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Aerobic selective oxidation of alcohols to aldehydes or ketones catalyzed by ionic liquid immobilized *TEMPO* under solvent-free conditions

Lin Liu, Liu-Yan Ji, Yun-Yang Wei

School of Chemical Engineering, Nanjing University of Science and Technology, Nanjing, P.R. China

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Abstract A selective ionic-liquid immobilized *TEMPO*/CuCl catalyzed oxidation procedure of alcohols to the corresponding aldehydes and ketones with molecular oxygen under solvent-free conditions was developed. The catalyst was easily recovered and reused in the reaction.

Keywords *TEMPO*; Task-specific ionic liquids; Immobilized catalyst; Oxidation.

Introduction

The selective oxidation of alcohols to the corresponding aldehydes or ketones is a fundamental transformation in both laboratory synthesis and industrial production. Numerous oxidizing reagents [1] (*e.g.*, CrO_3, $KMnO_4$, and MnO_2) in stoichiometric amounts have been traditionally employed to accomplish this transformation with considerable drawbacks, such as use of expensive reagents and volatile organic solvents, and discharge of environmentally pernicious wastes. From economic and environmental perspectives, the development of new catalytic oxidation systems with cheap and green oxidation reagents, such as molecular oxygen or hydrogen peroxide is particularly attractive.

TEMPO (2,2,6,6-tetramethyl-piperidyl-1-oxy), a type of stable nitroxyl radical, has emerged to be the catalyst of choice for the mild and selective oxidation of alcohols to aldehydes or ketones [2] and has been reviewed by *Sheldon et al.* [3]. Of particular interest is the catalytic system consisting of *TEMPO* and inexpensive transition-metal compound (*e.g.*, copper) [4]. *Gree et al.* have reported the CuCl/*TEMPO* catalytic system in the ionic liquid [*bmim*][PF_6] for selective oxidation of alcohols [5]. However, separation of *TEMPO* from the products and recycling could be problematic, especially when the reactions are run on a large scale. Although numerous immobilized *TEMPO* variants on both organic and inorganic supports have been synthesized [6], only few examples are known where molecular oxygen is used as terminal oxidant [4a, 7]. Moreover *TEMPO* immobilized on inorganic supports in some cases shows lower catalytic activity, and prolonged reaction times are needed for high conversion [8].

Room temperature ionic liquids have received recognition as novel and promising solvents for synthesis chemistry. They have also been referred to as "designer solvents" as their chemical and physical properties could be adjusted by careful choice of cation or anion. Recent advances in ionic liquids provided efficient routes for the preparation of task-specific ionic liquids (TSILs). *Muzart* has reviewed the development of ionic liquids as solvents for catalyzed oxidations of organic compounds, and some methods about the modification of *Gree*'s procedure by using ionic liquid immobilized *TEMPO* were summarized [9]. Herein we re-

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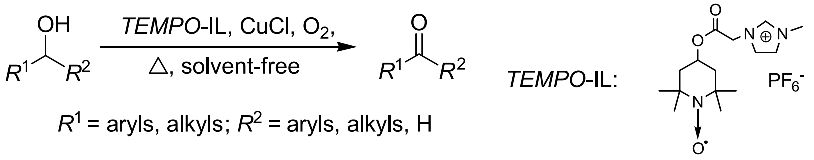
Correspondence: Yun-Yang Wei, School of Chemical Engineering, Nanjing University of Science and Technology, 210094 Nanjing, P.R. China. E-mail: ywei@mail.njust.edu.cn



Scheme 1

port our recent studies on the ionic liquid immobilized *TEMPO* (*TEMPO*-IL) and CuCl catalyzed oxidation of alcohols to the corresponding aldehydes or ketones under solvent-free conditions (Scheme 1).

Results and discussion

At first, a series of inexpensive transition-metal salts including Co(O*Ac*)$_2$, CoCl$_2$, Mn(O*Ac*)$_2$, NiCl$_2$, FeCl$_3$, CuCl, CuCl$_2$, and Cu(O*Ac*)$_2$ were used as co-catalyst with *TEMPO*-IL to oxidize benzyl alcohol to benzaldehyde under solvent-free conditions, and the results are summarized in Table 1.

Table 1 Effects of co-catalysts on *TEMPO*-IL catalyzed oxidation of benzyl alcohol to benzaldehyde under solvent-free conditions[a]

Entry	Metal salt	Convn./Sel.[b]/%	Yield[c]/%
1	none	4/75	–
2	Co(O*Ac*)$_2$	3/98	–
3	CoCl$_2$	0/–	–
4	FeCl$_3$	0/–	–
5	Mn(O*Ac*)$_2$	20/98	–
6	NiCl$_2$	30/96	–
7	CuCl	99/99	94
8	CuCl$_2$	78/99	65
9	Cu(O*Ac*)$_2$	71/99	61

[a] Reaction conditions: benzyl alcohol (5 mmol), metal salt (0.25 mmol), *TEMPO*-IL (0.25 mmol), O$_2$ atmosphere, at 65°C, 12 h; [b] GC conversion and selectivity; [c] Isolated yield

It can be seen from the data listed in Table 1 that among the salts tested, copper salts showed much higher catalytic activity than the other transition metal salts with 71–99% conversion of benzyl alcohol and 99% selectivity to benzaldehyde (Table 1, entries 7–9). CuCl was found to be the best catalyst with 99% conversion, 99% selectivity, and 94% isolated yield. The Mn and Ni salts showed moderate catalytic activity with 20–30% conversion (Table 1, entries 5–6), and the Co or Fe containing catalyst showed no catalytic activity (Table 1, entries 2–4).

The catalytic system *TEMPO*-IL/CuCl was then applied to the oxidation of various types of benzylic, allylic, heterocyclic, and aliphatic alcohols under solvent-free conditions, and the results are summarized in Table 2.

As shown in Table 2, all types of benzylic, allylic, heterocyclic, and aliphatic alcohols undergo oxidation into the corresponding aldehydes or ketones under solvent-free conditions. The oxidation of benzylic and allylic alcohols is faster with high conversions and yields (Table 2, entries 1–7). Electron-rich and electron-deficient benzylic alcohols did not show obvious differences. However, heterocyclic

Table 2 *TEMPO*-IL/CuCl catalyzed oxidation of alcohols to aldehydes or ketones[a]

Entry	Substrate	Temp./°C	Time/h	Convn.[b]/%	Yield[c]/%	Ref.[d]
1	benzyl alcohol	40	12	67	55	[10a, 11a]
2		65	12	99	94	
3	cinnamyl alcohol	65	30	99	84	[10b, 11b]
4	4-nitrobenzyl alcohol	100	24	96	84	[10c, 11c]
5	4-chlorbenzyl alcohol	75	19	99	88	[10d, 11d]
6	4-methoxybenzyl alcohol	65	21	99	91	[10e, 11e]
7	diphenyl carbinol	65	21	94	85	[10f, 11f]
8	2-phenylethanol	65	30	54	30	[10g, 11g]
9	furfuryl alcohol	65	50	40	–	[10h, 11h]
10	cyclohexanol	65	40	–	–	[10i, 11i]
11	lauryl alcohol	65	40	23	–	[10j, 11j]

[a] Reaction conditions: alcohol (5 mmol), CuCl (0.25 mmol), *TEMPO*-IL (0.25 mmol), O$_2$ atmosphere; [b] GC conversion; [c] Isolated yield; [d] References for isolated product

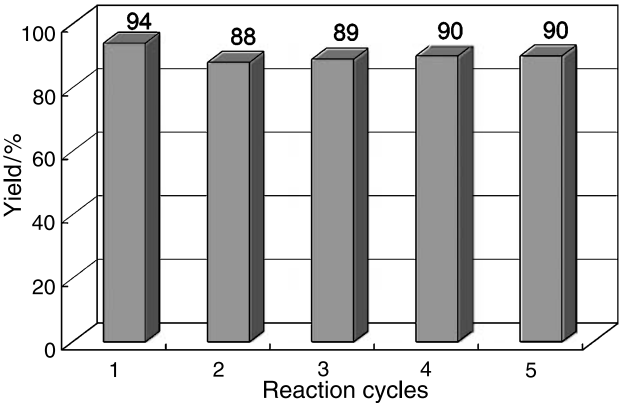


Fig. 1 Recycling of the catalytic system for the selective oxidation of benzyl alcohol

and aliphatic alcohols were less reactive (Table 2, entries 8–11), and lower conversions and yields were observed even after prolonged reaction time. The catalytic system shows high selectivity, and only a trace amount of acid (below 1%) was formed, and the double bond of allylic alcohol was not oxidized.

Extraction of the product with ether led the separation of the catalyst system from the product. The recycling and reuse of the CuCl/*TEMPO*-IL catalytic system for the oxidation of benzyl alcohol was examined. The catalytic phase was distilled under vacuum to remove residual ether and water formed in the reaction and reused in the oxidation for five times with no significant loss in catalytic activity (Fig. 1).

In conclusion, an efficient ionic liquid immobilized *TEMPO*/CuCl catalyzed procedure was developed, which allows the aerobic oxidation of benzylic and allylic alcohols to the corresponding aldehydes or ketones in high selectivity and yield under solvent-free conditions. The catalytic system was easily recovered and reused for further reactions. In the case of the oxidation of benzyl alcohol, the catalyst could be recovered and reused five times with no significant loss of catalytic activity.

Experimental

All chemicals (AR grade) were obtained from commercial resources and used without further purification. Products were all known compounds and were identified by comparing their physical and spectroscopic data with those reported in literature; ^{1}H NMR spectra were obtained with *TMS* as internal standard using a Bruker DRX 500 (500 MHz) spectrometer; IR spectra were recorded on a Shimadzu spectrometer using KBr discs. The ionic liquid immobilized *TEMPO* was synthesized according to Ref. [12].

Aerobic oxidation of alcohols under solvent-free conditions
In a glass reaction vessel were placed 5 mmol alcohol, 0.11 g *TEMPO*-IL (0.25 mmol), and 25 mg CuCl (0.25 mmol). The resulting reaction mixture was heated under an oxygen atmosphere (1 atm.) with magnetic stirring. The mixture was extracted with ether ($5 \times 10\,\text{cm}^3$). The combined ether phase was concentrated under vacuum; the crude product was purified by column chromatography (petroleum ether/ethyl acetate = 10/1). The catalyst phase was distilled under vacuum at 80°C for 0.5 h, and then it was reused in the next run for a recycling experiment.

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