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Highly efficient alcohol oxidation catalyzed by palladium(II)–alkylamine complexes using atmospheric molecular oxygen

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Abstract

Two series of palladium(II)–alkylamine ($Pd(Me_2NCn)_2(OAc)_2$, Me_2NCn: *N*,*N*′-dimethylalkylamine, $n=4$, 8, 12, and 16) and palladium(II)-*N*,*N*′-dialkylamine ($Pd(Cn_2NH)_2(OAc)_2$, Cn_2NH: *N*,*N*′-dialkylamine, $n=4$, 8, and 12) were prepared. These homogeneous Pd complexes catalyzed the aerobic oxidation of wide range of alcohols into the corresponding aldehydes and ketones efficiently. For example, a benzylalcohol oxidation proceeded rapidly by means of $Pd(Me_2NC12)_2(OAc)_2$ with an excellent turnover frequency of up to $96\,h^{-1}$.

Keywords: Alcohol oxidation; Molecular oxygen; Palladium(II)–alkylamine complex

1. Introduction

The selective oxidation of alcohols is widely recognized as one of the most fundamental organic transformations in both laboratory and industrial synthetic chemistry, because the resulting carbonyl compounds are of paramount importance as synthetic intermediates for fine chemicals and pharmaceuticals [1]. Due to ever-growing environmental concerns, there is a strong need for the establishment of promising catalytic protocols using molecular oxygen as a sole oxidant, which is readily available and produces only water as a by-product [2]. For that reason, many transition metal-catalyzed aerobic processes, both homogeneous and heterogeneous, have been developed [3].

In 1998 Uemura and co-workers reported pyridine ligand combined with palladium acetate catalytically promoted aerobic alcohol oxidation in the presence of MS3A [4a, 4b]. Sigman et al. demonstrated aerobic alcohol oxidation proceeded smoothly even at room temperature by use of $Pd(OAc)_2$/triethylamine catalyst system in 2002 [4c]. Inspired by those publications, we set out to explore the effective and commercially available nitrogen-based ligands in Pd(II)-catalyzed aerobic alcohol oxidations, since alkylamines are useful ligands to form various metal complex supramolecular assembly such as films [5], micelles [6], dendrimers [7], liquid crystals [8], and so on.

In this work, we wish to report $Pd(OAc)_2$ in combination with tertiary amines with long alkyl chains (Me_2NCn and Cn_2NH) act as an effective catalyst system toward oxidative dehydrogenation of alcohols in the presence of molecular oxygen (Scheme 1). Our catalytic system possesses remarkably attractive features: (i) high catalytic efficiency under mild reaction conditions, (ii) a simple preparation procedure of the catalyst using cheap and commercially available amine ligands, (iii) no requirement for any other additives, and (iv) applicable to a wide range of alcohols.

2. Experimental

2.1. General

Characterization of synthesized palladium complexes and products of oxidation reactions were carried out using ^1H NMR (JEOL LA-400, 400 MHz), FT-IR (JEOL JIR-7000), UV–vis (Shimadzu UV-2101PC), elemental analysis, and MS (Shimadzu QP-5000). Progress of the reaction was monitored by GC analysis (Shimadzu GC-8A, OV-101 and Thermon 3000T packed column, FID). All substrates and solvents were commercially obtained from Tokyo Chemical Industry Co. Ltd., WAKO Pure Chemical Industries Ltd., Aldrich (reagent grade) and purified by standard methods [9].

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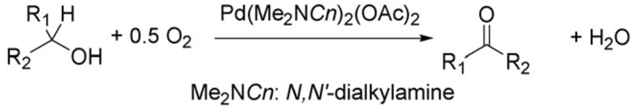


Scheme 1.

2.2. *Synthesis of* $\mathrm{Pd(Me_2N}\mathit{Cn}\mathrm{)_2(OAc)_2}$ *complex* ($n = 4$, *8, 12, and 16)*

$\mathrm{Me_2N}\mathit{Cn}$ (1.78 mmol) was added to $\mathrm{Pd(OAc)_2}$ (0.2 g, 0.891 mmol) dissolved in 20 mL of dry acetone under $\mathrm{N_2}$. After 1 h stirring at room temperature, the yellow solution was evaporated in vacuo. The resulting yellow powder was recrystallized from pentane affording $\mathrm{Pd(Me_2N}\mathit{Cn}\mathrm{)_2(OAc)_2}$ complex.

$\mathrm{Pd(Me_2N}\mathit{C4}\mathrm{)_2(OAc)_2}$: Yield 60%. ^{1}H NMR ($\mathrm{CDCl_3}$) δ 1.03 (t, 6H, –$\mathrm{NC_3H_6C}\mathit{H}_3$), 1.39 (m, 4H, –$\mathrm{NC_2H_4C}\mathit{H}_2\mathrm{CH_3}$), 1.90 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 2.05 (m, 4H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_2H_5}$), 2.32 (s, 12H, –$\mathrm{NC}\mathit{H}_3$), 2.36 (m, 6H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_3H_7}$). ^{13}C NMR ($\mathrm{CDCl_3}$) δ 24.1 (–$\mathrm{OCO}\mathit{C}\mathrm{H_3}$), 41.9 (–$\mathrm{NC_3H_6}\mathit{C}\mathrm{H_3}$), 45.1 (–$\mathrm{NC_2H_4}\mathit{C}\mathrm{H_2CH_3}$), 47.5 (–$\mathrm{NCH_2}\mathit{C}\mathrm{H_2C_2H_5}$), 57.0 (–$\mathrm{N}\mathit{C}\mathrm{H_3}$), 74.9 (–$\mathrm{N}\mathit{C}\mathrm{H_2C_3H_7}$), 178.1 (–$\mathrm{O}\mathit{C}\mathrm{OCH_3}$). FT-IR $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2985, 2870 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1624 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1462 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1308 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 45.02; H: 8.50; N: 6.56%. Found: C: 44.35; H: 8.48, N: 6.20%.

$\mathrm{Pd(Me_2N}\mathit{C8}\mathrm{)_2(OAc)_2}$: Yield 63%. ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.90 (t, 6H, –$\mathrm{NC_7H_{14}C}\mathit{H}_3$), 1.31 (m, 20H, –$\mathrm{NC_2H_4C_5}\mathit{H}_{10}\mathrm{CH_3}$), 1.90 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 2.03 (m, 4H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_6H_{13}}$), 2.31 (s, 12H, –$\mathrm{NC}\mathit{H}_3$), 2.36 (m, 4H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_7H_{15}}$). ^{13}C NMR ($\mathrm{CDCl_3}$) δ 14.1 (–$\mathrm{NC_7H_{14}}\mathit{C}\mathrm{H_3}$), 22.7 (–$\mathrm{NC_6H_{12}}\mathit{C}\mathrm{H_2CH_3}$), 24.1 (–$\mathrm{OCO}\mathit{C}\mathrm{H_3}$), 27.4 (–$\mathrm{NC_5H_{10}}\mathit{C}\mathrm{H_2C_2H_5}$), 27.5 (–$\mathrm{NC_4H_8}$ $\mathit{C}\mathrm{H_2C_3H_7}$), 29.4 (–$\mathrm{NC_3H_6}\mathit{C}\mathrm{H_2C_4H_9}$), 29.6 (–$\mathrm{NC_2H_4}\mathit{C}\mathrm{H_2C_5}$ $\mathrm{H_{11}}$), 31.9 (–$\mathrm{NCH_2}\mathit{C}\mathrm{H_2C_6H_{13}}$), 50.7 (–$\mathrm{N}\mathit{C}\mathrm{H_3}$), 64.6 (–$\mathrm{N}\mathit{C}\mathrm{H_2C_7H_{15}}$), 178.0 (–$\mathrm{O}\mathit{C}\mathrm{OCH_3}$). FT-IR $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2920, 2854 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1622 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1463 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1309 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 53.47; H: 9.72; N: 5.20%. Found: C: 53.44; H: 9.85, N: 4.97%.

$\mathrm{Pd(Me_2N}\mathit{C12}\mathrm{)_2(OAc)_2}$: Yield 91%. ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.89 (m, 6H, –$\mathrm{NC_{11}H_{22}C}\mathit{H}_3$), 1.27 (m, 36H, –$\mathrm{NC_2H_4C_9}\mathit{H}_{18}\mathrm{CH_3}$), 1.90 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 2.03 (m, 4H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_{10}H_{21}}$), 2.36 (s, 12H, –$\mathrm{NC}\mathit{H}_3$), 2.36 (m, 4H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_{11}H_{23}}$). ^{13}C NMR ($\mathrm{CDCl_3}$) δ 14.1 (–$\mathrm{NC_{11}H_{22}}\mathit{C}\mathrm{H_3}$), 22.7 (–$\mathrm{C_{10}H_{20}}\mathit{C}\mathrm{H_2CH_3}$), 24.0 (–$\mathrm{OCO}\mathit{C}\mathrm{H_3}$), 24.1 (–$\mathrm{NC_9H_{18}}\mathit{C}\mathrm{H_2C_2H_5}$), 27.4 (–$\mathrm{NC_8H_{16}}$ $\mathit{C}\mathrm{H_2C_3H_7}$), 29.4 (–$\mathrm{NC_7H_{14}}\mathit{C}\mathrm{H_2C_4H_9}$), 29.6 (–$\mathrm{NC_6H_{12}}$ $\mathit{C}\mathrm{H_2C_5H_{11}}$), 29.7 (–$\mathrm{NC_2H_4}\mathit{C}_4\mathrm{H_8C_6H_{13}}$), 32.0 (–$\mathrm{NCH_2}\mathit{C}\mathrm{H_2}$ $\mathrm{C_{10}H_{21}}$), 50.7 (–$\mathrm{N}\mathit{C}\mathrm{H_3}$), 64.6 (–$\mathrm{N}\mathit{C}\mathrm{H_2C_{11}H_{23}}$), 178.1 (–$\mathrm{O}\mathit{C}\mathrm{OCH_3}$). FT-IR $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2918, 2850 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1621 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1462 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1309 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 59.01; H: 10.52; N: 4.30%. Found: C: 59.26; H: 10.77, N: 4.26%.

$\mathrm{Pd(Me_2N}\mathit{C16}\mathrm{)_2(OAc)_2}$: Yield 95%. ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.88 (t, 6H, –$\mathrm{NC_{15}H_{30}C}\mathit{H}_3$), 1.26 (m, 52H, –$\mathrm{NC_2H_4C_{13}}\mathit{H}_{26}\mathrm{CH_3}$), 1.90 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 2.31 (m, 4H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_{14}H_{29}}$), 2.04 (s, 12H, –$\mathrm{NC}\mathit{H}_3$), 2.35 (m, 4H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_{15}H_{31}}$). ^{13}C NMR ($\mathrm{CDCl_3}$) δ 14.1 (–$\mathrm{NC_{15}H_{30}}\mathit{C}\mathrm{H_3}$), 22.7 (–$\mathrm{NC_{14}H_{28}}\mathit{C}\mathrm{H_2CH_3}$), 24.0 (–$\mathrm{OCO}\mathit{C}\mathrm{H_3}$), 24.1 (–$\mathrm{NC_{13}H_{26}}\mathit{C}\mathrm{H_2C_2H_5}$), 27.4 (–$\mathrm{NC_{12}H_{24}}\mathit{C}\mathrm{H_2C_3H_7}$), 29.4 (–$\mathrm{NC_{11}H_{22}}\mathit{C}\mathrm{H_2C_4H_9}$), 29.6 (–$\mathrm{NC_{10}H_{20}}\mathit{C}\mathrm{H_2C_5H_{11}}$), 29.8 (–$\mathrm{NC_2H_4}\mathit{C}_8\mathrm{H_{16}C_6H_{13}}$), 32.0 (–$\mathrm{NCH_2}\mathit{C}\mathrm{H_2C_{14}H_{29}}$), 50.8 (–$\mathrm{N}\mathit{C}\mathrm{H_3}$), 64.6 (–$\mathrm{N}\mathit{C}\mathrm{H_2C_{15}H_{31}}$), 178.1 (–$\mathrm{O}\mathit{C}\mathrm{OCH_3}$). FT-IR $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2918, 2855 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1622 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1466 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1309 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 62.92; H: 11.09; N: 3.67%. Found: C: 62.68; H: 11.30, N: 3.55%.

2.3. *Synthesis of* $\mathrm{Pd(}\mathit{Cn}_2\mathrm{NH)_2(OAc)_2}$ *complex* ($n = 4$, *8, and 12)*

N,*N*′-Dibutylamine and *N*,*N*′-dioctylamine were purchased from Tokyo Chemical Industry Co. Ltd. *N*,*N*′-Didodecylamine was prepared by the literature method [10]. $\mathit{Cn}_2\mathrm{NH}$ (1.78 mmol) was added to $\mathrm{Pd(OAc)_2}$ (0.2 g, 0.891 mmol) dissolved in 20 mL of dry toluene under $\mathrm{N_2}$. After 1 h stirring at room temperature, the yellow solution was evaporated in vacuo. The resulting yellow powder was recrystallized from acetonitrile or pentane affording $\mathrm{Pd(}\mathit{Cn}_2\mathrm{NH)_2(OAc)_2}$ complex.

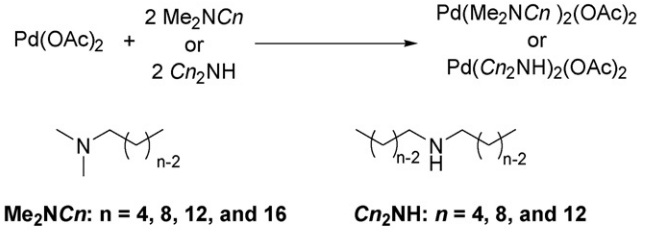
$\mathrm{Pd(}\mathit{C4}_2\mathrm{NH)_2(OAc)_2}$: Yield 42%: ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.99 (t, 12H, –$\mathrm{NC_3H_6C}\mathit{H}_3$), 1.41 (m, 8H, –$\mathrm{NC_2H_4C}\mathit{H}_2\mathrm{CH_3}$), 1.89 (m, 8H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_2H_5}$), 2.41 (m, 8H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_3H_7}$), 1.87 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 6.54 (m, 2H, –$\mathrm{N}\mathit{H}$). FT-IR $\nu(\mathrm{NH})$: 3121 (w); $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2927, 2873 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1601 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1468 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1321 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 49.85; H: 9.26; N: 5.58%. Found: C: 49.85; H: 9.18, N: 5.80%.

$\mathrm{Pd(}\mathit{C8}_2\mathrm{NH)_2(OAc)_2}$: Yield 52%: ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.89 (t, 12H, –$\mathrm{NC_7H_{14}C}\mathit{H}_3$), 1.29 (m, 40H, –$\mathrm{NC_2H_4C_5}\mathit{H}_{10}\mathrm{CH_3}$), 1.86 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 1.90 (m, 8H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_6H_{13}}$), 2.42 (m, 8H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_7H_{15}}$), 7.26 (m, 2H, –$\mathrm{N}\mathit{H}$). FT-IR $\nu(\mathrm{NH})$: 3125 (w); $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2925, 2854 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1600 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1466 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1321 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 61.12; H: 10.83; N: 3.96%. Found: C: 60.95; H: 10.99, N: 3.72%.

$\mathrm{Pd(}\mathit{C12}_2\mathrm{NH)_2(OAc)_2}$: Yield 67%: ^{1}H NMR ($\mathrm{CDCl_3}$) δ 0.88 (t, 12H, –$\mathrm{NC_{11}H_{22}C}\mathit{H}_3$), 1.27 (m, 72H, –$\mathrm{NC_2H_4C_9}\mathit{H}_{18}\mathrm{CH_3}$), 1.86 (s, 6H, –$\mathrm{OCOC}\mathit{H}_3$), 1.95 (m, 8H, –$\mathrm{NCH_2C}\mathit{H}_2\mathrm{C_{10}H_{21}}$), 2.44 (m, 8H, –$\mathrm{NC}\mathit{H}_2\mathrm{C_{11}H_{23}}$), 7.26 (m, 2H, –$\mathrm{N}\mathit{H}$). FT-IR $\nu(\mathrm{NH})$: 3115 (w); $\nu(\mathrm{CH_2}, \mathrm{sp^3})$: 2920, 2850 (s); $\nu_{\mathrm{as}}(\mathrm{CO_2})$: 1598 (s); δ ($\mathrm{CH_2}$, $\mathrm{sp^3}$): 1466 (m), $\nu_{\mathrm{s}}(\mathrm{CO_2})$: 1321 (s) $\mathrm{cm^{-1}}$. Anal. Calc.: C: 67.02; H: 11.68; N: 3.01%. Found: C: 66.76; H: 12.09, N: 2.89%.

2.4. *A typical procedure of the aerobic oxidation of 4-methylbenzyl alcohol*

Into a reaction vessel with a reflux condenser was placed 4-methylbenzyl alcohol (1 mmol, 0.12 g), *trans*-decahydronaphthalene (internal standard; 0.5 mmol, 0.0691 g), $\mathrm{Pd(Me_2N}\mathit{C12}\mathrm{)_2(OAc)_2}$ (0.02 mmol, 0.0130 g), and toluene (5 mL). The resulting mixture was stirred at 80 °C under an oxygen atmosphere (equipped with a balloon). 4-Methylbenzyl alcohol conversion and 4-methylbenzaldehyde selectivity were determined by GC analysis using an internal standard technique. After 1 h, removal of toluene under the reduced pressure, followed by column chromatography (*n*-hexane/EtOAc = 9/1), afforded analytically pure 4-methylbenzaldehyde as a colorless oil (0.10 g, 86% isolated yield).



Scheme 2.

2.5. A procedure of aerobic alcohol oxidation under air at room temperature

Into a reaction vessel was placed benzylalcohol (1 mmol, 0.11 g), *trans*-decahydronaphthalene (internal standard; 0.5 mmol, 0.0691 g), Pd(Me_2NC12)$_2$(OAc)$_2$ (0.02 mmol, 0.0130 g), and toluene (10 mL). The resulting mixture was stirred at room temperature under air atmosphere. Benzylalcohol conversion and benzaldehyde selectivity were determined by GC analysis using the internal standard technique. After 24 h, 90% benzylalcohol was converted into benzaldehyde.

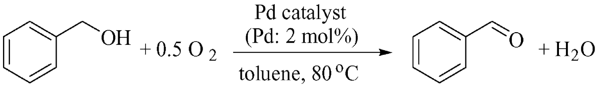
2.6. Oxygen uptake measurement

The uptake of molecular oxygen was measured by the following experiment. Pd(Me_2NC12)$_2$(OAc)$_2$ (0.02 mmol, 0.130 g) was placed in a sidearmed flask with a reflux condenser attached to a gas buret. The system was evacuated and filled with molecular oxygen, followed by the addition of toluene (10 mL) and benzylalcohol (1 mmol, 0.11 g), and then reacted for 0.5 h at 80 °C. The molar ratio of uptaken O_2 gas to benzaldehyde was ca. 1:2.

3. Results and discussion

First of all, we tried to isolated Pd complex using various amine ligands according to the previously reported method [11]. Each palladium complex was obtained from acetone solution of Pd(OAc)$_2$ and amines, and analytically pure crystals were obtained by recrystalization (Scheme 2). Effects of the ligand on the aerobic oxidation of benzylalcohol are summarized in Table 1. The use of Pd(OAc)$_2$ as a catalyst resulted in the Pd aggregation and no reaction was observed (entry 1) [12]. Pd complexes using *N*,*N*′-dimethylalkyl amines (Me_2NCn; $n=4$, 8, 12, and 16) ligands acted as an effective catalyst (entries 2–4, and 6). The addition of excess Me_2NC12 ligand did not affect the reaction rate (entry 5). These Pd complexes were stable under the reaction conditions and thus the reaction solution remained clear yellow state (Fig. 1a). With *N*,*N*′-dialkylamimes (Cn_2NH; $n=4$, 8, and 12), the reaction rates decreased dramatically, accompanied with the formation of Pd black (entries 7–9, Fig. 1b). The Pd aggregation could be prevented by the addition of 0.04 mmol of $C12_2NH$ ligand, however, the oxidation reaction did not proceed (entry 10). Concerning the high activity and yield, we conclude that Pd(Me_2NC12)$_2$(OAc)$_2$ is the best complex toward oxidation of alcohols with molecular oxygen.

Table 1
Catalyst effect[a]



Entry	Catalyst	Time (h)	Convn. (%)[b]	Yield (%)[b]	Pd black formation
1	Pd(OAc)$_2$	0.5	Trace	Trace	+
2	Pd(Me_2NC4)$_2$(OAc)$_2$	0.5	93	93	–
3	Pd(Me_2NC8)$_2$(OAc)$_2$	0.5	96	95	–
4	Pd(Me_2NC12)$_2$(OAc)$_2$	0.5	96	95	–
5[c]	Pd(Me_2NC12)$_2$(OAc)$_2$	0.5	91	91	–
6	Pd(Me_2NC16)$_2$(OAc)$_2$	0.5	93	92	–
7	Pd($C4_2NH$)$_2$(OAc)$_2$	24	76	76	+
8	Pd($C8_2NH$)$_2$(OAc)$_2$	24	74	74	+
9	Pd($C12_2NH$)$_2$(OAc)$_2$	24	67	67	+
10[d]	Pd($C12_2NH$)$_2$(OAc)$_2$	24	6	5	–

[a] Benzylalcohol (0.5 mmol), Pd catalyst (0.01 mmol, Pd: 2 mol.%), toluene (5 mL), O_2 atmosphere, 80 °C.

[b] Determined by GC using an internal standard technique.

[c] Me_2NC12 (0.02 mmol) was added.

[d] $C12_2NH$ (0.04 mmol) was added.

Optimization of the reaction conditions is summarized in Table 2. The oxidation proceeded in poor conversion under air and did not take place under N_2 atmosphere (entries 2 and 3). The consumption of oxygen gas was measured

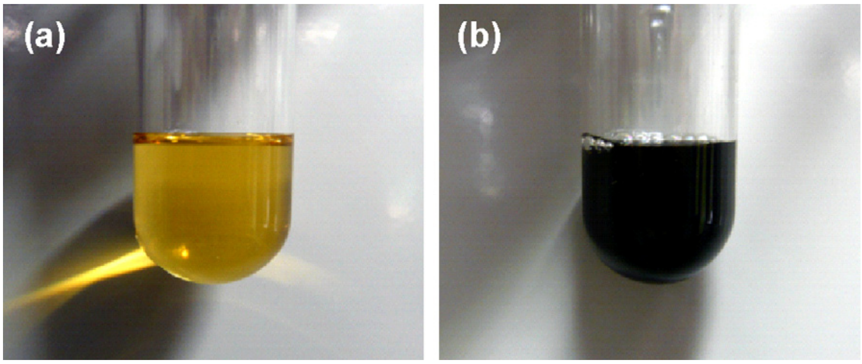


Fig. 1. Photo images of the catalytic reaction mixture: (a) Pd(Me_2NC12)$_2$(OAc)$_2$ and (b) Pd($C8_2NH$)$_2$(OAc)$_2$.

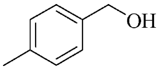
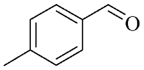
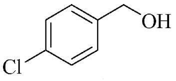
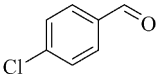
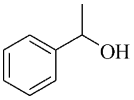
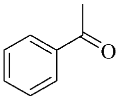
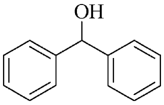
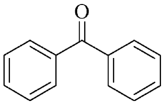
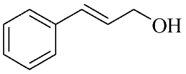
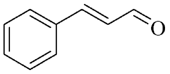
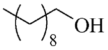
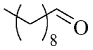
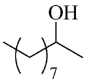
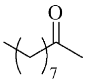
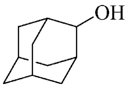
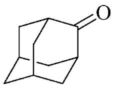
Table 2
Aerobic benzylalcohol oxidation with $Pd(Me_2N\textit{C12})_2(OAc)_2$ under various conditions[a]

Entry	Solvent	Pd conc. (mM)	Time (min)	Convn. (%)[b]	Yield (%)[b]	Pd black formation
1	Toluene	1	30	96	96	–
2[c]	Toluene	1	30	14	14	+
3[d]	Toluene	1	30	Trace	Trace	+
4	Toluene	1	10	62	61	–
5	Toluene	2	10	74	70	–
6	Toluene	5	10	78	77	–
7	Toluene	6	10	28	27	+
8	Toluene	8	10	20	20	+
9	Toluene	10	10	23	22	+
10	CH_3CN	1	30	32	32	–
11	DMF	1	30	17	17	–
12	2-PrOH	1	30	Trace	Trace	+
13	EtOAc	1	30	23	23	+
14	1,2-DCE[e]	1	30	Trace	Trace	+
15	H_2O	1	30	Trace	Trace	+

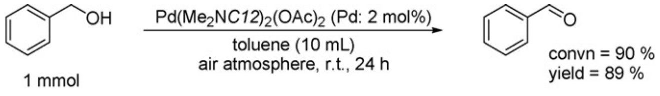
[a] Benzylalcohol (0.5 mmol), $Pd(Me_2N\textit{C12})_2(OAc)_2$ (0.01 mmol, Pd: 2 mol.%), solvent (1–10 mL), O_2 atmosphere, 80 °C.
[b] Determined by GC using an internal standard technique.
[c] Under air instead of O_2.
[d] Under N_2 atmosphere.
[e] 1,2-Dichloroethane.

and ca. 1:2 ratio of the oxygen uptake to benzaldehyde yield was observed in the oxidation of benzylalcohol. It is noted that the stability of $Pd(Me_2N\textit{C12})_2(OAc)_2$ catalyst is affected by the Pd concentration [13]. When the reaction was carried out with Pd concentration higher than 5 mM of $Pd(Me_2N\textit{C12})_2(OAc)_2$ under the above described conditions, the reaction mixture turned black to give palladium precipitate, resulting in slow reaction (entries 4–9). This new complex

Table 3
Aerobic alcohol oxidation catalyzed by $Pd(Me_2N\textit{C12})_2(OAc)_2$[a]

Entry	Substrate	Pd (mol.%)	Time (h)	Product	Convn. (%)[b]	Yield (%)[b]
1		2	1		94	90 (86)
2		2	3		67	66
3		2	1		>99	>99
4		2	2		>99	>99
5[c]		5	1		>99	>99
6[c]		5	1		>99	>99
7[c]		5	2		>99	>99
8		2	3		91	91

[a] $Pd(Me_2N\textit{C12})_2(OAc)_2$ (Pd: 2–5 mol.%), substrate (1 mmol), toluene (5 mL), O_2 atmosphere, and 80 °C.
[b] Determined by GC analysis using an internal standard technique. Value in parentheses is isolated yield.
[c] Toluene (10 mL).



Scheme 3.

efficiently catalyzed aerobic oxidation of benzylalcohol, as highlighted in entry 1. Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst showed a high turnover frequency (TOF; mol of product per mol of Pd content per hour) of 96 h^{-1}. This TOF value of the Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst is the highest ever reported for the palladium complex-catalyzed aerobic alcohol oxidations so far: Pd(OAc)$_2$/pyridine/MS3A (10 h^{-1}) [4a,4b], Pd(OAc)$_2$/triethylamine/MS3A (33 h^{-1}) [4c], Pd(OAc)$_2$/Phen*S/NaOAc (40 h^{-1}) [4d], Pd(OAc)$_2$/Dendron/NaOAc (16 h^{-1}) [4e], Pd(I*i*Pr)(OAc)(H$_2$O)/NaOAc/MS3A (50 h^{-1}) [4f], and Pd(dba)$_2$/thiourea/NaOAc (0.21 h^{-1}) [4g]. Among the solvents examined, toluene yielded favorable result (entry 1), whereas CH_3CN, DMF, 2-PrOH, EtOAc, 1,2-DCE, and H_2O were not effective (entries 10–15). To achieve more environmentally friendly alcohol oxidation, the reaction was carried out under air atmosphere at room temperature (Scheme 3). The oxidation proceeded smoothly without the formation of Pd black and benzylalcohol converted to benzaldehyde in 90% after 24 h.

The scope of the present Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst system towards various kinds of alcohols was examined. The results are summarized in Table 3. Primary benzylic alcohol with electron donating substituent such as *p*-methylbenzyl alcohol was also converted to the *p*-tolualdehyde in excellent yield (entry 1). On the other hands, the reaction rate of *p*-chlorobenzylalcohol oxidation slightly decreased (entry 2). In the case of primary alcohol oxidation, the overoxidation of aldehyde into carboxylic acid was not observed and the corresponding aldehydes were obtained selectively. The oxidation of secondary benzylic alcohol remains general to afford the ketone in high yield (entries 3 and 4). Importantly, this catalyst system was applicable to allylic alcohol, nonactivated aliphatic alcohols, and cyclic aliphatic alcohol into corresponding carbonyl compounds smoothly (entries 5–8). It is well known that the excess of amine ligand is necessary to inhibit the formation of palladium metal. In Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst system, however, the reaction proceeded efficiently without additional amine ligands and bases. Following the above results, our new Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst system allows simple and practical alcohol oxidation while meeting the increasing criteria for environmentally friendly chemical processes in the synthesis of fine chemicals and pharmaceuticals.

A plausible reaction mechanism for this alcohol oxidation was as follows: [14] initially, the catalytic cycle begins with binding of the alcohol to the Pd(II) species to form a Pd(II)-alkoxide specie and acetic acid. Following a β-hydride elimination, a Pd(II)-hydride species and the carbonyl product are formed. Then, the Pd(II)-hydride can reductively eliminate an equivalent of acid to form Pd(0), which is then reoxidized by molecular oxygen and 2 equiv. of acetic acid.

4. Conclusion

We have demonstrated a Pd(Me$_2$N*C12*)$_2$(OAc)$_2$ catalyst system efficiently catalyzes the aerobic alcohol oxidation of a wide range of alcohols into corresponding carbonyl compounds in high yield. We are now investigating the further application of our novel complex to brand-new catalyst design, for example the use of a pillar reagents of intercalation into various catalyst supports.

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