

Molybdenum(VI) Dichloride Dioxide/Copper(II) Perchlorate: An Efficient Bimetallic Catalyst for Aerobic Oxidation of Alcohols

Kandasamy Jeyakumar and Dillip Kumar Chand*

Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India

Abstract: The bimetallic system, $\text{MoO}_2\text{Cl}_2/\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ was used as an efficient catalyst for aerobic oxidation of alcohols. Aromatic, aliphatic, and allylic alcohols; also hydroxy esters were oxidized to the corresponding carbonyl compounds. The bimetallic catalyst showed higher reactivity for alcohol oxidation as compared to individual metal catalysts.

Keywords: Molybdenum(VI), copper(II), bimetallic catalyst, alcohol oxidation.

1. INTRODUCTION

From synthetic view point, oxidation of alcohols to the corresponding carbonyl compounds is one of the most important reactions in organic synthesis [1]. Chromium, manganese and hypervalent iodine reagents are widely used for alcohol oxidation. However, requirement of stoichiometric amount, safety hazards, formation of by-products and difficulty in work-up are major experimental problems [2]. Recently, catalytic oxidation employing complexes of transition metal ions, such as Fe, V, Cu, Co, Pd, Pt, Ru, etc. in the presence of (2,2,6,6-Tetramethylpiperidine-1-oxyl, i.e. TEMPO)/base are developed [3]. There are only few reports on alcohol oxidation using molybdenum compounds, however, in presence of H_2O_2 [4].

The application of bimetallic systems in organic synthesis has emerged in oxidation, coupling and conjugate addition reactions [5,6]. There are few reports available on selective oxidation of alcohols to aldehydes or ketones by using bimetallic systems [6]. The use of bimetallic systems for alcohol oxidation can offer the advantage of one metal activating the alcohol while the other activates molecular oxygen and thus results in more efficient catalysis than individual metals.

Recently, molybdenum(VI) dichloride dioxide (MoO_2Cl_2) has been used as an efficient catalyst for several organic transformations [7]. In our ongoing research work on the catalytic role of MoO_2Cl_2 , we have reported controlled and selective oxidation of sulfides to sulfoxides/sulfones [8a], aerobic oxidation of secondary and activated primary benzyl alcohols [8b], ring opening reaction of epoxides [8c], C-H insertion of ethyl diazoacetate into aldehydes [8d] and oxidation followed by bromination of β -hydroxycarbonyls [8e]. Apart from these work, we have also reported copper(II) perchlorate ($\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$) as an efficient catalyst for acetylation reactions [8f].

Since, MoO_2Cl_2 can oxidize only secondary and activated primary benzyl alcohols [8b] modification of the condition is

required to widen the scope of alcohol oxidation reaction. Herein we disclose further developments on alcohol oxidation (i.e. oxidation of activated/un-activated benzyl alcohols and aliphatic secondary alcohols) using $\text{MoO}_2\text{Cl}_2/\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ as an efficient bimetallic catalyst. The choice of Cu(II) as a co-catalyst is considered because this metal ion is known to activate molecular oxygen.

2. EXPERIMENTAL SECTION

2.1. General Consideration

Alcohols **1**, **3-16**, molybdenum(VI) dichloride dioxide (MoO_2Cl_2) and copper salts were purchased from Aldrich. Alcohols **2** and **17-21** were prepared by literature methods [9]. Alcohols and solvents were purified before use for the reactions [10]. The products were characterized by recording ^1H & ^{13}C NMR spectra, IR spectra and melting points using Bruker 400 MHz NMR spectrometer, Jasco FT/IR 660 plus and Toshnival-India melting point apparatus respectively. The spectral data are comparable with literature [11].

2.2. Experimental Procedure for Alcohol Oxidation

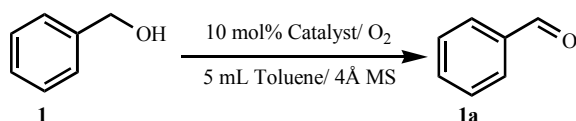
A mixture of 1 mmol of alcohol, 5 mol% of MoO_2Cl_2 , 5 mol% of $\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ and 50 mg of 4Å molecular sieve (MS) in 3 mL of toluene was stirred under reflux condition while bubbling oxygen. The conversion of alcohol was monitored by thin layer chromatography (TLC). After completion of the reaction, the solvent was evaporated and crude sample was subjected to aqueous work up followed by column chromatography purification to afford the carbonyl compound.

3. RESULTS AND DISCUSSION

3.1. Comparison of Bimetallic Catalyst

As preliminary study we have tested the oxidation of benzyl alcohol (**1**) under various conditions (Table 1). The reactions were carried out under reflux in toluene with 10 mol% of the catalyst. Molybdenum and copper catalysts alone could not oxidize benzyl alcohol (**1**) (no product was detected in thin layer chromatography (TLC)) whereas the bimetallic systems i.e. $\text{MoO}_2\text{Cl}_2/\text{CuX}_2$ (where X = Cl, OAc, NO_3 and ClO_4) could oxidize benzyl alcohol (**1**) to benzaldehyde (**1a**) in 52-89% of

*Address correspondence to this author at the Department of Chemistry, Indian Institute of Technology Madras, Chennai-600036, India; Tel: +91(44)22574224; Fax: +91(44)22574202; E-mail: dillip@iitm.ac.in; d.chand@lycos.com

Table 1. Oxidation of Benzyl Alcohol Under Various Conditions^a

Entry	Catalyst	Time (min)	Yield (%) ^b
1	10 mol% MoO ₂ Cl ₂	720	-- ^c
2	10 mol% CuX ₂	720	-- ^{c,d}
3	5 mol% MoO ₂ Cl ₂ / 5 mol% CuX ₂	720	52-89 ^d
4	5 mol% MoO ₂ Cl ₂ / 5 mol% Cu(ClO ₄) ₂ ·6H ₂ O	60	89

^aReaction conditions: A mixture of 1 mmol of alcohol, 10 mol% of catalyst and 50 mg

of 4Å molecular sieve was stirred under reflux condition while bubbling oxygen.

^bIsolated yield. ^cNo product was detected in thin layer chromatography (TLC). ^dX = Cl, OAc, NO₃ and ClO₄

yields. Among the various copper salts used here Cu(ClO₄)₂·6H₂O was found to be most efficient when combined with

MoO₂Cl₂ to provide 89% of benzaldehyde (1a). Further application of the MoO₂Cl₂/Cu (ClO₄)₂·6H₂O system was studied by oxidizing various primary benzyl alcohols, aliphatic and aromatic secondary alcohols and hydroxy esters (Tables 2-4).

3.2. Oxidation of alcohols to aldehydes

The summarized results for the oxidation of primary benzyl alcohols are provided in Table 2. The activated primary benzyl alcohols 2 and 3 (Table 2, entries 2 and 3) were oxidized to corresponding aldehydes 2a and 3a in quantitative yields within 15-30 minutes. It is also interesting to note that these two substrates possess other oxidisable functional groups i.e. *tert*-amine and sulfide which were intact in the present condition. Deactivated primary benzyl alcohols 4 and 5 (i.e. 4-nitro and 4-bromo benzyl alcohols) and the heterocyclic alcohol i.e. 2-pyridine methanol (6) were oxidized to corresponding aldehydes 4a-6a in 62-89 % of yields within 60 minutes. Cinnamyl alcohol (7) was oxidized to cinnamaldehyde (7a) in a good yield without affecting the double bond. The deactivated benzyl alcohol, e.g. 5 is less reactive and provide lower yield of aldehyde as compared to the substrate having electron releasing group on the ring.

Table 2. Oxidation of Primary Benzyl Alcohols Using MoO₂Cl₂/Cu(ClO₄)₂·6H₂O as the Bimetallic System^a

Entry	Substrates	Product	Time (min)	Yield (%) ^b
1			60	89
2			30	90
3			15	95
4			15	85
5			90	62
6			60	89
7			60	78

^aReaction conditions: A mixture of 1 mmol of alcohol, 5 mol% of MoO₂Cl₂, 5 mol% of Cu(ClO₄)₂·6H₂O and 50 mg of 4Å molecular sieve was stirred under reflux condition while bubbling oxygen. ^bIsolated yield.

3.3. Oxidation of Alcohols to Ketones

The summarized results for the oxidation of secondary alcohols were provided in Table 3. Unactivated, activated and deactivated benzyl alcohols, **8-11** (Table 3, entries 8-11) were oxidized to corresponding ketones **8a-11a** in above 80% of yields. Further efficiency of the $\text{MoO}_2\text{Cl}_2/\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ system was studied on oxidation of aliphatic secondary alcohols; cyclic and acyclic secondary alcohols **12-14**

(Table 3, entries 12-14) were oxidized to corresponding ketones **12a-14a** in 52-60% of yields. Thus aliphatic alcohols are found to be less reactive.

3.4. Oxidation of Esters to Keto Esters

The summarized results for the oxidation of α - and β -hydroxy esters are provided in Table 4. Aryl substituted α - and β -hydroxy esters, **15-20** (Table 4, entries 15-20) were

Table 3. Oxidation of Secondary Alcohols Using $\text{MoO}_2\text{Cl}_2/\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ as the Bimetallic System^a

Entry	Substrates	Product	Time (min)	Yield (%) ^b
8			60	85
9			30	89
10			180	83
11			90	93
12			720	60
13			720	59
14			720	52

^aReaction conditions: A mixture of 1 mmol of alcohol, 5 mol% of MoO_2Cl_2 , 5 mol% of $\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ and 50 mg of 4Å molecular sieve was stirred under reflux condition while bubbling oxygen. ^bIsolated yield.

Table 4. Oxidation of α - and β -Hydroxy Ester Using $\text{MoO}_2\text{Cl}_2/\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ as the Bimetallic System^a

Entry	Substrates	Product	Time (min)	Yield (%) ^b
15			180	92
16			60	89
17			180	76
18			180	82
19			60	79
20			240	70
21			720	18

^aReaction conditions: A mixture of 1 mmol of alcohol, 5 mol% of MoO_2Cl_2 , 5 mol% of $\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ and 50 mg of 4Å molecular sieve was stirred under reflux condition while bubbling oxygen. ^bIsolated yield.

oxidized to corresponding keto esters **15a-20a** in 70-92% of yields. Alkyl substituted β -hydroxy ester **21** was oxidized to corresponding β -keto ester **21a** in 18% of yield. In this class of compounds the aliphatic compounds are found to be less reactive as observed from the lower yield of the desired product.

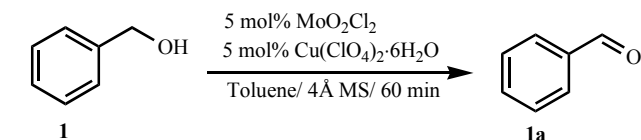
3.5. Mechanism of Alcohol Oxidation in the Bimetallic System

We have studied the role of oxygen in this reaction, by oxidizing benzyl alcohol (**1**) under various conditions (Table 5) by controlling the atmosphere of the reaction. The reaction provides 71% benzaldehyde when exposed to air where as under bubbling oxygen 89% of benzaldehyde was obtained. Under N_2 atmosphere the reaction does not proceed, which shows the participation of aerobic oxygen in the oxidation process.

During the oxidation of alcohols using the bimetallic catalyst, it is proposed that, Mo(VI) species undergoes reduction to Mo(IV) which could be re-oxidized to Mo(VI) by Cu(II) (Scheme 1). The Cu(I) so formed could be re-oxidized to Cu(II) by molecular oxygen [5]. These molybdenum species present in the catalytic cycle are expected to bind alcohol/alkoxide to initiate and sustain the oxidation reaction. When the Mo(IV) species is bound to alcohol/alkoxide having electron withdrawing group then the Mo(IV) center will experience decrease of electron density around it and hence oxidation to generate Mo(VI) by oxygen should be hampered. In the same line presence of electron releasing group should favor the oxidation of Mo(IV) to Mo(VI). The reactivity patterns of the alcohols to provide aldehydes support this argument. Addition of the Cu(II) as a cocatalyst somewhat circumvent this problem by activating molecular oxy-

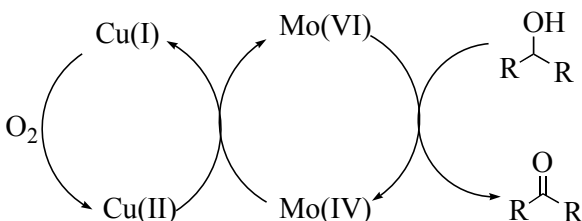
gen and facilitating oxidation of Mo(IV) to Mo(VI) and hence before the catalyst is deactivated oxidation of less reactive alcohols is also realised.

Table 5. Oxidation of Benzyl Alcohol Under Various Atmospheres^a



Reaction Condition	Yield (%) ^b
Open air	71
Under O ₂	89
Under N ₂	— ^c

^aReaction conditions: A mixture of 1 mmol of benzyl alcohol, 5 mol% of MoO₂Cl₂, 5 mol% of Cu(ClO₄)₂·6H₂O and 50 mg of 4Å molecular sieve was stirred under reflux condition. ^bIsolated yield. ^cNo product was detected in thin layer chromatography (TLC).



Scheme 1. Proposed mechanism for redox reactions in the bimetallic system during alcohol oxidation.

4. CONCLUSIONS

In conclusion, we have demonstrated the use of MoO₂Cl₂/Cu(ClO₄)₂·6H₂O as a bimetallic catalyst for alcohol oxidation. Various alcohols were oxidized to corresponding carbonyl compounds in good yields. The individual metal catalysts are found to be less efficient for alcohol oxidation. More importantly, benzyl alcohols having no ring substituent or electron withdrawing substituent could be oxidized by the bimetallic catalyst which is not possible with MoO₂Cl₂. Some oxidisable functional groups like amine, pyridine, sulfide and olefin groups are tolerated during the conversion. Synthesis of dicarbonyls is also achieved using this method.

ACKNOWLEDGEMENTS

This study was supported by a grant in aid for scientific research from the CSIR, (No. 01(2108)/07/EMR-II New Delhi, India). K. J. thanks CSIR, New Delhi for a Senior Research Fellowship.

REFERENCES

[1] Hudlicky, M. *Oxidations in Organic Chemistry*; ACS: Washington, DC, 1990.

- [2] (a) Sheldon, R.A.; Kochi, J.K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981; (b) Ley, S.V.; Norman, J.; Griffith, W.P.; Marsden, P. *Synthesis*, 1994, 639; (c) Cainelli, G.; Cardillo, G. *Chromium Oxidations in Organic Chemistry*; Springer: Berlin, 1984.
- [3] (a) Arends, I. W. C. E.; Sheldon, R. A. In *Modern Oxidation Methods*; J.E. Backvall, Ed.; Wiley-VCH: Weinheim, Germany, 2004; pp. 83-118; (b) Schultz, M. J.; Sigman, M. S. *Tetrahedron*, 2006, 62, 8227.
- [4] (a) Maignien, S.; Mohand, S.A.; Muzart, J. *Synlett*, 1996, 439; (b) Maiti, S. K.; Malik, K.M.A.; Bhattacharyya, R. *Inorg. Chem. Commun.*, 2004, 7, 823.
- [5] Shibasaki, M.; Yamamoto, Y. *Multimetallic Catalysts in Organic Synthesis*; Wiley: Weinheim, 2004.
- [6] (a) Muldoon, J.; Brown, S. N. *Org. Lett.*, 2002, 4, 1043; (b) Shapley, P. A.; Zhang, N.; Allen, J. L.; Pool, D. H.; Liang, H. C. *J. Am. Chem. Soc.*, 2000, 122, 1079; (c) Lorber, C. Y.; Smidt, S. P.; Osborn, J. A. *Eur. J. Inorg. Chem.*, 2000, 655.
- [7] (a) Sanz, R.; Aguado, R.; Pedrosa, M. R.; Arnaiz, F. J. *Synthesis*, 2002, 856; (b) Sanz, R.; Escribano, J.; Aguado, R.; Pedrosa, M. R.; Arnaiz, F. J. *Synthesis*, 2004, 1629; (c) Sanz, R.; Escribano, J.; Fernandez, Y.; Aguado, R.; Pedrosa, M. R.; Arnaiz, F. J. *Synlett*, 2005, 1389; (d) Chen, C. T.; Kuo, J. H.; Pawar, V. D.; Munot, Y. S.; Weng, S. S.; Ku, C. H.; Liu, C. Y. *J. Org. Chem.*, 2005, 70, 1188; (e) Fernandes, A. C.; Fernandes, R.; Romao, C. C.; Royo, B. *Chem. Commun.*, 2005, 213; (f) Weng, S. S.; Lin, Y. D.; Chen, C.-T. *Org. Lett.*, 2006, 8, 5633; (g) Sanz, R.; Escribano, J.; Pedrosa, M. R.; Aguado, R.; Arnaiz, F. J. *Adv. Synth. Catal.*, 2007, 349, 713; (h) Fernandes, A. C.; Romao, C. C. *Tetrahedron Lett.*, 2007, 48, 9176; (i) Fernandes, A. C.; Romao, C. C. *J. Mol. Catal. A: Chem.*, 2006, 253, 96; (j) Fernandes, A. C.; Romao, C. C. *J. Mol. Catal. A: Chem.*, 2007, 72, 60; (k) Goswami, S.; Maity, A.C.; *Tetrahedron Lett.*, 2008, 49, 3092.
- [8] (a) Jeyakumar, K.; Chand, D. K. *Tetrahedron Lett.*, 2006, 47, 4573; (b) Jeyakumar, K.; Chand, D. K. *Appl. Organomet. Chem.*, 2006, 20, 840; (c) Jeyakumar, K.; Chand, D. K. *Synthesis*, 2008, 807; (d) Jeyakumar, K.; Chand, D. K. *Synthesis*, 2008, 1685; (e) Jeyakumar, K.; Chand, D. K. *Synthesis*, 2008, (in press); (f) Jeyakumar, K.; Chand, D. K. *J. Mol. Catal. A: Chem.*, 2006, 255, 275.
- [9] (a) Mohanazadeh, F.; Hosini, M.; Tajbakhsh, M. *Monatsh. Chem.*, 2005, 13, 2041-2043; (b) Ianni, A.; Waldvogel, S. R. *Synthesis*, 2006, 2103; (c) Fosdick, L. S.; Wessinger, G. D. *J. Am. Chem. Soc.*, 1938, 60, 1465; (d) Beignet, J.; Cox, L. R. *Org. Lett.*, 2003, 5, 4231; (e) Bang, K.; Lee, K.; Park, Y. K.; Lee, P. H. *Bull. Korean Chem. Soc.*, 2002, 23, 1272; (f) Xu, L.; Cheng, J.; Trudell, M.L. *J. Org. Chem.*, 2003, 68, 5388; (g) Nakamura, K.; Miyai, T.; Nozaki, K.; Ushio, K.; Oka, S.; Onho, A. *Tetrahedron Lett.*, 1986, 27, 3155.
- [10] Armarego, W. L. F.; Perrin, D. *Purification of Laboratory Chemicals*, 4th ed.; Butterworth-Heinemann: Oxford, 2002.
- [11] Analytical data for the products: (a) Gogoi, P.; Hazarika, P.; Konwar, D. *J. Org. Chem.*, 2005, 70, 1934; (b) Schultz, M. J.; Hamilton, S.S.; Jensen, D. R.; Sigman, M. S. *J. Org. Chem.*, 2005, 70, 3343; (c) Ali, M. H.; Stricklin, S. *Synth. Commun.*, 2006, 36, 1779; (d) Baciocchi, E.; Gerini, M.F.; Lapi, A. *J. Org. Chem.*, 2004, 69, 3586; (e) Jiang, N.; Ragauskas, A. J. *Org. Lett.*, 2005, 7, 3689; (f) Singh, R. P.; Kamble, R. M.; Chandra, K. L.; Saravanan, P.; Singh, V. K. *Tetrahedron* 2001, 57, 241; (g) Zheng, Z. H.; Tang, Y. *J. Org. Chem.*, 2002, 67, 5320; (h) Velusamy, S.; Punniyamurthy, T. *Org. Lett.*, 2004, 6, 217; (i) Tran, K. V.; Bickar, D. *J. Org. Chem.*, 2006, 71, 6640; (j) Jain, S. L.; Sharma, V. B.; Sain, B. *Tetrahedron*, 2006, 62, 6841; (k) Shimizu, H.; Murakami, M. *Chem. Commun.*, 2007, 2855; (l) Makosza, M.; Sienkiewicz, K.; Wojciechowski, K. *Synthesis*, 1990, 850; (m) Balaji, B. S.; Chanda, B. M. *Tetrahedron*, 1998, 54, 13237; (n) Elaridi, J.; Thaqi, A.; Prosser, A.; Jackson, W. R.; Robinson, A. J. *Tetrahedron: Asymmetry*, 2005, 16, 1309.

Received: September 19, 2008

Revised: October 17, 2008

Accepted: October 22, 2008

© Jeyakumar and Chand; Licensee Bentham Open.

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.