

Full Research Paper

Efficient Copper-bisisoquinoline-based Catalysts for Selective Aerobic Oxidation of Alcohols to Aldehydes and Ketones

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Abstract: The selective oxidation of alcohols with molecular oxygen was efficiently completed in high conversion and selectivity using copper-bisisoquinoline-based catalysts under mild reaction condition. The effects of various parameters such as reaction temperature, reaction time, oxidant, ligands, etc, were studied. Solvent effect has been as well studied in ionic liquids [bmim]PF₆, [omim]BF₄ and [hmim]BF₄, comparing to traditional volatile organic solvent. The use of ionic liquids was found to enhance the catalytic properties of the catalysts used.

Keywords: selective oxidation of alcohols; copper-bisisoquinoline-based catalysts; ionic liquids.

1. Introduction

The oxidation of alcohols into corresponding aldehydes and ketones is a crucial transformation in organic chemistry, both with academic and industry relevance [1-4]. Traditionally, this reaction is realized by using inorganic oxidants (e.g. Cr(VI) reagents). These reagents are needed in stoichiometric

amounts and are usually toxic or hazardous and hard to be separated from products, which are not environmental friendly and economically. Moreover, most of them are not effective with a broad range of alcohols, especially those in the presence of other oxidizable functional groups such as olefinic group and heteroatoms [5]. Recently, more and more efforts have been put in high valuable catalytic oxidizing process. Among these, protocols based on O₂, air or H₂O₂ [6-9] are particularly attractive because of cheap and readily available oxidants and with H₂O as the only byproduct. Successful examples include both homogeneous catalysts (e.g. Ru-, Pd-, Cu- complexes; bi-metallic complexes systems) and heterogeneous catalysts (e.g. metal catalysts and supported catalysts, including mesoporous materials, zeolites, etc.) [10].

Room-temperature ionic liquids [11] are finding growing applications as alternative reaction media for separations [12] and organic transformations [13-21]. Recent examples of such organic transformations include hydrogenations [13], Friedel-Crafts reactions [14], Diels-Alder reactions [15], Heck reactions [16], Bischler-Napieralsky reactions [17], olefin dimerizations [18], cross-couplings [19], hydroformylations [20] and alkylations [21]. The desirable advantages of ionic liquids such as low vapor pressure, wide liquid range and thermal stability have made them exceptional reaction media. Accordingly, they are emerging as novel replacements for volatile organic compounds, mainly used as solvents in organic transformations. Ionic liquids have already been used as solvents for oxidation of alcohols with hypervalent iodine reagents, Cu(ClO₄)₂/acetamido-TEMPO/DMAP catalytic system, tetravalent cerium salts as oxidizing agents, and manganese dioxide, etc. [22].

In pursuing economical and environmentally friendly processes for the production of the selective oxidation of alcohols with molecular oxygen is particularly desirable. In this work, we report effective copper-bisisoquinoline-based catalysts for this purpose. The chose of copper-bisisoquinoline-based catalysts is based on the fact that copper chloride can mediate oxidation of alcohols very efficiently, in the presence of a nitrogen-contained ligand. However, the studies on copper-bisisoquinoline-based catalysts for selective oxidation of alcohols under air conditions using ionic liquid solvent system has not yet reported. The effects of some important variables, like oxidants and some additives, such as base or solid support are investigated. Solvent effect has been as well studied in ionic liquids [bmim]PF₆ (IL1), [omim]BF₄ (IL2) and [hmim]BF₄ (IL3) (Figure 1), comparing to traditional volatile organic solvent. The present work revealed that copper-bisisoquinoline-based catalysts has potential applications in the oxidation of alcohols into corresponding aldehydes and ketones with excellent conversion and good selectivity. The use of ionic liquids was found to enhance the catalytic properties of the catalysts used.

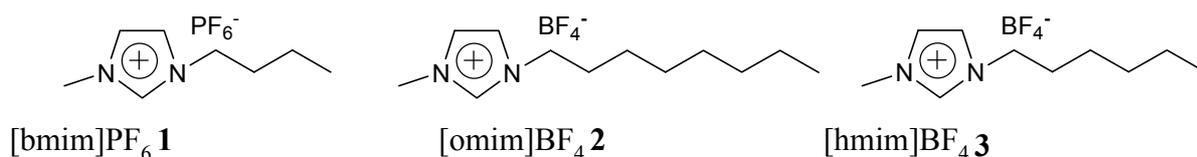


Figure 1. Structure of ionic liquids 1-3.

2. Results and Discussion

8 substrates with a wide range of primary, secondary, allylic, and benzylic alcohols can be smoothly oxidized to the corresponding aldehydes or ketones with good conversions. The results were listed in Table 1. The selectivity of the catalytic products of the 8 studied substrates at different experimental conditions was conducted by GC-MS. All the studied alcohols were able to be selected converted to corresponding aldehydes at selectivity higher than 80 %.

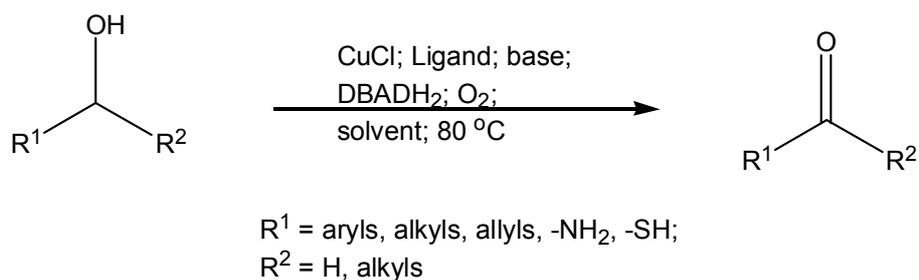
For the effects of the ligands, although the difference between L₁ and L₂ is only on the C-C (in L₁) and C=C (in L₂) bond in the nitrogen ring, the conversion of the alcohols are investigated higher in the catalytic system containing L₂ than that of L₁. This may be due to the results of L₂ has a better conjugated structure, which may stabilize the Cu-L complex system for better catalytic properties.

Air can be conveniently used instead of oxygen without affecting the efficiency of the process. However, the use of air requires slightly longer reaction times.

Remarkably, catalyst deactivation is not observed during these extended reaction times. The catalyst shows excellent tolerance for a broad range of alcohol substrates and is notably not deactivated by nitrogen- and sulfur-containing compounds. Sensitive aldehydes, are not isomerized under the reaction conditions. The active catalyst appears to be heterogeneous and adsorbed on the insoluble K₂CO₃. Besides its role as a solid support, the carbonate also acts as a base, initiating the addition of the alcohol, or DBADH₂ (di-tert-butylazodicarboxylate), or both to the copper complex, and as a water scavenger. K₂CO₃ could be replaced by a nonoxidizable base such as KOH or KOBut, with slightly effects on the conversion and selectivity.

The reaction solvent, toluene, can be replaced by Ionic liquids [bmim]PF₆ (IL1), [omim]BF₄ (IL2) and [hmim]BF₄ (IL3) used in this study. 2 ml of ionic liquids are needed for the reactions, with at least 1 % improvement of the conversion of alcohols. Not much effect on the conversion of alcohols was observed with the variation of the anion of the IIs, or the side chain length of the imidazole cation part of the IIs. The reaction can be carried out with high conversion and selectivity without base (Table 1 e-g), while base strictly necessary when toluene is used as solvent.

In this work, we have discovered an efficient catalytic system that oxidizes a wide range of alcohols into the corresponding aldehydes or ketones under mild conditions and that uses O₂ as the oxidant. The present work revealed that copper-bisisoquinoline-based catalysts has potential applications in the oxidation of alcohols into corresponding aldehydes and ketones with excellent conversion and good selectivity. Higher catalytic activity was investigated when L₂ was applied; which may be due to the aromatic ring can make the Cu-L complex more stable. For different substrates, the present catalytic system was more effective to the aromatic alcohols than the aliphatic ones; Primer alcohols were observed more active than the secondary ones in the present system. The use of ionic liquids was found to enhance the catalytic properties of the catalysts used. Further studies are needed to delineate the intimate mechanistic steps and expand the scope of this oxidation process.

Table 1. Oxidation of alcohols catalyzed by Cu-bisisoquinoline catalytic systems.

| entry | substrate | product | Time (h) | Conversion * (%) | | | | | | |
|-------|-----------|---------|-------------|------------------|-----|-----|-----|-----|-----|-----|
| | | | | Selectivity(%) | | | | | | |
| | | | | (a) | (b) | (c) | (d) | (e) | (f) | (g) |
| 1 | | | 1.5 | 93 | 96 | 95 | 95 | 97 | 96 | 96 |
| | | | | 93 | 96 | 98 | 96 | 98 | 97 | 98 |
| 2 | | | 1 | 91 | 97 | 97 | 97 | 98 | 98 | 99 |
| | | | | 92 | 93 | 92 | 95 | 95 | 93 | 92 |
| 3 | | | 1 | 93 | 99 | 98 | 98 | 99 | 99 | 99 |
| | | | | 90 | 91 | 92 | 94 | 95 | 93 | 94 |
| 4 | | | 2.5 | 94 | 97 | 96 | 97 | 97 | 98 | 97 |
| | | | | 88 | 89 | 92 | 88 | 90 | 91 | 90 |
| 5 | | | 2.5 | 85 | 88 | 88 | 88 | 90 | 91 | 91 |
| | | | | 80 | 81 | 82 | 80 | 85 | 85 | 84 |
| 6 | | | 2.5 | 81 | 83 | 82 | 82 | 89 | 90 | 90 |
| | | | | 80 | 82 | 82 | 80 | 82 | 83 | 83 |
| 7 | | | 2.5 | 86 | 89 | 88 | 88 | 91 | 91 | 92 |
| | | | | 82 | 84 | 83 | 81 | 85 | 84 | 85 |
| 8 | | | 3 | 96 | 99 | 99 | 99 | 99 | 99 | 99 |
| | | | | 92 | 94 | 95 | 96 | 96 | 94 | 95 |

* (a) L = L₁, base = K₂CO₃, reaction carried out in toluene; (b) L = L₂, base = K₂CO₃, reaction carried out in toluene; (c) L = L₂, base = KOH, reaction carried out in toluene; (d) L = L₂, base = KOBut, reaction carried out in toluene; (e) L = L₂, without base, reaction carried out in IL1, at 20 °C; (f) L = L₂, without base, reaction carried out in IL2, at 20 °C; (g) L = L₂, without base, reaction carried out in IL3; at 20 °C

3. Experimental Section

3.1. Materials

Ionic liquids [bmim]PF₆ (IL1), [omim]BF₄ (IL2) and [hmim]BF₄ (IL3) were purchased from Solvent-Innovation GmbH and purified by washing with ethyl acetate, and diethyl ether, and dried in vacuum. All the studied alcohols, light petroleum, dichloromethane, and hexane were purchased from Fluka with purity higher than 99% and used as received.

The preparation of bisisoquinoline ligands were reported elsewhere [23]. The structure of the bisisoquinoline ligands (L₁ and L₂) were shown in Figure 2.



Figure 2. Structures of ligand L₁ and L₂.

3.2. Catalytic reaction

The experimental procedure of the studied 8 substrates with a wide range of primary, secondary, allylic, and benzylic alcohols were similar. The oxidation of cinnamyl alcohol carried out in toluene was taken as an example.

Typical experimental procedure was carried out as follows: In a 100 ml two-necked flask, CuCl (0.05 g, 0.5 mmol) and L₁ or L₂ (0.19 g, 0.5 mmol) were dissolved in toluene (20 ml). Then, K₂CO₃ (2.75 g, 0.02 mol) were added and the mixture was stirred for 30 min at room temperature. DBADH₂ (ditert-butylazodicarboxylate) (0.115 g, 0.5 mmol) and Cinnamyl alcohol (0.134 g, 0.01 mol) were added successively, and the mixture was heated for 1.5 hours on an oil-bath at 80 °C while O₂ was gently bubbled through the reaction mixture. After cooling down to room temperature, the mixture was diluted by addition of Et₂O and filtered through a pad of silica gel. The solution was washed successively with water, 1 M HCl, and saturated aqueous NaCl solution, dried over MgSO₄, and distilled out all the organic portions.

For the reactions carried out in ionic liquids, no K₂CO₃ or other base was needed. The reactions can be realized at room temperature (20 °C). The rest procedures were similar to the ones carried out in toluene.

In order to monitor the reaction, samples were taken at intervals, treated with passing through a silica gel pad and diluted with toluene before injecting in GC. Qualitative analyses were conducted with a HP 6890N/5973N GC-MS with chemstation containing a NIST Mass Spectral Database. Quantitative analyses were conducted with a HP 6890 GC equipped with a FID detector. The

conversion was measured by gas chromatography. An HP-5 capillary column containing crossed linked 5%-phenyl 95%-dimethylsiloxane copolymer was used for GC separation.

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