 4.6 Hz, 3H), 2.33 – 2.22 (m, 1H), 2.06 – 1.97 (m, 2H), 1.90 – 1.77 (m, 2H), 1.74 – 1.19 (m, 12H), 1.17 (s, 3H), 1.16 – 1.14 (m, 1H), 1.14 – 1.10 (m, 3H), 1.09 – 1.06 (m, 1H), 1.06 – 0.96 (m, 3H), 0.90 (d, *J* = 6.5 Hz, 3H), 0.86 (dd, *J* = 6.6, 1.8 Hz, 6H), 0.70 (s, 3H). ^{13}C NMR {^{1}H} (101 MHz, $CDCl_3$): δ 199.8, 171.9, 123.8, 56.2, 56.0, 53.9, 42.5, 39.7, 39.6, 38.7, 36.2, 35.7, 35.8, 35.7, 34.1, 33.1, 32.1, 28.3, 28.1, 24.3, 23.9, 23.0, 22.7, 21.1, 18.8, 17.5, 12.1. HRMS (ESI-MS) calcd for $C_{27}H_{45}O^+$ ($M + H^+$) 385.3470, found 385.3468.

ASSOCIATED CONTENT

Supporting Information

The supplementary experimental data. Contained figures of Catalyst recycling, Labeling experiments with K^{18}OH and ^{1}H and ^{13}C NMR spectra for all products (PDF).

ACKNOWLEDGMENT

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