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Preparation of $Ru_3(CO)_8$-pyridine-alcohol cluster and its use for selective catalytic transformation of primary to secondary amines†

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Abstract

The synthesis of pyridine alcohol based ruthenium carbonyl clusters $Ru_3(hep)_2(CO)_8$ (**1**), $Ru_3(hpp)_2(CO)_8$ (**2**), and $Ru_3(bhmp\text{-}H)_2(CO)_8$ (**3**) {hep-H = 2-(2-hydroxyethyl)pyridine, hpp-H = 2-(3-hydroxypropyl)pyridine and bhmp-H_2 = 2,6-bis(hydroxymethyl)pyridine} has been carried out by the reaction of corresponding pyridine-alcohol ligands with $Ru_3(CO)_{12}$. Clusters **1**–**3** have been characterized by elemental analysis, NMR, FT-IR, TGA, mass spectrometry and single-crystal X-ray structures. The clusters were explored for selective catalytic transformation of primary amines into secondary amines using alcohols as the mono alkylating agents via hydrogen transfer reactions. All three display efficient catalytic activity with **1** being the most effective.

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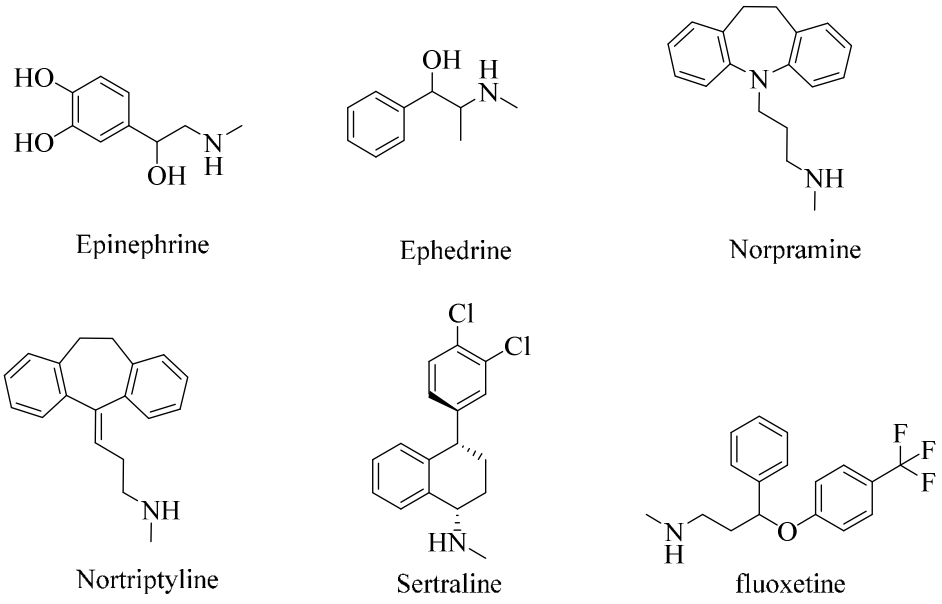
Introduction

Pyridines based ruthenium complexes and clusters have attracted much attention over the last few decades as innovative catalysts for selective transformations and functionalization of specific substrates.[1-8] Park and Ko et al. have reported the influence of the size of the alkyl formate chain in a 2-alkylformate ligand with $Ru_3(CO)_{12}$ as the catalyst for the hydroesterification reactions of alkenes without decarbonylation incase of 2-pyridyl methylformate.[9, 10] Ko et al. also introduced chelating N-(pyridin-2-yl)formamide with $Ru_3(CO)_{12}$ as an efficient catalyst for hydroamidation reaction of alkenes.[11]



Epinephrine Ephedrine Norpramine

Nortriptyline Sertraline fluoxetine

Chart A. Secondary amine derivatives present in various psychoactive drugs

Preparation of secondary amines as scaffolds present in various psychoactive drugs[12-14] poses a challenge (Chart A), as alkylation of primary amine, in general, yields a mixture of secondary and tertiary amines.[15-19] Therefore, we undertook to study the selective N-alkylation of primary amines.

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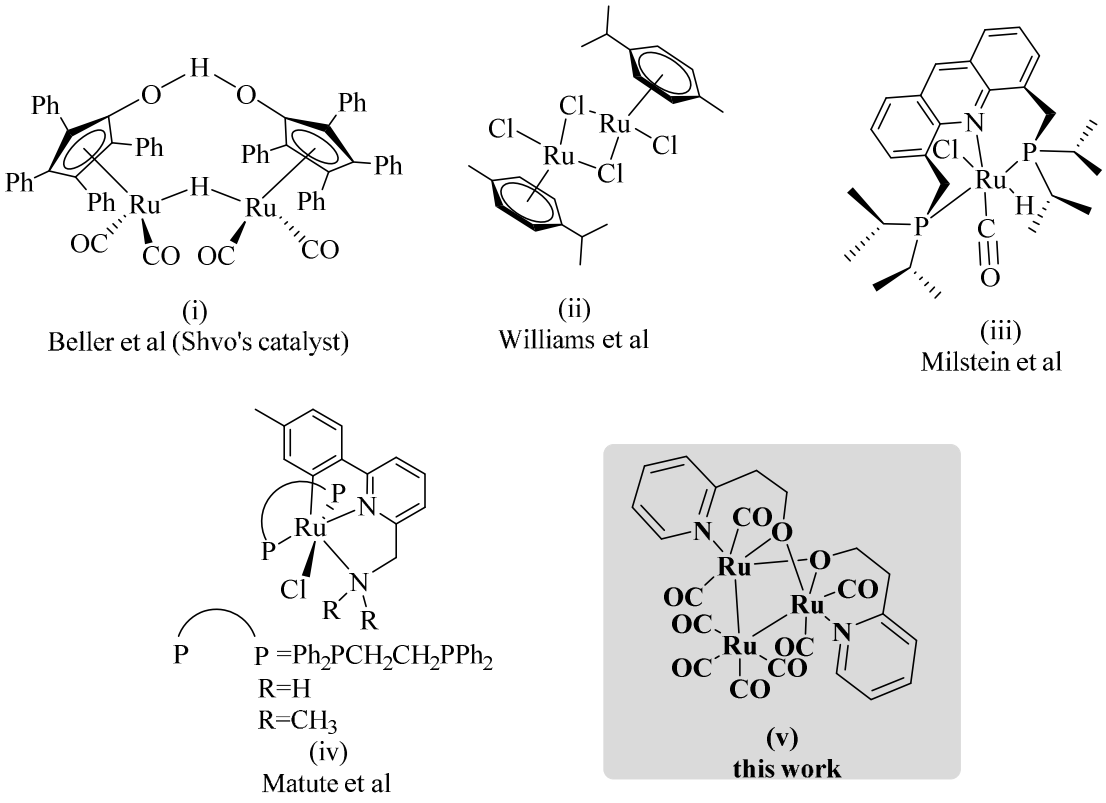

Chart B. Homogeneous catalysts (**i–iv**) used so far for N-alkylation of primary amine

Grigg[20] and Watanabe[21] have reported N-alkylation using homogeneous catalysts $RhH(PPh_3)_4$ and $RuCl_2(PPh_3)_3$, respectively. Yamaguchi[22] and Kempe[23, 24] used $[Cp^*IrCl_2]_2$, and [IrCl(PN)COD], respectively to perform N-mono and N,N-di alkylation reactions. Hollmann et al. utilized Shvo's ruthenium catalyst (Chart B, **i**) for alkylation of indoles[25] whereas Williams employed a ruthenium-dimer catalyst (Chart B, **ii**) for N-alkylation of primary amines.[26] Milstein and co-workers contributed to N-alkylation or the primary amine preparation from ammonia and primary alcohol using PNP pincer ruthenium complex (Chart B, **iii**) at high temperature (130–180 °C).[27] Matute and co-workers also reported N-alkylation of primary amines using Ru-CNN pincer complex (Chart B, i**v**)[28] whereas Ramachandran et al. made use of mononuclear phosphine-ruthenium complex for N-alkylation of primary amines.[29, 30]

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The earlier reported ruthenium catalysts for the N-alkylation of primary amine involve ruthenium-hydride, phosphine, or pincer ruthenium catalyst. Either the synthesis of those catalysts requires sophisticated conditions or the catalyst loading for the N-alkylation reaction is relatively high. In contrast, we report a facile preparation of ruthenium carbonyl clusters involving chelation of simple pyridine alcohol as ligands, with the catalyst loading as low as 0.5mol % which is much lower than previously reported other catalyst loading. Additionally, the cluster catalyst is found to be active for a variety of aromatic and aliphatic amines.

Kim et al. had shown that *in situ* addition of various pyridine alcohols viz. 2-hydroxypyridine, 2-(2-hydroxyethyl)pyridine, 2-(3-hydroxypropyl)pyridine and 2,6-bis(hydroxymethyl)pyridine along with $Ru_3(CO)_{12}$ and sodium formate catalyzed the hydroesterification reaction of alkenes at 170 °C, in which the 2-(hydroxymethyl)pyridine ligand offers better catalyst activity than other pyridine alcohols.[4] This proved that the chelating functional pyridine alcohols have a positive influence on $Ru_3(CO)_{12}$ to promote as a catalytic hydroesterification reaction of alkenes.

The chelation effect observations of pyridine-alcohol ligands motivated us to explore the structural modifications of the triruthenium unit by varying the nature and length of the side chain of the functional pyridine-alcohol ligands. Thus, the coordination of 2-(2-hydroxyethyl)pyridine (hep-H), 2-(3-hydroxypropyl)pyridine (hpp-H) and 2,6-bis(hydroxymethyl)pyridine (bhmp-H_2) with the $Ru_3(CO)_{12}$ precursor have been studied. We report that two of these ligands can be incorporated into the trinuclear structure to afford the ruthenium cluster complexes $Ru_3(hep)_2(CO)_8$ **(1)**, $Ru_3(hpp)_2(CO)_8$ **(2)**, and $Ru_3(bhmp\text{-}H)_2(CO)_8$ **(3)**. The compound **1** and its analogues have been reported by Doorn et al.,[31] Herein, we report for the first time the crystal structures of **1**–**3** which have the similar mode of ligand binding as reported by them.

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We also report that the clusters **1–3** catalyze the mono N-alkylation of primary amines with alcohols via a hydrogen transfer reaction resulting in the selective production of secondary amines and show the influence of the nature of the chelating ligand in the Ru_3 clusters as catalysts.

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Experimental

All reactions were done under an inert gas atmosphere. Ruthenium carbonyl, pyridine alcohols, and other alcohols along with amine derivatives were purchased from Aldrich and TCI chemicals. Reagents used for purification and crystallization were purchased either from Rankem or Merck and distilled before use. NMR spectra were recorded in deuterated acetone (CD_3COCD_3) on a Bruker Avance (III) spectrometer (400 MHz). Single crystal x-ray diffraction studies of complexes **1–3** were carried out using an Agilent Technologies Supernova CCD system. The mass chromatograms were recorded on a Bruker-Daltonics-microTOF-QII mass spectrometer. Elemental analysis was performed by using a Thermo Scientific FLASH 200 instrument. GC Samples were analyzed in Shimadzu QP2010 Ultra. The parameters used in the column oven program were as follows: 40 °C (hold 5 min.) →20 °C/min.→ 280 °C (hold 13 min.) along with injection temperature 280 °C, the interface temperature was 300 °C, and the ion source temperature was 220 °C.

Preparation of cluster $Ru_3(hep)_2(CO)_8$ (1).

Pyridin-2-yl-ethanol (113 μL, 1 mmol) and KOH (42 mg, 1.05 mmol), were placed into a round bottom flask using water (1 mL) as a solvent, and the reaction mixture was stirred for 1 hour at room temperature. After 1 hour, water was evaporated and residual water was removed using high vacuum pump. $Ru_3(CO)_{12}$ (0.320 g, 0.5 mmol) was added along with 25 mL of dry toluene into the same flask and refluxed at 110 °C for 3 hours, the yellow colored solution was cooled and evaporated by rotavapor, and the resulting precipitate was washed with hexane five times and once with a small quantity of diethyl ether. Later, the precipitate was dissolved in acetone-dichloromethane mixture; filtered using celite and the filtered solvent was evaporated. The residue was recrystallized in toluene solvent. The yellow coloured crystalline solid was obtained. The identity of the complex was determined by using ^1H and ^{13}C NMR, mass spectrometry, CHN elemental analysis and a single-

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crystal XRD study. Yield: 62% (0.240 g), ^{1}H NMR (400 MHz, acetone-d^{6}, 25 °C , ppm): δ 8.97 (d, 1H), 7.94 (t, 1H), 7.50 (t, 1H), 7.41 (d, 1H), 4.08 (tt, 1H), 3.04 (m, 2H), 2.68 (t, 1H); ^{13}C NMR (100 MHz, acetone-d^{6}, 25 °C, ppm): δ 205.4, 205.2, 203.9, 196.1, 162.7, 155.2, 139.8, 127.1, 124.6, 65.5, 43.6; Elem. Anal. Calcd: C, 34.25; H, 2.09; N, 3.63; Found: C, 34.29; H, 1.95; N, 3.64; Selected IR on (KBr, cm^{-1}): 2950(w), 2915(w), 2847(s), 2060(s), 1985(s), 1914(s), 1603(w), 1079(s); ESI-MS (m/z) 687.55.

Preparation of cluster $Ru_3(hpp)_2(CO)_8$ (2)

Using same conditions as those for $Ru_3(hep)_2(CO)_8$ **(1)** preparation, the $Ru_3(hpp)_2(CO)_8$ **(2)** complex was prepared by using the 2-pyridin-2-yl-propanol (129 μL, 1 mmol) with KOH (41 mg, 1.03 mmol) and $Ru_3(CO)_{12}$ (0.320 g, 0.5 mmol) into 25 mL of toluene as the solvent. After recrystallization, red coloured complex **2** was obtained. Yield: 54%, ^{1}H NMR (400 MHz, acetone-d^{6}, 25 °C , ppm): δ 8.78 (d, 1H), 7.79 (t, 1H), 7.32 (dd, 2H), 4.28 (t, 1H), 3.90 (d, 1H), 3.36 (t, 1H), 3.12 (dd, 1H), 1.95 (t, 1H), 1.55 (q, 1H); ^{13}C NMR (100 MHz, acetone-d^{6}, 25 °C, ppm): δ 206.2, 205.8, 203.4, 195.7, 166.8, 154.0, 139.8, 127.9, 123.8, 74.8, 38.1, 35.9; Elem. Anal. Calcd: C, 36.05; H, 2.52; N, 3.50; Found: C, 36.99; H, 2.43; N, 3.61; Selected IR on (KBr, cm^{-1}): 2943(w), 2912(w), 2840(s), 2066(s), 1987(s), 1914(s), 1602(w), 1085(s); ESI-MS (m/z) 542.61

Preparation of cluster $Ru_3(bhmp\text{-}H)_2(CO)_8$ (3)

Using same conditions as those for $Ru_3(hep)_2(CO)_8$ **(1)** preparation, the $Ru_3(bhmp\text{-}H)_2(CO)_8$ **(3)** complex was prepared by using the (6-hydroxymethyl-pyridin-2-yl)-methanol (0.139 g, 1 mmol) with KOH (40 mg, 1 mmol) and $Ru_3(CO)_{12}$ (0.320 g, 0.5 mmol) with 25 mL of toluene as the solvent. After recrystallization, yellow crystalline solid was obtained. Yield: 58%, ^{1}H NMR (400 MHz, acetone-d^{6}, 25 °C , ppm): δ 7.76 (d, 2H), 6.73 (t, 1H), 5.16 (m, 2H), 5.01 (m, 2H), 4.27 (d, 1H); ^{13}C NMR (100 MHz, acetone-d^{6}, 25 °C, ppm): δ 207.7, 204.5, 203.6, 193.9, 167.4, 162.9,

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138.7, 121.0, 117.3, 78.5, 68.0; Elem. Anal. Calcd: C, 32.88; H, 2.01; N, 3.49. Found: C, 33.29; H, 2.06; N, 3.45; Selected IR on (KBr, cm^{-1}): 3408(br), 2925(w), 2855(w), 2076(s), 1993(s), 1910(s), 1604(w), 1078(s); ESI-MS (m/z) 750.20

Mercury Poisoning Study

Mercury Poisoning experiment for the mono-alkylation of primary amine was performed in a 25-mL tube capped with a glass stopper. In a sealed tube, an 8 x 4 mm oval-shaped stirring bar, 4 Å mol. sieves, 1mmol of picolylamine, 1mmol of benzyl alcohol, mercury (1mmol), and catalyst (4 mg) along with the KO^tBu (1mmol) along with 1mL of toluene was added and flushed with N_2. The reaction was carried out at 110°C for 24h. As the reaction was completed, the un-reacted drops of mercury were present in the reaction mixture. Then after washing out the reaction mixture, mercury was quenched. Furthermore, the yield was calculated.

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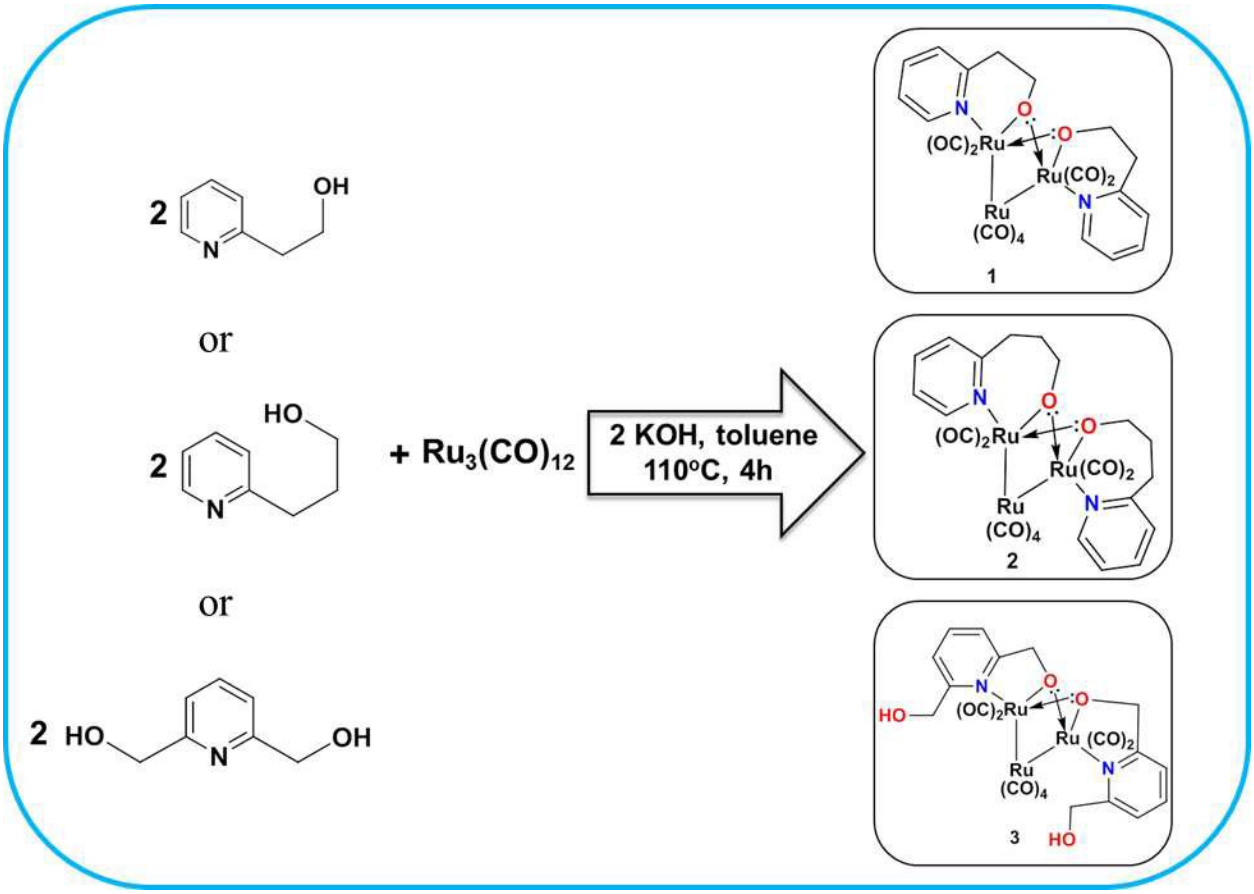
Results and Discussion

Synthesis of Ru_3 clusters 1–3

The reaction of $Ru_3(CO)_{12}$ with pyridine-alcohol, { 2-(2-hydroxyethyl)pyridine (hep-H) (for cluster **1**) and 2-(3-hydroxypropyl)pyridine (hpp-H) (for cluster **2**) has been carried out in 1:2 molar ratio in toluene (25 mL) at 110 °C for 4h using 2 equivalent of KOH (Scheme 1).



Scheme 1. Synthesis of pyridine alcohol containing ruthenium carbonyl complexes **1–3**

On varying the ratio, 1:4 and 1:6 of $Ru_3(CO)_{12}$: ligand the same products, **1** and **2** were obtained in good yield. We investigated whether 2,6-bis(hydroxymethyl)pyridine (bhmp-H_2) would change the nature of the resulting cluster by maintaining the above synthetic conditions. Surprisingly, we obtained cluster **3**, similar to **1** and **2**, but with two pendant CH_2OH arms. Fine crystals of **1–3** were

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obtained from toluene, (Fig. S1†), and the new clusters have been characterized by infrared and ^{1}H, and ^{13}C NMR spectroscopy, mass spectrometry, and CHN analysis. Their molecular structures were established by single crystal X-ray diffraction studies. Infrared and ^{13}C NMR spectra of **1–3** confirmed the presence of only terminal carbonyls. Mass spectra of all three compounds showed the respective molecular ion peaks and additional ones corresponding to successive loss of carbonyl groups (Fig. S2–S13†).

The molecular structures of **1–3** are shown in Fig. 1, and their structural parameters are presented in Table 1. The distance between two neighbouring unbonded Ru1 and Ru2 atoms in **1–3** are in the range of 3.030 Å – 3.045 Å which is larger than the bonded Ru-Ru distances (2.775 Å – 2.815 Å).[32] In **3**, the two free -OH groups are oriented away from the Ru_3 unit, other structural features are unexceptional (Fig. S14–S27†). Along with **1–3,** the other toluene solvated form of cluster **1** is also analyzed and named as Cluster **1a** (Fig. S14†, Table S5).

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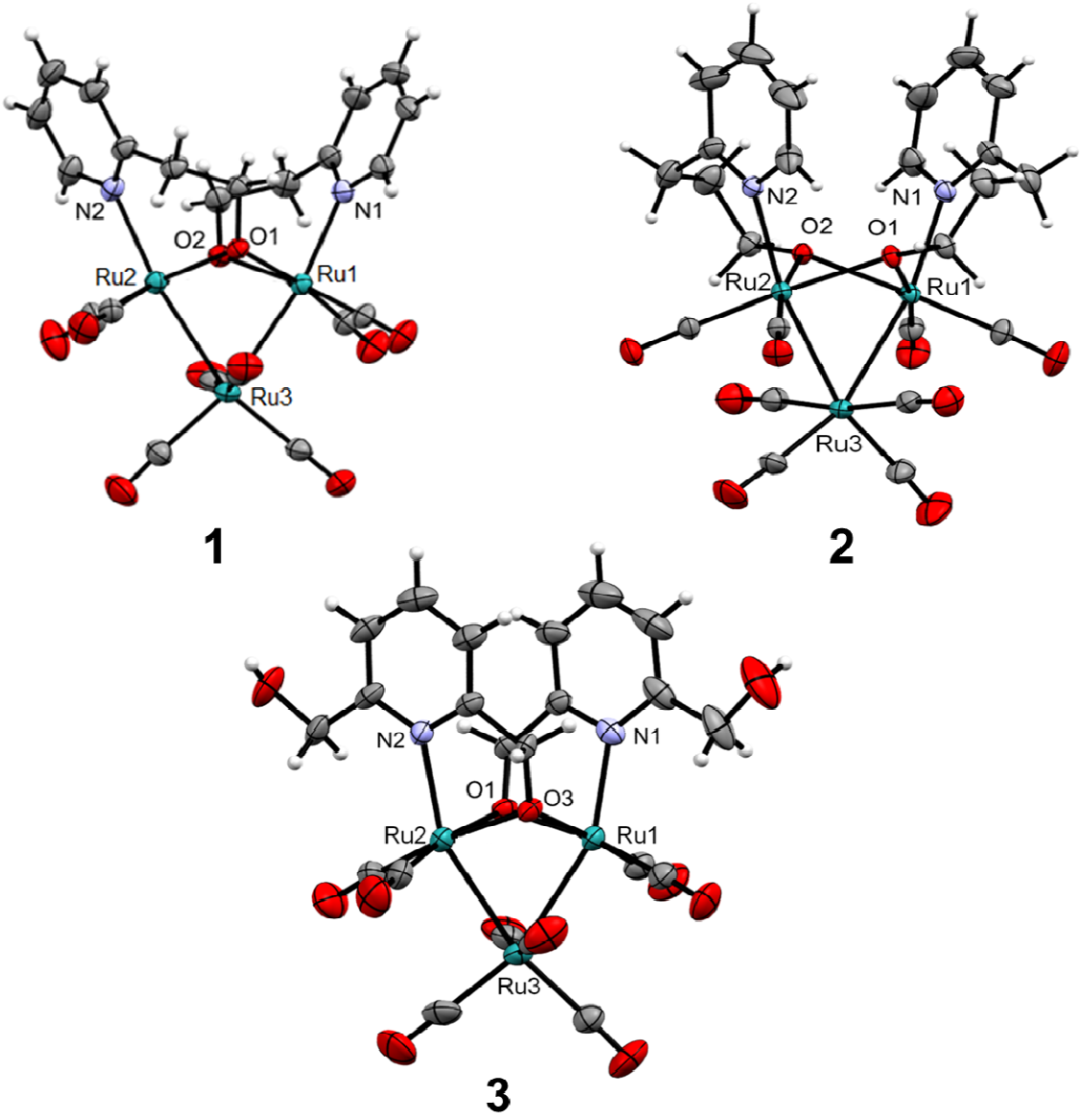

Fig. 1 Perspective view of **1**, **2** and **3**

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Table 1 Crystal data and structure refinement[33,34] for **1**, **2** and **3**

Identification code	**1**	**2**	**3**
Empirical formula	$C_{22}H_{16}N_2O_{10}Ru_3$	$C_{24}H_{20}N_2O_{10}Ru_3$	$C_{22}H_{16}N_2O_{12}Ru_3$
Formula weight	771.58	799.63	803.58
Temperature/K	293	293(2)	293(2)
Crystal system	monoclinic	Triclinic	monoclinic
Space group	$P2_{1/}n$	$P\bar{1}$	$P2_1/n$
a/Å	10.5526(2)	9.9410(6)	10.5934(7)
b/Å	14.8131(3)	9.9539(8)	13.4587(9)
c/Å	16.8846(2)	14.4372(10)	18.7560(11)
α/°	90	89.273(6)	90
β/°	93.161(2)	76.892(6)	97.916(7)
γ/°	90	81.270(6)	90
Volume/Å^3	2635.33(10)	1374.89(17)	2648.6(3)
Z	4	2	4
ρ_{calc} Mg/m^3	1.945	1.932	2.015
μ/mm^{-1}	1.753	1.683	1.754
F(000)	1496.0	780	1560.0
Crystal size/mm^3	0.34× 0.32 × 0.28	0.34 × 0.32 × 0.3	0.32 × 0.30 × 0.28
Radiation	Mo Kα (λ = 0.71073)	MoKα (λ = 0.71073)	MoKα (λ = 0.71073)
2θ range for data collection/°	3.004 to 29.007	3.182 to 32.247	3.027 to 32.156
Index ranges	$-13 \le h \le 14$, $-19 \le k \le 20$, $-22 \le l \le 22$	$-14 \le h \le 14$, $-12 \le k \le 14$, $-21 \le l \le 17$	$-15 \le h \le 15$, $-18 \le k \le 20$, $-28 \le l \le 27$
Reflections collected	30798	16236	35820
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Independent reflections	6385 [R_{int} = 0.0365, R_{sigma} = 0.0236]	8893 [R_{int} = 0.0271, R_{sigma} = 0.0380]	8800 [R_{int} = 0.1548, R_{sigma} = 0.1626]
Data/restraints/parameters	6385/0/334	8893/40/439	8800/0/354
Goodness-of-fit on F^2	1.059	1.147	1.002
Final R indexes [I>=2σ (I)]	R_1 = 0.0264, wR_2 = 0.658	R1 = 0.0379, wR2 = 0.0838	R_1 = 0.0650, wR_2 = 0.1071
Final R indexes [all data]	R_1 = 0.0314, wR_2 = 0.0696	R_1 = 0.0504, wR_2 = 0.0932	R_1 = 0.1830, wR_2 = 0.1519
Largest diff. peak/hole / e Å^{-3}	0.561/-0.698	1.185/-1.019	1.068/-1.188
CCDC No.	1852237	1539166	1541897

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Ru_3 clusters catalyzed mono-alkylation of primary amines with alcohol

A search of the literature reveals the presence of several hydride/pincer complexes of rhodium, iridium, and ruthenium along with their phosphine complexes for catalysis of mono-alkylation of amines with alcohols (**Table 2**). Grigg et al. used Rh catalyst (5 mol %) to achieve the N-methylation of pyrrolidine. Aminoarenes were converted to secondary and tertiary amines by the reaction around 180 °C with primary alcohols in the presence of dichlorotris(tripheny1phosphine)-ruthenium (1 mol %). Fujita et al. utilized $[Cp^*IrCl_2]_2$ (1.0 mol % Ir catalyst) for N-alkylation reaction. Blank and Yamaguchi also utilized the Ir catalysts for the N-alkylation of amines using primary alcohols. Hollman et al. used 1 mol % ruthenium catalyst and performed the N-alkylation reaction at 150 °C. Hamid et al. utilized ruthenium catalyst (0.5–2.5 mol %) for excellent N-alkylation of amines in reflux toluene. Gunanathan and Milstein performed the outstanding direct primary amine synthesis utilizing ruthenium PNP catalyst using only 0.1 mol % of the catalyst. Ramachandran et al. used mononuclear phosphine-ruthenium complex for the N-alkylation reaction, but they used 1.0 mol % or KOH in their reaction. Our catalyst is comparable to many catalysts reported so far (Table 2) as, the catalytic reaction used a smaller amount of catalyst (0.5 mol %), the catalyzed reaction is performed at a relatively low temperature (110 °C). The synthetic procedure for cluster **1–3**, is relatively uncomplicated and requires shorter time and to the best of our knowledge, this is the first example of use of ruthenium carbonyl clusters **1–3** for catalysis of mono-alkylation of amines with primary alcohols.

Table 2. Comparison of cluster **1** with previous homogeneous catalysts for alkylation reaction of primary amines with primary alcohols

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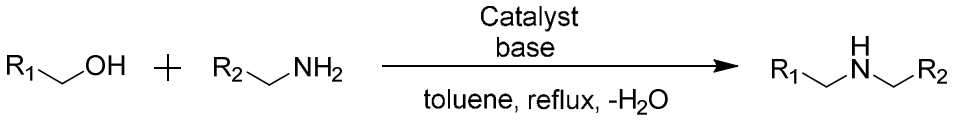
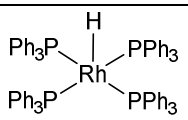
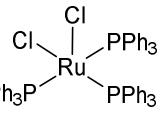
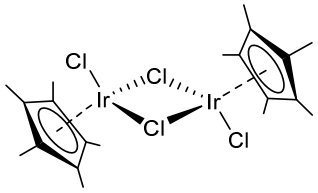
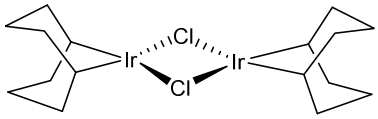
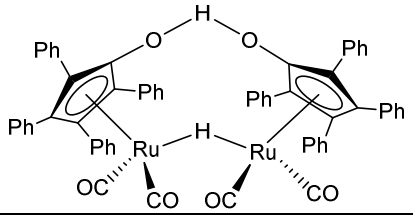
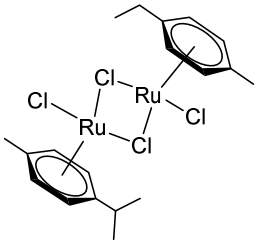
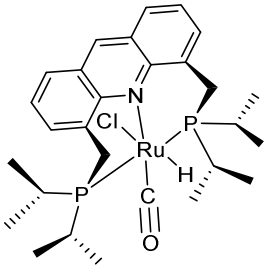


Entry No.	Catalyst or pre-catalyst	Substrates R_1OH and R_2NH_2	Reaction parameters	Yield (%)	Reference
1		pyrrolidine + MeOH	Reflux, 4 h, 70 °C	98%	20
2		Aniline + EtOH	180 °C, 5 h.	74%	21
3		NH_4BF_4 + RCH_2OH Aniline + benzyl alcohol	$NaHCO_3$, 140 °C, 17h $NaHCO_3$, 110 °C, 17h	75% 94%	22, 35
4		o-amino pyridine + benzyl alcohol	KO^tBu, 70 °C, 17h (2 mol % catalyst)	97%	24
5		Hexyl amine, aryl amine	2-methyl-butan-ol, 150 °C (1 mol % catalyst)	98%	25
6		$^tBuNH_2$, benzyl alcohol	5 mol % dppf, toluene, 110 °C, 24h (2.5 mol % catalyst)	94%	26
7		Benzyl alcohol, NH_3	toluene, 110 °C, 24h (0.1 mol % catalyst)	83%	27

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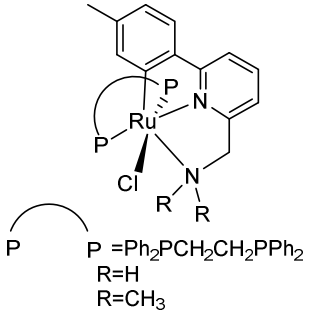
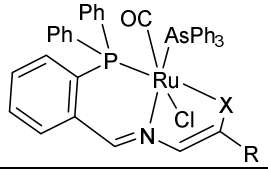
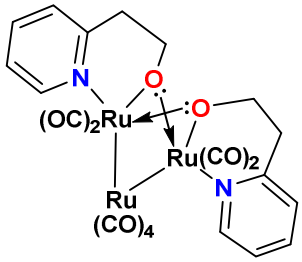
8		Benzyl alcohol, NH_3	KO^tBu, toluene, 110 °C, 24h (1 mol % catalyst)	92%	**28**
9		2-amino benzothiazole, benzyl alcohol	KOH, toluene, 110 °C, 12h (0.5 mol % catalyst)	96%	**29**
10	 **1**	**2-amino pyridine, benzyl alcohol**	**KO^tBu, toluene, 110 °C, 24h (0.5 mol % catalyst)**	**96%**	**this work**

Catalytic application of clusters 1–3 for amine mono-alkylation with primary alcohols

Clusters **1–3** and $Ru_3(CO)_{12}$ were evaluated as catalysts for the transformation of primary amine 2-picolylamine to a secondary amine in the model reaction (Table 3). Typically, the reaction was performed using 1.0 mmol of benzyl alcohol and 2-picolylamine as reactants, low loading (0.5 mol %) of catalyst **1–3** and 1.0 mmol potassium tert-butoxide as a base, 4 Å mol. sieve, and stirred in 600 μL of toluene.

In the absence of ruthenium catalyst and base, the amine alkylation was not observed (Table 3, entries 1, 2). The optimization of reaction conditions was performed at room temperature, 55 °C, 75 °C and 110 °C. The reaction was not observed below 110 °C. The effect of time on the reaction was observed, and within 24 h at 110 °C, the reaction was completed with catalyst **1** (entries 3–6). Among all the ruthenium-based clusters, **1–3**, similar catalytic activity was obtained, but the most

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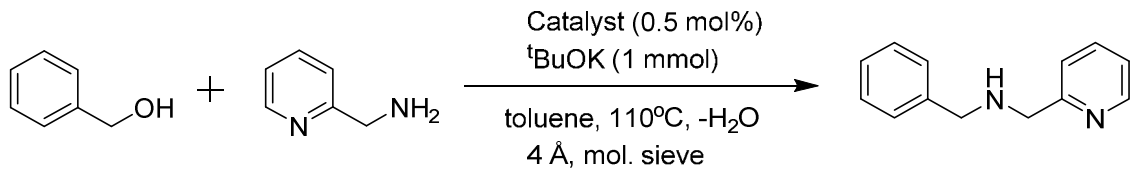
active catalyst was cluster **1**, likely due to the six-membered ring formed by the coordination of 2-(2-hydroxyethyl)pyridine ligand to $Ru_3(CO)_8$ (entries 6–8). The precursor $Ru_3(CO)_{12}$ in the absence of pyridine-alcohol shows a much lower conversion (entry 9) thus, demonstrating the importance of the chelating ligand (N⌒O).

Table 3. Optimization of the catalytic reaction conditions for N-alkylation of 2-picolylamine using benzyl alcohol and Ru_3 cluster catalysts.



Entry	Catalyst	Base	Time (h)	Conv.	Yield
1	NA	^{t}BuOK	24	0	0
2	Cat.**1**	NA	24	0	0
3	Cat. **1**	^{t}BuOK	6	79	74
4	Cat. **1**	^{t}BuOK	12	85	80
5	Cat. **1**	^{t}BuOK	18	92	88
6	Cat. **1**	^{t}BuOK	24	100	96
7	Cat. **2**	^{t}BuOK	24	90	85
8	Cat. **3**	^{t}BuOK	24	95	90
9	$Ru_3(CO)_{12}$	^{t}BuOK	24	70	54

Under the optimized conditions (entry 6) {cat.**1** (0.5 mol %), benzyl alcohol (1.0 mmol), 2-picolylamine (1.0 mmol), and 1.0 mmol potassium tert-butoxide in toluene (500 µL) charged with 4 Å, mol. sieves, were heated in a closed tube}; the desired secondary amine was obtained in high yield (96%).

Encouraged by this catalytic transformation, the mono-alkylation of various primary amines bearing electron donating or electron withdrawing substituents were explored (Table 4). Higher

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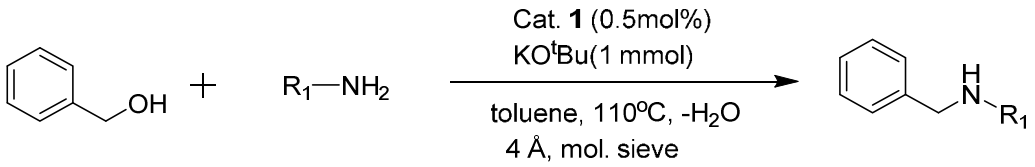
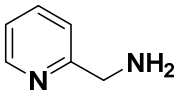
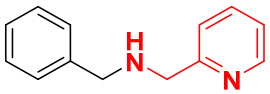
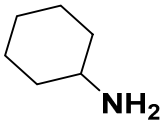
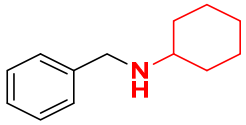
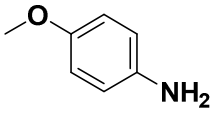
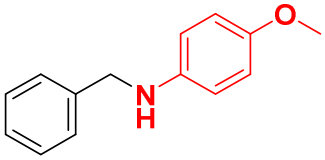
yields were observed with *para* electron donating substituents on the aniline ring whereas the *ortho*-substituted aniline was less reactive likely due to the steric hindrance (Table 4, entries 3, 4 and 7). With halogen substituents on pyridine ring, the conversion was observed, but the desired product yields were low. The catalyst was active even with aliphatic amines (entries 2, 6 and 8) but for heterocycles containing the imidazole and furan rings (entries 9–10), the mono-alkylation was not observed. 4-aminopyridine and piperonylamine also gave excellent yields for the mono-alkylation of primary amines (entries 11–12). In case of halo-aniline, the para-fluoro aniline gave the highest yield followed by chloro, bromo and iodo aniline (entries 13–16). Aniline, (2-chlorophenyl)methanamine, and p-tolylmethanamine, also gave the desired product in good yield, and at last reactant with maximum substitution like trimethoxyaniline mono-alkylation also produced the secondary amine product in better yield (entries 17–20).

Table 4. Direct formation of secondary amines from benzyl alcohol and various primary amines with cluster **1** as catalyst



Entry	RNH_2	Conv.	$C_6H_5CH_2HNR$	Yield
1		100%		96%
2		52%		51%
3		64%		56%

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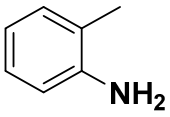
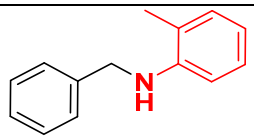
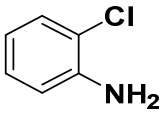
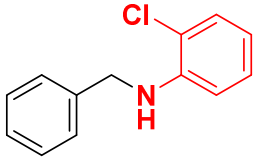
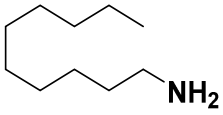
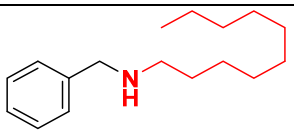
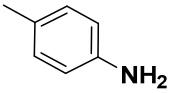
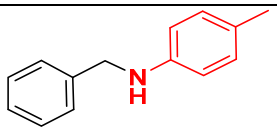
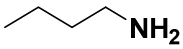
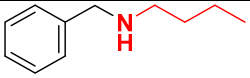
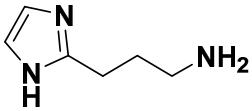
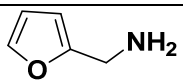
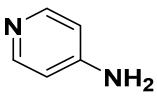
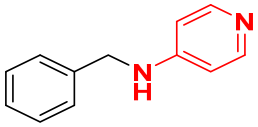
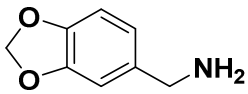
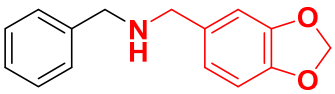
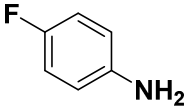
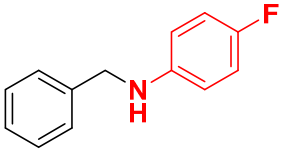
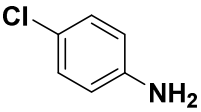
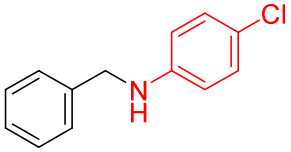
4		**44%**		**41%**
5		**65%**		**19%**
6		**72%**		**55%**
7		**48%**		**46%**
8		**22%**		**20%**
9		--	-NR-	--
10		--	-NR-	
11		**73%**		**70%**
12		**>90%**		**62%**
13		**79%**		**72%**
14		**64%**		**62%**

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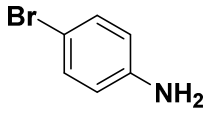
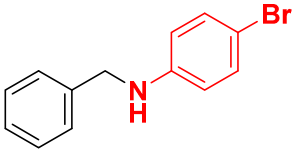
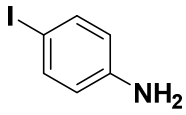
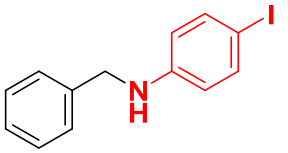
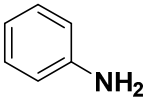
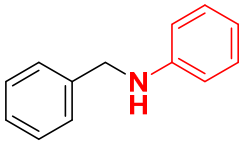
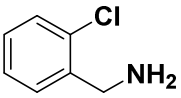
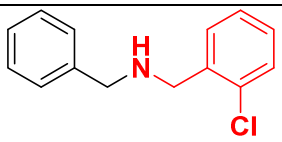
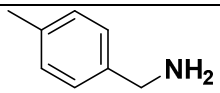
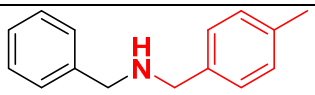
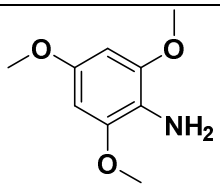
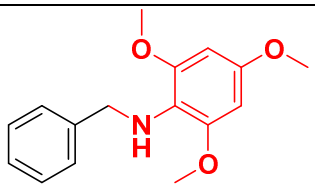
15		**55%**		**50%**
16		**52%**		**38%**
17		**72%**		**68%**
18		**58%**		**50%**
19		**70%**		**47%**
20		**74%**		**60%**

[a]Complex **1** (0.5 mol %), benzyl alcohol (1.0 mmol), primary amine (1.0 mmol), and toluene (500 µL) charged with 4 Å, mol. sieves, were heated in a closed tube. [b]Conversion of alcohol and yield of products were determined by GC-MS. [c]Isolated yields (1, 4, 7, 11, 20) were analyzed by ^{1}H and ^{13}C NMR along with GC-MS.

Catalyst **1** showed significant results even when pyridine alcohols, pyridin-2-ylmethanol, pyridin-2-ylethanol, and pyridin-2-ylpropanol were screened (Table 5, entries 1–3). The three synthesized dipyridyl secondary amines are the precursors of significant NNN-pincer ligands. Presence of functional groups on benzyl alcohol substrates did not prevent the catalytic secondary amine formation (Table 5, entries 5, 6). Halo-benzyl alcohol also gave the expected product, but the less stable bromo derivative gave lower yield in the reaction (Table 5, entries 7, 8).

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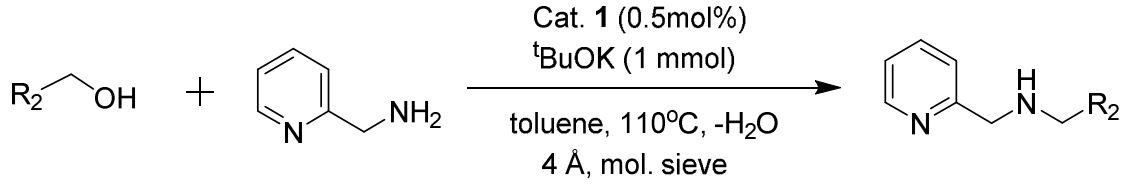
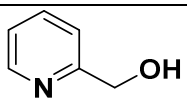
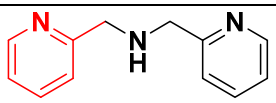
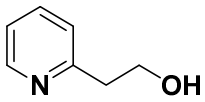
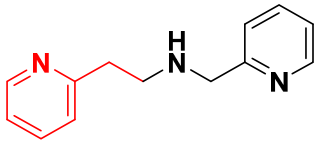
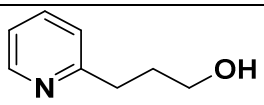
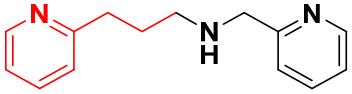
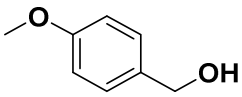
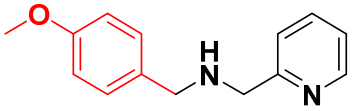
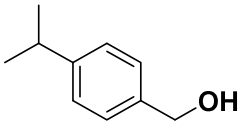
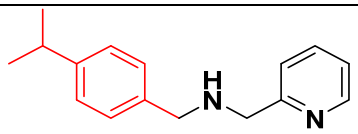
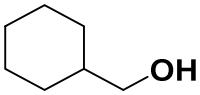
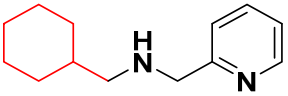
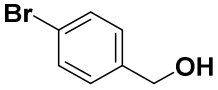
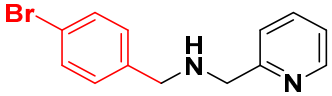
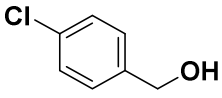
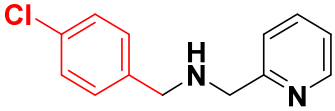
Table 5. Direct formation of secondary amines from primary amines and varying alcohols using **1** as catalyst



Entry	R_2CH_2OH	Conv.	$C_5H_4NCH_2NHCH_2R_2$	Yield
1		52%		41%
2		82%		75%
3		90%		54%
4		75%		64%
5		90%		78%
6		67%		50%
7		80%		8%
8		73%		55%

[a]Complex **1** (0.5 mol %), primary alcohol (1.0 mmol), pyridin-2-ylmethanamine (1.0 mmol), and toluene (500 µL) charged with 4 Å, mol. sieves, were heated in a closed tube. [b]Conversion of alcohols and yield of products were analyzed by GC-MS. [c]Isolated yields (1, 5) were analyzed by ^1H and ^{13}C NMR along with GC-MS. NMR and GC-MS data can be found in Fig. S28–S73†.

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Mercury Poisoning Study

We have also investigated the influence of mercury(0)[36] on the mono-alkylation of primary amines using alcohol in the presence of **1**. The yield of the mono-alkylation does not reduce significantly when mercury(0) is introduced in the reaction mixture (from 96% to 84%). The failure of Hg(0) to halt the reaction suggests that the reaction involves the homogenous ruthenium pyridine alcohol cluster catalyst. Fig. 2 displays condition 1 as the optimized reaction condition (Fig. S31†) and condition 2 as the reaction condition in the presence of Hg(0) (Fig. S74†) with the respective yields.

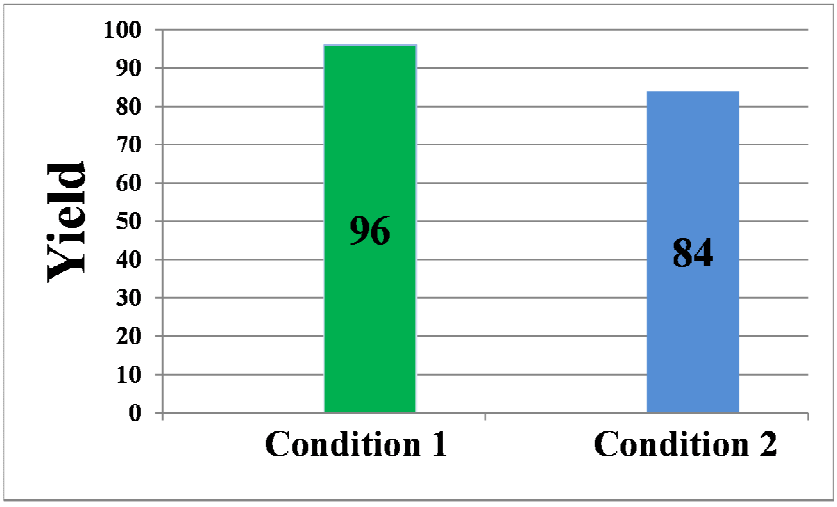

Fig. 2 Mercury poisoning study of $Ru_3(hep)_2(CO)_8$ cluster catalyst for mono-alkylation of amine with alcohol

Conclusion

The above results show that pyridine alcohols react with $Ru_3(CO)_{12}$ to form clusters $Ru_3(hep)_2(CO)_8$ (**1**), $Ru_3(hpp)_2(CO)_8$ (**2**), and $Ru_3(bhmp\text{-}H)_2(CO)_8$ (**3**). They all contain a trans py-Ru-Ru-py arrangement, and the chelating ligands offer 2 oxygen atom bridging the non-bonded Ru(1) and Ru(2) sites. The catalytic transformation highlights the high efficiency and versatility of the clusters $Ru_3(N\frown O)_2(CO)_8$ catalyst (L= hep, hpp, bhmp-H). Cluster **1** was the most efficient

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catalyst for the N-alkylation reactions of primary amines. The catalytic transformations are entirely selective leading to excellent yields of secondary amine. This work has created simple Ru3 catalysts, with pyridine alcohol chelating ligands, which do not contain pincer or hydride ligands, and excellent catalytic activity for mono-alkylation for primary amines is achieved successfully. Other catalytic transformations like hydrogen production from renewable alcohols, oxidation of alcohols into carboxylates, usually performed by pincer metal catalysts, can be explored by employing these Ru3 **1–3** clusters.

Conflicts of interest

There are no conflicts of interest to declare

Associated Content:

Electronic Supplementary Information

The electronic supplementary information includes all spectral data and explanations of interaction present in crystals **1–3**. CCDC Number 1852237, 1539166, and 1541897 contain the supplementary crystallographic data for **1**, **2** and **3**, respectively. The data is available free of charge at http://www.ccdc.cam.ac.uk/conts/retrieving.html, or the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk.

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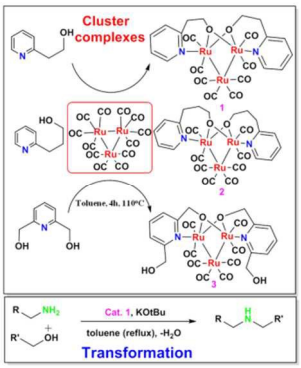

This report has created simple Ru3 pyridine alcohol cluster catalysts which are excellent catalyst for mono-alkylation for primary amines.