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Copper catalyzed oxidation of benzylic alcohols in water with H₂O₂

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1. Introduction

ABSTRACT

A straightforward, efficient and sustainable copper catalyzed method was developed for oxidation of benzylic alcohols with 30% H₂O₂ in water. The reaction proceeded with CuSO₄ catalyst (1 mol%) at 100 °C without additional base or ligand. Primary benzylic alcohols were converted almost quantitatively to aldehydes with 70–90% selectivity, corresponding acids being the major side products. Also secondary benzylic alcohols afforded the corresponding ketones in high conversion with selectivities greater than 90%. It was demonstrated that the CuSO₄ catalyst can be recycled and reused at least for three runs, even though with some loss of catalytic activity. Selectivity of the CuSO₄ based catalyst system could be further increased by using 2-*N*-(*p*-fluorophenyl)-pyrrolecarbaldimine (1) as a ligand in combination with TEMPO in K₂CO₃ solution. The catalyst system was individually optimized (1 mol% CuSO₄, 2 mol% 1, 0.1 M K₂CO₃ and 5 mol% TEMPO) for a wide range of benzylic and allylic alcohols, which were quantitatively and selectively converted into the corresponding aldehydes with 3 eq. of H₂O₂ in 1 h.

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Aldehydes and ketones are important intermediates in the synthesis of other organic compounds and they are utilized particularly in the manufacture of medicines, flavors, fragrances and aniline dyes [1]. Therefore selective oxidation of alcohols toward carbonyl compounds by transition metal catalysts is a broadly studied field and various catalytic methods have been developed [2]. Regarding sustainable systems, O_2 and H_2O_2 are preferred oxidants. H_2O_2 is easy to handle and it has higher oxidation potential than O_2 . Only a few examples of catalytic systems based on Mn, Fe, Mo, W and Re with H_2O_2 are reported [3]. Reports in respect of Cu and H_2O_2 are still sparse [4] even though a system based on Cu–diphenoxydiamine complex is encouraging [5].

Our interest lies in developing green catalytic systems for alcohol oxidation [6]. We have recently reported aerobic oxidation of benzylic alcohols catalyzed by Cu(II)-2-*N*-arylpyrrolecarbaldimino complexes in combination with TEMPO in alkaline water solution under mild reaction conditions [7]. These catalysts could employ both O_2 and H_2O_2 as an oxidant. Related to this finding, herein are reported detailed studies on oxidation of benzylic alcohols in water using several copper salts as catalyst and H_2O_2 as an end oxidant (Scheme 1). The influence of various additives, such as acids or bases, radical scavengers and N-containing ligands, on the efficiency/selectivity of the catalyst system is demonstrated as well.

2. Experimental

2.1. General

All reagents were purchased from commercial suppliers and used as received. The ligands (**1–2**) used in this work were synthesized by published procedures [6(b),7] and purities were confirmed by ¹H NMR and melting point measurements. UV–vis spectra were recorded with a Hewlett Packard 8453 spectrophotometer. The oxidation products were quantitatively analyzed by GC (Agilent 6890 chromatograph, Agilent 19091J-413 capillary column 0.32 mm × 30 m × 0.25 μ m, FID detector) using internal standards. GC–MS method was used for identification of the products (Agilent 6890N equipped with Agilent 5973 mass selective detector, HP 19091 L-102 capillary columns, 200 mm × 24 m × 0.31 μ m).

2.2. Oxidation experiment

The catalytic oxidation reactions were carried out in a 100 mL two-neck round-bottomed flask equipped with a condenser and a magnetic stirring bar. Typically, 0.03 mmol of $CuSO_4 \cdot 5H_2O$ (stock solution of 50 mg/mL in H₂O) and a ligand in 1:2 molar ratio, respectively, were loaded to the flask and diluted with 5 mL of 0.1 M K₂CO₃ water solution. The reaction mixture was heated at 80 °C for 30 min to ensure complex formation and then cooled to room temperature. TEMPO (0.15 mmol), a substrate and 30% H₂O₂ (1 mL, 3 eq. to substrate) were introduced. The reaction was performed at the selected temperature, ranging from ambient temperature to 80 °C, for 1.5 h after which the reaction mixture was first allowed to cool to room temperature and then it was acidified with 1 M HCl solution (1 mL).

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Scheme 1. CuSO₄ catalyzes oxidation of primary and secondary benzylic alcohols with H₂O₂ in sole water at 100 °C with high efficiencies but selectivities are high only for secondary alcohols. By introducing a ligand, TEMPO and K₂CO₃ to the system, high oxidation selectivities are obtained for both primary and secondary benzylic alcohols at 60 °C but the conversions are high only for primary alcohols.

The procedure for reactions catalyzed solely by copper salts was rather similar to the procedure described above. A mixture of substrate and copper salt was stirred at the chosen temperature for 15 min and then 1 mL of 30% H_2O_2 was added. After ethylacetate extraction (10 mL), the solution was treated with a saturated $Na_2S_2O_3$ solution (1 mL) and the organic layer was separated. For quantitative analysis by GC, 200 μ L of reaction mixture was placed in a GC sample vial and diluted with 1 mL of ethylacetate. Acetophenone (0.86 mmol, 100 μ L) was used as an internal standard.

3. Results and discussion

3.1. Copper salt catalyzed oxidation of benzylic alcohols and effect of base and acid additives

Benzyl alcohol is chosen as a model substrate for this study. When the reaction is performed at 80 °C in distilled water using 30% H_2O_2 as an end oxidant and a variety of copper salts as catalysts, it is found that CuSO₄ is the most efficient catalyst. Other copper salts, except CuBr₂, give high conversions as well (Table 1, entries 1–5). The lower catalytic activity of CuBr₂ may be due to the formation of copper oxide or hydroxide as brown precipitation is observed after the oxidation reaction.

The effect of additives on the efficiency and selectivity of the $CuSO_4$ based system is studied by introducing various acids and bases to the reaction medium prior to the oxidant addition (Table 1, entries 6–9). The results show that under acidic and basic conditions the reaction is inhibited.

TEMPO is considered as a radical trap and it prevents the overoxidation of the substrate and thus sustains the selective oxidation of alcohols [8]. With TEMPO addition the conversion and selectivity are similar to those obtained with $CuSO_4$ alone (Table 1, entry 10). Interestingly, when the reaction is carried out in the presence of TEMPO and K_2CO_3 , the conversion decreases to 24% but the selectivity increases to 100% (Table 1, entry 12).

CuSO₄ catalyzed oxidation of benzyl alcohol with H_2O_2 is simple, efficient and very fast as within 15 min it is quantitatively oxidized in pure water (Table 2, entry 1). Although major product is benzaldehyde, other side products such as benzoic acid and derivatives of benzaldehyde are also formed. Selectivity cannot be improved by changing the reaction parameters (time, temperature, concentration) as when any of them is increased, the selectivity decreases below 70% (see Supplementary material). In addition, even the use of base or acid additive is not beneficial for the selectivity (see Table 1). The best selectivity is obtained when both TEMPO and K_2CO_3 are used but then the activity is reduced (Table 1, entry 12).

After establishing the optimal conditions $(1 \text{ mol}\% \text{ CuSO}_4, 1 \text{ mL} \text{ of } 30\% \text{ H}_2\text{O}_2, 100 \,^{\circ}\text{C})$ for the CuSO₄ system, other substrates were also studied under optimized conditions (Table 2). While substrates with an electron donating group, such as *p*-methoxy and

p-methyl derivatives of benzyl alcohol, are almost quantitatively converted to the corresponding aldehydes with 70-80% selectivity, p-nitrobenzyl alcohol with an electron withdrawing group is overoxidized to carboxylic acid (Table 2, entries 2-5). Surprisingly, allylic cinnamyl alcohol is quantitatively oxidized mainly to benzaldehyde (60%) rather than to the expected cinnamaldehyde (11%) (Table 2, entry 6). Similarly, 1-phenyl-1,2-ethanediol is quantitatively converted to benzaldehyde (50%) and to major side products benzoic acid (35%) and 2-hydroxy-1-phenylethanone (15%) (Table 2, entry 7). Conversely, 1,4-phenylenedimethanol can be quantitatively oxidized to 4-(hydroxymethyl)benzaldehyde (70%), terephthalaldehyde (16%) and 4-formyl benzoic acid (14%) (Table 2, entry 8). In comparison to the primary benzylic alcohols, secondary benzylic alcohols with an alkyl fragment are actively and selectively oxidized to the corresponding ketones as only minor components of hydroxyl derivatives of the corresponding ketones are observed (Table 2, entries 9 and 10). In addition, diphenylmethanol, a secondary benzylic alcohol with a phenyl fragment, is selectively and quantitatively converted to benzophenone within 30 min (Table 2, entry 11). Furthermore, 1naphthylmethanol, which is a relatively inert substrate, can be oxidized to 1-naphthaldehyde with moderate conversion but with excellent selectivity (Table 2, entry 12).

3.2. CuSO₄ catalyst recycling

Due to the high water solubility of CuSO₄, it can be easily recovered from the reaction mixture after oxidation and reused as catalyst. *p*-Chlorobenzyl alcohol was chosen herein for a substrate as it and its corresponding oxidation products are solids at room temperature. Once the oxidation was completed, the reaction mixture was cooled in an ice bath to precipitate oxidation products and any unreacted substrate. The solid was separated by filtration and washed with ice cold water. The volume of the aqueous solution was then reduced back to the original 5 mL by rotary evaporator. The recovered CuSO₄ solution was then reused for additional two runs. The respective conversions and selectivities of the 2nd and 3rd runs remained over 70% and 90%, as analyzed from the isolated crude products by GC–MS (Table 2, entry 4). These studies demonstrate that the CuSO₄ catalyst can be recycled without loss of selectivity although with a gradual drop in conversion.

3.3. Kinetics studies on CuSO₄ catalyzed oxidation of benzyl alcohol

The CuSO₄ catalyzed oxidation of benzyl alcohol with H_2O_2 is carried out in sole water, which is highly desirable from the green chemistry points of view. Therefore this catalyst system is studied in more detail. Figs. 1–3 reveal that the reaction is first order with respect to CuSO₄ and H_2O_2 concentrations, and second order with respect to benzyl alcohol concentration. These findings

1	82	

Table 1 Oxidation of benzyl alcohol in water catalyzed by Cu salt/H₂O₂.

Entry	Catalyst	Additive	Major product (%)	Major side product (%)	Conv. ^a (%)	Select. ^e (%)
1	CuSO ₄	None	Benzaldehyde (66)	Benzoic acid (19)	90	76
2	$Cu(OAc)_2$	None	Benzaldehyde (62)	Benzoic acid (18)	80	79
3	$Cu(NO_3)_2$	None	Benzaldehyde (52)	Benzoic acid (16)	71	83
4	CuCl ₂	None	Benzaldehyde (53)	Benzoic acid (16)	71	82
5	CuBr ₂	None	Benzaldehyde (44)	Benzoic acid (11)	57	84
6 ^b	CuSO ₄	H_2SO_4	Benzyladehyde (28)	Benzoic acid (10)	38	89
7 ^b	CuSO ₄	CF ₃ COOH	Benzaldehyde (39)	Benzoic acid (22)	63	74
8 ^b	CuSO ₄	NaOH	Benzaldehyde (2)	None	2	100
9 ^b	CuSO ₄	K ₂ CO ₃	Benzaldehyde (4)	None	4	100
10 ^c	CuSO ₄	TEMPO	Benzaldehyde (52)	Benzoic acid (21)	80	72
11 ^d	CuSO ₄	hydroquinone	Benzaldehyde (49)	Benzoic acid (38)	93	56
12 ^{b,c}	CuSO ₄	K_2CO_3 + TEMPO	Benzaldehyde (24)	None	24	100

^a Reaction conditions: 1.5 h, 3 mmol benzyl alcohol, 1 mol% catalyst, 5 mL H₂O, 1 mL (0.97 mmol, 3 eq. to substrate) 30% H₂O₂, 80 °C.

^b 5 mL 0.1 M acid or base solution.

^c 5 mol% TEMPO.

^d 0.97 mmol of hydroquinone (in stoichiometric amount with respect to oxidant).

^e Selectivity corresponds to major product.

Table 2

Oxidation of alcohols to carbonyl compounds catalyzed by CuSO₄/H₂O₂.^a

Entry	Substrate	Major product (%) ^b	Time (min)	Conv. (%)	Select ^c . (%)
1	C ₆ H ₅ CH ₂ OH	C ₆ H ₅ CHO (69)	15	98	71
2	p-MeOC ₆ H ₅ CH ₂ OH	p-MeOC ₆ H ₅ CHO (84)	15	>99	84
3	p-MeC ₆ H ₅ CH ₂ OH	p-MeC ₆ H ₅ CHO (82)	120	92	90
4 ^{run 1}	p-ClC ₆ H ₅ CH ₂ OH	p-ClC ₆ H ₅ CHO (84)	120	90	94
4 ^{run 2}	p-ClC ₆ H ₅ CH ₂ OH	p-ClC ₆ H ₅ CHO (73)	120	80	95
4 ^{run 3}	p-ClC ₆ H ₅ CH ₂ OH	$p-ClC_6H_5CHO$ (65)	120	71	94
5	p-NO ₂ C ₆ H ₅ CH ₂ OH	$p-NO_2C_6H_5COOH(73)$	15	94/78 ^d	80
6	C ₆ H ₅ CH=CHCHOH	C ₆ H ₅ CHO (60)	180	100	60
7	C ₆ H ₅ CHOHCH ₂ OH	C ₆ H ₅ CHO (50)	30	100	50
8	OHCH ₂ C ₆ H ₅ CH ₂ OH	$OHCH_2C_6H_5CHO(70)$	120	100	70
9	C ₆ H ₅ CHOHCH ₃	C ₆ H ₅ COCH ₃ (89)	180	98	92
10	C ₆ H ₅ CHOHCH ₂ CH ₃	$C_6H_5COCH_2CH_3$ (84)	180	90	95
11	C ₆ H ₅ CHOHC ₆ H ₅	C ₆ H ₅ COC ₆ H ₅ (89)	30	100	98
12	1-Naphthylmethanol	1-Naphthaldehyde (47)	180	48	99

 $^a\,$ Reaction conditions: 3 mmol benzyl alcohol, 1 mol% CuSO4, 5 mL H2O, 1 mL 30% H2O2, 100 $^\circ$ C.

^b Conversion (mol%) of the major product.

^c Selectivity is obtained from the conversion of the major product.

^d Isolated yield.



Fig. 1. Effect of catalyst concentration on catalytic performance of CuSO₄ for oxidation of benzyl alcohol with H₂O₂ in distilled water. Reaction conditions: 3 mmol benzyl alcohol, 0.005–0.03 mmol CuSO₄, 5 mL H₂O, 1 mL 30% H₂O₂, 100 °C. R² = 0.99 (average).



Fig. 2. Effect of oxidant concentration on catalytic performance of CuSO₄ for oxidation of benzyl alcohol with H₂O₂ in distilled water. Reaction conditions: 3 mmol benzyl alcohol, 0.03 mmol CuSO₄, 5 mL H₂O, 0.12–0.97 mmol 30% H₂O₂, 100 °C. *R*² = 0.99 (average).



Fig. 3. Effect of substrate concentration on catalytic performance of CuSO₄ for oxidation of benzyl alcohol with H₂O₂ in distilled water. Reaction conditions: 3.0–4.5 mmol benzyl alcohol, 0.03 mmol CuSO₄, 5 mL H₂O, 1 mL 30% H₂O₂, 100 °C. *R*² = 0.99 (average).



Fig. 4. Effect of temperature on catalytic performance of CuSO₄ for oxidation of benzyl alcohol with H₂O₂ in distilled water. Reaction conditions: 3 mmol benzyl alcohol, 0.03 mmol CuSO₄, 5 mL H₂O, 1 mL 30% H₂O₂, 70–100 °C. *R*² = 0.98 (average).

support conclusion that a mononuclear copper complex is involved in the process. By using van't Hoff's method, Fig. 4 gives activation parameters, $E^a = -128.66 \text{ J} \text{ mol}^{-1}$, $\Delta S^\circ = 261.24 \text{ J} \text{ mol}^{-1} \text{ K}^{-1}$ and $\Delta G^\circ_{25 \,^\circ\text{C}} = -77.72 \text{ kJ} \text{ mol}^{-1}$.

3.4. Proposed reaction mechanism

Several studies have suggested that the oxidation of organic substrates with H_2O_2 proceeds via a free radical mechanism [9]. To research whether the CuSO₄ catalyzed oxidation of benzyl alcohol with H_2O_2 proceeds via this mechanism, the influence of radical scavengers TEMPO and hydroquinone (in quantitative amount with respect to the oxidant) to the reaction was investigated under the basic conditions. Unpredictably, the oxidation is not hampered (Table 1, entries 10 and 11) which strongly suggests that the reactions studied herein proceed through ionic rather than free radical pathways.

To study the possible oxidation state of copper during the oxidation of benzyl alcohol with H_2O_2 in water, UV–vis experiments were carried out under argon atmosphere (see Fig. S2 in Supplementary material). CuSO₄ water solution exhibits absorption band at 834 nm, which is assignable to Cu^{II} [10(a)]. The oxidation reaction occurs vigorously if CuSO₄/benzyl alcohol reaction mixture, which shows a band at 835 nm, is stirred at 100 °C for about 15 min prior to the oxidant addition. The colorless reaction mixture turns to yellowish brown after the addition of 30% H_2O_2 and the absorption band is shifted to 836 nm. Therefore, it is likely that the catalytic reaction proceeds through peroxometal pathway where the oxidation [10(b)].

In order to obtain further evidence for the possible reaction path, a 1 mM Cu^{II} salt water solution containing benzyl alcohol (2 μ L) was treated with 30% H₂O₂ and the progress of the reaction was monitored by UV–vis spectroscopy. Gradual 5 μ L additions of 30% H₂O₂ into the solution resulted in the spectral changes shown

in Fig. 5. The spectrum of the Cu^{II} and benzyl alcohol solution exhibits a strong band at 257 nm. After addition of H_2O_2 , a new band is observed at 363 nm. Intensities of these bands increase upon the H_2O_2 additions, which suggest interaction between Cu^{II} and H_2O_2 . To further uncover this interaction, separate water solutions of Cu^{II} and benzyl alcohol were treated with H_2O_2 . Titration of Cu^{II} solution with H_2O_2 resulted in the same observations as with the Cu^{II}/benzyl alcohol solution whereas benzyl alcohol solution showed only an increase in the intensity of a band at 257 nm (see Figs. S3 and S4 in Supplementary material). Based on our experimental data and existing literature [10], we propose the following reaction mechanism (Scheme 2).

The catalytic cycle begins by the formation of an anticipated perhydroxy–Cu^{II} complex (**A**) in the presence of benzyl alcohol and H_2O_2 . This kind of monomeric copper complex has been postulated



Fig. 5. Spectral changes during gradual addition of 30% H₂O₂ into Cu^{II} and benzyl alcohol water solution. Reaction conditions: 2 mL 1 mM Cu(OAc)₂, 2 μ L benzyl alcohol, 5 × 7 μ L 30% H₂O₂, room temperature.



Scheme 2. Proposed reaction mechanism for the CuSO₄ catalyzed oxidation of benzylic alcohols in sole water with H₂O₂.

to be an active species in various other catalytic reactions [10(c-h)]. Benzaldehyde is obtained by an intramolecular abstraction of β -hydrogen by perhydroxy moiety of **A** [10(i,j)]. Since this Habstraction is energetically unfavorable, Cu^{II}-oxyl species (**B**) is expected to be formed and it is stabilized only when there is one π bonding interaction between the copper and the oxyl [10(k)]. In the next step, H₂O₂ converts the Cu^{II}-oxyl species to Cu^{II}-perhydroxide (**C**) which is then regenerated back to the perhydroxy–Cu^{II} complex (**A**) with the help of benzyl alcohol.

3.5. Selective oxidation of benzylic and allylic alcohols by CuSO₄/TEMPO/ligand systems

As shown above, solely CuSO₄ is highly active in alcohol oxidation with H₂O₂ in water but unfortunately it gives unsatisfactory selectivities with primary alcohols. Only secondary alcohols are oxidized with high selectivity and activity. In our previous study, it was shown that pyrrole-2-carbaldimine type ligands react easily with CuSO₄ in water giving the corresponding L₂Cu complexes [7]. The in situ made complexes had similar catalytic oxidation properties as pre-made complexes, which were first isolated and then applied in the reaction. Therefore, the most efficient ligand, namely 2-*N*-(*p*-fluorophenyl)-pyrrolecarbaldimine (1), from the previous study is selected for the current studies. When it is employed with CuSO₄ and TEMPO in sole water at $80 \,^{\circ}$ C, the resulting catalytic activity (Table 3, entry 1) is similar to that obtained with CuSO₄ and TEMPO in K₂CO₃ solution described above (Table 1, entry 12). However, when the oxidation is done in K₂CO₃ solution, almost quantitative conversion of benzyl alcohol with 100% selectivity is achieved (Table 3, entry 2). Surprisingly, if this reaction is carried out in NaOH solution instead of K₂CO₃, both conversion and selectivity are diminished (Table 3, entry 3).

2-N-(p-fluorophenyl)-The results obtained with pyrrolecarbaldimine (1) prompted us to study the influence of other commonly used ligands (3-9, see Table 3 for compound names) together with the recently published [6(b)]ligand N-(2-phenylethyl)-3,5-di-tert-butyl salicylaldimine (2) in K_2CO_3 solution (Table 3, entries 4–11). The use of the 2 in the CuSO₄/TEMPO catalyzed oxidation of benzyl alcohol by H₂O₂ in K₂CO₃ solution at 80 °C gives 89% conversion with 99% selectivity toward benzaldehyde (Table 3, entry 4). In contrast, the use of phenanthroline (3) and bipyridine ligands (4–5) produce benzoic acid as a main product with poor conversions (Table 3, entries 5–7). However, the use of biquinoline (**6–7**) as a ligand results in only ca. 20% conversions with 90% selectivities (Table 3, entries 8 and 9). Reactions with 9,10-diaminophenantroline (8) and 4,4'-trimethyline-dipyridine (9) provide excellent selectivities (Table 3, entries 10 and 11) but very low conversions (34–38%). In conclusion, of the studied systems using additional ligand system comprising of CuSO₄/TEMPO/1 is the most beneficial for the selective oxidation of benzyl alcohol with H_2O_2 in K_2CO_3 solution.

The CuSO₄/TEMPO/**1** system was optimized with respect to temperature, pH and TEMPO concentration for the oxidation of benzyl alcohol with H_2O_2 in K_2CO_3 solution (see Supplementary material for more details). The in situ made Cu–**1** complex is inactive at room temperature and has an activation temperature of approximately 35 °C. The activity increases significantly with an increasing temperature until up to 60 °C. Observed reduced catalytic activity at 80 °C is considered to be mainly caused by H_2O_2 decomposition in alkaline conditions. Therefore temperatures higher than 80 °C were not applied. The optimum temperature for the system is 60 °C and a quantitative conversion of benzyl alcohol with CuSO₄/TEMPO/**1** in K₂CO₃ solution is achieved after 1 h. Thus further studies are carried out at 60 °C.

In general, the pH of the reaction solution has a crucial effect on the catalytic activity. For example, alcohol oxidation with O_2 , Cubipy and Cu-phen catalysts has been reported to be efficient when a base, such as NaOH [6(a,b)], K₂CO₃ [6c] or KOBu^t [11], has been used. Interestingly, the ligand assisted catalyst system studied in this work gives moderate activity (22% conversion of benzyl alcohol with H₂O₂) in distilled water. However, the highest conversion of benzyl alcohol is obtained in 0.1 M K₂CO₃ (pH 11) solution. If the concentration of the selected base is higher than this, the catalytic activity is diminished although side reactions are not occurring. The increased activity in 0.1 M K₂CO₃ solutions is most likely caused by increased deprotonation of alcohol substrate making it more susceptible to oxidation. Therefore, the optimum pH of the solution is approximately 11 and 0.1 M K₂CO₃ solution was selected as solvent for the rest of the experiments.

In situ made Cu–1 is nearly inactive in oxidation of benzyl alcohol with H_2O_2 in K_2CO_3 solution without TEMPO. By increasing concentration of TEMPO, almost a linear dependency between the reaction rate and the amount of TEMPO is observed. Quantitative conversion of benzyl alcohol is obtained with 5 mol% of TEMPO. To summarize, the optimized reaction conditions with respect to both conversion and selectivity for the studied catalytic system are 1 mol% CuSO₄, 1 mL of 30% H₂O₂, 2 mol% 1, 5 mol% TEMPO, 5 mL of 0.1 M K₂CO₃, 1 h and 60 °C temperature.

Table 3

Selective oxidation of benzyl alcohol catalyzed by CuSO₄/TEMPO/ligand systems with and without base addition.^a

Entry	Catalyst	Ligand	Major product (%) ^b	Conv. (%)	Select. ^c (%)
1 ^d	CuSO ₄	1	Benzaldehyde (23)	23	>99.9
2	CuSO ₄	1	Benzaldehyde (95)	95	100
3 ^e	CuSO ₄	1	Benzaldehyde (20)	32	88
4	CuSO ₄	2	Benzaldehyde (88)	89	99
5	CuSO ₄	3	Benzoic acid (22)	36	78
6	CuSO ₄	4	Benzoic acid (27)	37	73
7	CuSO ₄	5	Benzoic acid (19)	34	81
8	CuSO ₄	6	Benzaldehyde (13)	19	94
9	CuSO ₄	7	Benzaldehyde (13)	20	93
10	CuSO ₄	8	Benzaldehyde (38)	38	100
11	CuSO ₄	9	Benzaldehyde (34)	34	100

^a Reaction conditions: 1.5 h, 3 mmol benzyl alcohol, 1 mol% CuSO₄, 2 mol% **1–9**, 5 mol% TEMPO. 5 mL 0.1 M K₂CO₃, 1 mL 30% H₂O₂, 80 °C. **1**=2-*N*-(*p*-fluorophenyl)-pyrrolecarbaldimine, **2**=*N*-(2-phenylethyl)-3,5-di-*tert*-butyl salicylaldimine, **3**=1,10-phenanthroline, **4**=4,4'-dimethyl-2,2'-bipyridine, **5**=4,4'-dimethoxy-2,2'-bipyridine, **6**=2,2'-biquinoline-4,4-dicarboxylic acid dipotassium salt, **8**=9,10-diaminophenantroline, **9**=4,4'-trimethyline-dipyridine (see Scheme S1 in Supplementary material for structures of **1–9**.

^b Conversion (mol%) of the major product.

^c Selectivity is obtained from the conversion of the major product.

 $^d~5\,mL\,H_2O$ instead of 0.1 M $K_2CO_3.$

^e 5 mL 0.1 M NaOH instead of 0.1 M K₂CO₃.

Table 4

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Selective oxidation of benzylic and allylic alcohols catalyzed by CuSO₄/TEMPO/1 system.^a

Entry	Substrate	Product	Conversion, % (mL) ^b	Conversion, % (mL) ^b		
			-/o-/2,3-di/2,4,5-tri	<i>m</i> -/2,4-di/3,4,5-tri	<i>p</i> -/3,4-di	
1	ОН		100 (5)			
2		$O_2 N \frac{\Pi}{U} O$	100 (10)	100 (10)	82 (20)	
3	CI		100 (10)	100 (10)	100 (20)	
4	MeO	MeO	100 (15)	100 (10)	100 (15)	
5	(MeO) ₂ U OH	(MeO) ₂ II	60 (10)	100 ((20)	82 (5)	
6	(MeO) ₃ II OH	(MeO) ₃ II	99 (5)	98 (10)		
7	Me	Me	97 (20)	100 (5)	100 (10)	
8	ОН		89 (10)			
9	Ме	Me	10 (10)			
10	СН	Et O	8 (10)			
11	С ^S — _{ОН}	ſ\$∕	62 (5)			
12	ОН	€ N O	8 (5)			

^a Optimized reaction conditions: 1 h, 1 mL 30% H₂O₂, 5 mol% TEMPO, 1 mol% CuSO₄, 2 mol% 1, 60 °C. Samples were directly analyzed by GC–MS. Selectivities were >99% according to GC–MS analysis.

^b Optimized volume of 0.1 M K₂CO₃.

3.6. Oxidation of other alcohols catalyzed by $CuSO_4/TEMPO/1$ system

A series of other alcohols was selected to study the influence of different substituents on the phenyl ring. When reaction conditions are optimized for each alcohol, in general all benzylic alcohols are nearly quantitatively converted to aldehydes without overoxidation regardless the type, position and number of the substituents (Table 4, entries 2–7). Oxidations of such alcohols have been recently reported to be catalyzed also by a Cu–diphenoxydiamine complex with H_2O_2 [5]. However, with this catalyst alcohols were oxidized to acids and the reactions were carried out in organic solvent (CH₃CN) at 80 °C in the presence of high excess of H_2O_2 (10 eq. to substrate). The ligand assisted catalyst oxidizes efficiently cinnamyl alcohol to the corresponding α , β -unsaturated aldehyde without affecting the double bond (Table 4, entry 8) unlike the CuSO₄ system (see Table 2, entry 6).

Despite of successful oxidation of primary benzylic and π activated alcohols with the ligand modified catalyst, secondary benzylic alcohols such as 1-phenylethanol and 1-phenylpropanol are hardly reactive (Table 4, entries 9 and 10). 2-Thiophene methyl alcohol, an example of heterocyclic alcohol, is also smoothly converted to the aldehyde in moderate conversion (Table 4, entry 11). With 2-pyridine methanol only a very low conversion is obtained (Table 4, entry 12) due to the formation of a new complex with overoxidized product, i.e., picolinic acid. After the oxidation with H₂O₂, blue crystals suitable for X-ray crystallography measurement were isolated and identified as the Cu complex of picolinic acid $(m/z 307 \text{ for } C_{12}H_8CuN_2O_4)$. It is worth noting that the ligandassisted system is highly selective toward primary benzylic and allylic alcohols as secondary benzylic alcohols are oxidized in poor conversions. Primary and secondary aliphatic alcohols are barely active or totally inactive with both systems. On the other hand, CuSO₄ system alone has high activities and selectivities toward secondary alcohols.

4. Conclusions

Efficient, simple and sustainable Cu^{II} catalyzed methods were developed for the preparation of aldehydes and ketones. The reactions catalyzed solely by CuSO₄ (1 mol%) were carried out in water at $100 \circ C$ in the presence of H_2O_2 (3 eq. to substrate). Under these conditions, most of the studied primary benzylic alcohols afforded the desired products with 70-90% selectivities and with almost quantitative conversions. This system was, anyhow, highly applicable for secondary benzylic alcohols as the corresponding ketones were obtained in high conversions with selectivities greater than 90%. The CuSO₄ catalyst was recycled and reused for three runs with no decrease in selectivity but with a slight loss of catalytic activity. Kinetics studies showed that selectivity decreased when any of the reaction parameters was increased, and that the reaction was first order with respect to CuSO₄ and H₂O₂ concentrations but second order in benzyl alcohol concentration. Addition of 2-N-(p-fluorophenyl)pyrrolecarbaldimine (1) ligand and TEMPO in alkaline water reduced exothermicity of the reactions and increased the efficiency of the catalytic system toward primary benzylic alcohols. Thus the CuSO₄/TEMPO/1 system was optimized separately for a variety of alcohols. Under optimized conditions (1 mol% CuSO₄, 2 mol% **1**, 0.1 M K₂CO₃, 5 mol% TEMPO, 1 mL of 30% H₂O₂, 60 °C), most benzylic alcohols were quantitatively and selectively converted to the corresponding aldehydes in 1 h. To summarize, the developed catalyst systems provided environmentally benign route to a highly efficient transformation of benzylic alcohols into carbonyl compounds. The ligand modified system was also highly selective as no overoxidation of aldehydes to carboxylic acids was observed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.apcata.2011.10.038.

References

- [1] (a) M. Musawir, P.N. Davey, G. Kelly, I.V. Kozhevnikov, Chem. Commun. 12 (2003) 1414–1415;
- (b) T. Mallat, A. Baiker, Catal. Today 19 (1994) 247–283.
- [2] (a) M.J. Schultz, M.S. Sigman, Tetrahedron 62 (2006) 8227–8241;
 (b) J. Piera, J.-E. Bäckvall, Angew. Chem. Int. Ed. Engl. 47 (2008) 3506–3523;
 (c) Z. Ma, H. Yang, Y. Qin, Y. Hao, G. Li, J. Mol. Catal. A: Chem. 331 (2010) 78–85;

(d) H. Yang, Z. Ma, Y. Qing, G. Xie, J. Gao, L. Zhang, J. Gao, L. Du, Appl. Catal. A 382 (2010) 312–332.

 [3] (a) G. Strukul (Ed.), Catalytic Oxidations with Hydrogen peroxide as Oxidant, Kluwer Academic Publishers, Dordrecht, Netherlands, 1992;
 (b) H.-K. Kwong, P.-K. Lo, K.-C. Lau, T.-C. Lau, Chem. Commun. 47 (2011) 4273–4275;

(c) N. Gharah, S. Chakraborty, A.K. Mukherjee, R. Bhattacharyya, Inorg. Chim. Acta 362 (2009) 1089–1100;

(d) S. Rani, B.R. Bhat, Tetrahedron Lett. 51 (2010) 6403-6405.

- [4] (a) S.M. Islam, A.S. Roy, P. Mondal, M. Mubarak, S. Mondal, D. Hossain, S. Banerjee, S.C. Santra, J. Mol. Catal. A: Chem. 336 (2011) 106–114;
 - (b) T. Chattopadhyay, M. Kogiso, M. Asakawa, T. Shimizu, M. Aoyagi, Catal. Commun. 12 (2010) 9–13;
 - (c) M. Salavati-Niasari, F. Davar, Inorg. Chem. Commun. 9 (2006) 304-309;

(d) C.N. Kato, M. Hasegawa, T. Sato, A. Yoshizawa, T. Inoue, W. Mori, J. Catal. 230 (2005) 226–236;

(e) N. Barooah, S. Sharma, B.C. Sarma, J.B. Baruah, Appl. Organomet. Chem. 18 (2004) 440–445.

- [5] S. Velusamy, T. Punniyamurthy, Eur. J. Org. Chem. (2003) 3913–3915.
- [6] (a) P. Lahtinen, J.U. Ahmad, E. Lankinen, P. Pihko, M. Leskelä, T. Repo, J. Mol. Catal. A: Chem. 275 (2007) 228–232;
 (b) P. Lahtinen, E. Lankinen, M. Leskelä, T. Repo, Appl. Catal. A 295 (2005)
 - 177–184;
 - (c) P.J. Figiel, M. Leskelä, T. Repo, Adv. Synth. Catal. 349 (2007) 1173–1179;
 - (d) H. Korpi, P. Lahtinen, V. Sippola, O. Krause, M. Leskelä, T. Repo, Appl. Catal. A 268 (2004) 199–206;
 - (e) P. Lahtinen, H. Korpi, E. Haavisto, M. Leskelä, T. Repo, J. Comb. Chem. 6 (2004) 967–973;
 - (f) J.U. Ahmad, P.J. Figiel, M.T. Raisanen, M. Leskela, T. Repo, Appl. Catal. A 371 (2009) 17-21;

(g) H. Korpi, P.J. Figiel, E. Lankinen, P. Ryan, M. Leskelä, T. Repo, Eur. J. Inorg. Chem. 17 (2007) 2465–2471.

- [7] P.J. Figiel, A. Sibaouih, J.U. Ahmad, M. Nieger, M.T. Räisänen, M. Leskelä, T. Repo, Adv. Synth. Catal. 351 (2009) 2625–2632.
- [8] (a) M.N. Kopylovich, K.T. Mahmudov, T. Kamran, M.F.C. Guedes da Silva, P.J. Figiel, Y.Y. Karabach, M.L. Kuznetsov, K.V. Luzyanin, A.J.L. Pombeiro, Inorg. Chem. 50 (2011) 918–931;
 (b) P.A. Sheldon, LW C.F. Aranda, L. Mel. Catal. A: Chem. 251 (2006).
 - (b) R.A. Sheldon, I.W.C.E. Arends, J. Mol. Catal. A: Chem. 251 (2006) 200–214.
- [9] (a) Q. uan, W. Deng, Q. Zhang, Y. Wang, Adv. Synth. Catal. 349 (2007) 1199–1209;
 (b) J. Mlochowski, K. Kloc, R. Lisiak, P. Potaczek, H. Wojtowicz, ARKIVOC 6 (2007)

(b); Michowski, K. Kiel, K. Elsiak, F. Foraczek, H. Wojtowicz, AKKVOCO(2007) 14–46; (c) H. Wojtowicz J. Mlochowski, J. Syner, H.S. Yaday, Synth Commun, 36(2006)

(c) H. Wojtowicz, J. Mlochowski, L. Syper, H.S. Yadav, Synth. Commun. 36 (2006) 1991–2000.

 [10] (a) C.L. Aravinda, S.M. Mayanna, V.S. Muralidharan, Proc. Indian Acad. Sci. (Chem. Sci.) 112 (2000) 543–550;
 (b) R.A. Sheldon, I.W.C.E. Arends, A. Dijksman, Catal. Today 57 (2000)

157-166;

(c) V.K. Bansal, P.P. Thankachan, R. Prasad, Appl. Catal. A 381 (2010) 8–17;
(d) M.R. Maurya, B. Singh, P. Adao, F. Avecilla, J.C. Pessoa, Eur. J. Inorg. Chem. 36

(2007) 5720–5734;

(e) J.-q. Xie, J.-z. Li, X.-g. Meng, C.-w. Hu, X.-C. Zeng, S.-X. Li, Trans. Met. Chem. 29 (2004) 388–393;

(f) J.P. Klinman, Chem. Rev. 96 (1996) 2541–2561;

(g) K.D. Karlin, R.W.G.Y. Cruse, J.C. Hayes, J. Zubieta, J. Am. Chem. Soc. 106 (1984) 3372–3374; (h) A.Y. Sychev, N.T. Bui, Zh. Fiz. Khim. 44 (1970) 2837-2841;

(i) J. Wang, L. Yan, G. Li, X. Wang, Y. Ding, J. Suo, Tetrahedron Lett. 46 (2005) 7023-7027;

- (j) A. Corma, P. Esteve, A. Martinez, Appl. Catal. A 143 (1996) 87–100; (k) E.I. Solomon, P. Chen, M. Metz, S.-K. Lee, A.E. Palmer, Angew. Chem. Int. Ed. Engl. 40 (2001) 4570–4590.
- [11] (a) P. Gamez, I.W.C.E. Arends, R.A. Sheldon, J. Reedijk, Adv. Synth. Catal. 346 (2004) 805-811;

(2004) 005-011; (b) J.S. Uber, Y. Vogels, D. van den Helder, I. Mutikainen, U. Turpeinen, W.T. Fu, O. Roubeau, P. Gamez, J. Reedijk, Eur. J. Inorg. Chem. 26 (2007) 4197-4206.