

Copper(II) chloride-catalyzed oxidative carbonylation of glycerol to glycerol carbonate



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ABSTRACT

A systematic study on copper(II) as catalyst for the synthesis of glycerol carbonate via oxidative carbonylation is here reported for the first time. Copper(II) chloride has been found to efficiently promote the process under homogeneous conditions treating glycerol with CO:O₂ ($P_{\text{tot}} = 4$ MPa; $P_{\text{O}_2} = 0.7$ MPa), in DMA at 130 °C and in the presence of pyridine as co-catalyst. Excellent conversions (>92%) and selectivities (>93%) are obtained in relatively short reaction times (3–4 h) also with copper(II) complexes. The catalyst overall TON is evaluated and new experimental evidences are provided allowing significant advancements in the mechanism comprehension.

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1. Introduction

An important goal of modern industry is the exploitation of secondary products coming from the industrial processes, mainly the ones destined to the disposal. A significant example is given by the large surplus of glycerol generated by bio-diesel industry, formerly considered a valuable by-product, but nowadays seen as a waste material.

Many practical applications of glycerol as raw material in several fields like pharmaceuticals, cosmetics, food industry, and explosives production [1], allow the valorization of this product and broaden the useful applications of biomass energy sources.

A number of value-added products can be obtained by chemical conversion of glycerol (1) by means of catalytic reactions [2]. Acrolein, glycerol ether and 1,2-propane diol are amongst the most

useful derivatives of glycerol, but its 5-membered cyclic carbonate has recently received particular attention [3].

Glycerol carbonate (2) is a polar, non-toxic and high-boiling liquid useful for industry as solvent, additive and chemical intermediate. It is used as non-volatile solvent for resins, plastics and paints [4], as component in coatings, detergents, lubricants and electrolyte of batteries [5], and due to the presence of two functional groups, it is also investigated as source of new polymeric materials [6]. The moisturizing properties and the low toxicity of 2 make this compound ideal for use in cosmetics, personal hygiene and medical applications [6]. In addition, it is a raw material for CO₂ absorption, for the synthesis of glycidol, polyesters and polycarbonate, and is a reactive solvent in polyurethane coatings [7].

The main synthetic routes of access to glycerol carbonate include: (i) the transesterification of ethylene carbonate or DMC with glycerol [8–10], (ii) the direct carboxylation with CO₂ [11,12], (iii) the reaction of glycidol with CO₂ [13], (iv) the glycerolysis of urea [14], (v) the phosgenation of glycerol [15] and (vi) the reaction of epichlorohydrin with alkaline bicarbonates [16].

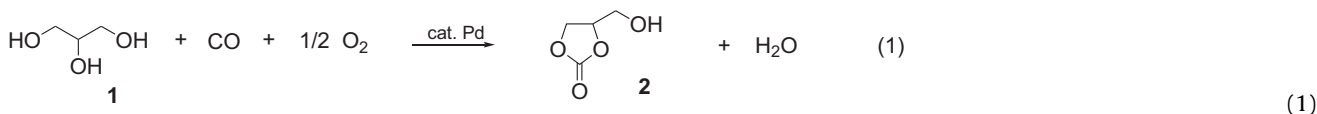
Recently, a promising and eco-friendly alternative has been proposed, that is the oxidative carbonylation of glycerol, which is accomplished with gaseous mixture of carbon monoxide and molecular oxygen, in the presence of palladium catalysts

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under both homogeneous and heterogeneous conditions (Eq. (1)) [17,18a].



Oxidative carbonylation is a useful method for the synthesis of carbonylated products starting from mono- and bi-functional reagents [19]. With this strategy, methanol and ethanol are respectively converted into DMC and DEC [20], diols lead to cyclic carbonate [21–23], while amino-alcohols and diamines give rise to the corresponding cyclic carbamates and ureas [24–28].

With diols as starting materials, the main catalysts employed until now are based on Pd [21], Cu [22] and Co [29], but in a very few cases this methodology has been applied to glycerol, specifically in an old patent [30] and in a very recent study [17,18a], where efficient but expensive palladium catalysts are predominantly employed.

In this context, finding suitable catalysts based on cheaper transition metals is mandatory and copper can be a valuable response to this problem. Copper salts are known to efficiently catalyze the synthesis of DMC in the Enichem process [31], and recently CuBr_2 has been found to promote the sulphur-assisted carbonylation of glycerol under stoichiometric conditions [32]. To the best of our knowledge, no catalytic applications of this metal to the oxidative carbonylation of glycerol have been reported until now.

Following our recent success on diols [22], we decided to extend these findings developing a copper-based catalytic systems for the synthesis of glycerol carbonate under homogeneous conditions.

2. Experimental

Unless otherwise stated, all manipulations were carried out in air. Copper salts [CuCl_2 , CuBr_2 , CuI , $\text{Cu}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$, $\text{Cu}(\text{OTf})_2$, CuSO_4 and $\text{Cu}(\text{OAc})_2$] (by Aldrich or Fluka) were dried under vacuum overnight before their use. Glycerol (1,2,3-propanetriol), solvents (CH_3CN , N,N -dimethylformamide DMA, N,N -dimethylacetamide DMF, 1-butanol, 1-methylimidazole), ligands (pyridine, triphenylphosphine oxide), external standard (4-methylanisole), dichloro(1,10-phenanthroline)copper(II) **8** and K_2CO_3 were Aldrich or Fluka products and were used as received.

Copper complex **7** [(29H, 31H-phthalocyaninato(2-)-N29,N30,N31,N32)copper(II)] was purchased by INTATRADE GmbH, while dichloro(2,2'-bipyridyl)copper(II) **9** [33] and dichlorobis(triphenylphosphine oxide)copper(II) **10** [34] were prepared according to the literature.

Reactions products were detected by GC–MS and identified by comparison of their IR and MS spectra with literature data. FT-IR spectra were recorded on a Perkin Elmer Spectrum BX spectrophotometer. GC–MS analyses were carried out with an Agilent GC 6850 (equipped with a capillary column: HP-5 MS, 30 m) linked to an Agilent 5975C selective mass detector.

XPS analyses were accomplished by a Thermo Fisher theta probe spectrometer equipped with a monochromatic Al K α X-ray source (1486.6 eV) with a spot size of 300 μm , corresponding to a power of 70 W and at a take-off angle of 53° relative to the sample normal. Survey spectra (0–1300 eV) were acquired at a pass energy of 200 eV with a resolution of 1 eV. High-resolution spectra for Cu 2p, Cl 2p, K 2p, C 1s and O 1s, were recorded at a pass energy of 100 eV with a resolution of 0.05 eV.

Charge compensation was accomplished by an electron flood gun (1 eV). Charge correction of the spectra was performed by taking the alkyl type carbon (C–C, C–H) component of the C1s spectrum as internal reference (binding energy, BE = 284.5 eV). Special care was devoted during the analyses to verify that no change in

the shape of the Cu 2p spectrum was induced by exposure to the X-ray and the electron flood gun.

Atomic percentages were calculated using the Scofield sensitivity factors set in the Thermo Avantage V4.87 software (Thermo Fisher Corporation) and a non-linear Shirley background subtraction algorithm. The high-resolution spectra were fitted with mixed Gaussian–Lorentzian peaks after a Shirley background subtraction.

Special care was devoted to the cleaning of the equipment (glass vials, magnetic stirrer, etc.) carried out with aqua-regia to prevent metal contaminations.

2.1. Safety advice

Although the oxidative carbonylation of methanol to DMC has been industrialized by ENIchem for 30 years under similar conditions [20,31] and even if in the last decade many studies on the oxidative carbonylation have been carried out within our proposed interval of pressures and without the occurrence of incidents [17,18,22], the high pressure experiments with CO/O_2 mixtures are potentially explosive in the range 16.7–93.5% [35] and may represent a significant risk. As a consequence, experiments with compressed gases should only be carried out in conjunction with the use of suitable equipments and special care. In this work, autoclaves equipped with appropriate rupture discs (strength 10 MPa) and mixtures of $\text{CO/O}_2 = 5:1$ ca. molar ratio (~83%) very close to the upper limit of the above-mentioned range were used.

In any case, a comparative carbonylation experiment has been performed at a $\text{CO:O}_2 = 15:1$ molar ratio, demonstrating that the catalyst works also under the safety conditions even if with longer reaction times. This result has been added in Table 2 (run 21) and the procedure described in Section 2.2.

2.2. Catalytic tests

Catalytic tests were carried out in a 55.6 mL stainless steel autoclave mounted in an electrical oven having a magnetic stirrer on its base. Catalyst, additives, solvent and reagents were introduced in a glass vial (~20 mL) and placed into the autoclave, in order to avoid any contact with metal walls. Under these conditions, the free volume for gaseous mixture is in the range 35–40 mL.

In a typical experiment the glass vial was charged with a DMA solution (5.0 mL) of glycerol (6 mmol), catalyst (CuCl_2 , 0.60 mmol) and pyridine (0.30 mmol), which appeared clean and green coloured. The vial was introduced into the autoclave, which was sealed, purged and charged with O_2 (0.7 MPa) and CO up to a total pressure of 4 MPa. Under these conditions, also taking into account the head space of the autoclave and the stoichiometry of the carbonylation process [Eq. (2)], glycerol is the limiting reagent. The mixture was heated at 130 °C and allowed to react for 4 h. After this time, the reaction mixture was analyzed by IR and GC–MS for assessing conversions and selectivities as reported below.

The IR spectrum of the reaction mixture showed the presence of a strong absorptions around 1800 cm^{-1} assigned to 4-(hydroxymethyl)-1,3-dioxolan-2-one (**2**), a broad absorptions in the range 3600–3500 cm^{-1} assigned to the hydroxyl groups of the carbonate and of the unreacted glycerol (**1**), a narrow signal at 2340 cm^{-1} assigned to the CO_2 formed during the reaction and 1640–1610 cm^{-1} , assigned to H_2O , co-product of reaction.

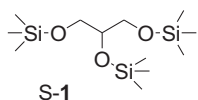
The carbonylation of glycerol under the other conditions discussed in the paper were carried out in the same way. The comparative experiment carried out under the safety conditions (CO:O₂ = 15:1 molar ratio), was performed on a DMA solution (3.0 mL) of glycerol (2.6 mmol), catalyst (CuCl₂, 0.26 mmol) and pyridine (0.13 mmol). The vial was introduced into the autoclave, which was sealed, purged and charged with O₂ (0.25 MPa) and CO up to a total pressure of 4 MPa. Under these conditions. The mixture was heated at 130 °C and allowed to react for 8 h. After this time, the reaction mixture was analyzed by IR and GC–MS for assessing conversions and selectivities as reported below.

2.3. Derivatization of the reaction products

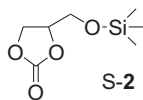
To obtain reproducible and resolved chromatographic peaks of **1** and **2** we decided to convert them into the corresponding silylated compounds. In a typical derivatization procedure [17], a weighed amount of the reaction mixture (150 mg ca.) was treated into a 10 mL centrifuge tube with excess amounts (1.00 g ca.) of the silylating reagent hexamethyldisilazane:trimethylchlorosilane:pyridine in a 3:1:9 weight ratio. The tube was sealed, stirred for 5 min and incubated at room temperature for 30 min causing the precipitation of NH₄Cl as a white solid. Then, 50 mg of 4-methylansole was added to the mixture as an external standard. After centrifugation at 2500 rpm for 5 min, the clear supernatant was analyzed by GC–MS to assess the conversions and selectivities reported in Tables 2 and 3, based on the peaks areas of the silylated derivatives of the unreacted glycerol **1** and the formed carbonate **2**.

Besides **1** and **2**, the silylation procedure allowed the detection of the main by-products arising from side-reactions involving the solvent [Section 3.1, Eqs. (3)–(6)]. The mass spectra of all compounds detected by GC–MS, including the ones formed upon derivatization, are given below:

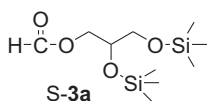
Silylated glycerol (S-1): *m/z* (%) 307 (1, M⁺–1) 293 (3, M⁺–CH₃), 263 (2, M⁺–3Me), 218 (10, M⁺–6Me), 205 (44, M⁺–CH₂OSiMe₃), 191 (5, M⁺–CH₂OSiMe₃–Me), 175 (5, M⁺–CH₂OSiMe₃–2Me), 147 (66, M⁺–OSiMe₃–SiMe₃), 133 (17, M⁺–CH₂OSiMe₃–SiMe₃), 117 (31, CHCH₂OSiMe₃⁺), 103 (24, CH₂OSiMe₃⁺), 101 (5, CHCH₂OSiMe₂⁺), 89 (4, OSiMe₃⁺), 73 (100, SiMe₃⁺).



Silylated glycerol carbonate (S-2): *m/z* (%) 189 (1, M⁺–1), 175 (1, M⁺–Me), 160 (1, M⁺–2Me), 145 (1, M⁺–3Me), 131 (48, M⁺–CH₂CO), 116 (4, M⁺–SiMe₃), 103 (26, CH₂OSiMe₃⁺), 101 (100, CHCH₂OSiMe₂⁺), 89 (3, OSiMe₃⁺), 73 (76, SiMe₃⁺).

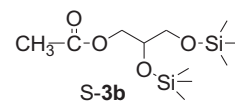


Silylated glycerol monoformate (S-3a): *m/z* (%) 243 (1, M⁺–Me), 191 (10, M⁺–CH₂OC(O)H), 161 (55, M⁺–CH₂OSiMe₃), 147 (65, M⁺–OSiMe₃–HCO), 133 (20, OCH₂CH₂OSiMe₃⁺), 117 (40, CH₂CH₂OSiMe₃⁺), 73 (100, SiMe₃⁺), 59 (25, MeCO₂⁺).

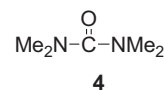


Silylated glycerol monoacetate (S-3b): *m/z* (%) 263 (1, M⁺–Me), 205 (9, M⁺–CH₂OC(O)Me), 175 (100, M⁺–CH₂OSiMe₃), 147 (69, M⁺–OSiMe₃–MeCO), 133 (48, OCH₂CH₂OSiMe₃⁺), 117 (43,

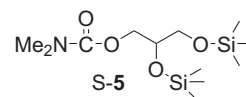
CH₂CH₂OSiMe₃⁺), 73 (97, SiMe₃⁺), 59 (16, MeCO₂⁺), 43 (83, MeCO⁺).



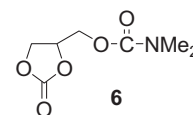
Tetramethyl urea (4): *m/z* (%) 116 (6, M⁺), 87 (1, M⁺–2Me), 72 (100, C(O)NMe₂⁺), 44 (23, Me₂N⁺).



Silylated 2,3-dihydroxypropyl dimethylcarbamate (S-5): *m/z* (%) 292 (2, M⁺–Me), 263 (1, M⁺–NMe₂), 218 (2, M⁺–HOC(O)NMe₂), 204 (52, M⁺–CH₂OSiMe₃), 147 (27, CH₂CHOCH₂OSiMe₃⁺), 73 (51, SiMe₃⁺), 72 (100, C(O)NMe₂⁺).



(2-oxo-1,3-dioxolan-4-yl)methyl dimethylcarbamate (6): *m/z* (%) 189 (10, M⁺), 102 (5, CH₂OC(O)NMe₂⁺), 88 (10, CH₂OC(O)NMe₂⁺), 72 (100, C(O)NMe₂⁺), 58 (22, NCO₂⁺), 44 (43, NMe₂⁺).



2.4. Catalyst stability and scale-up

The glass vial was charged with 70 mmol of glycerol (4.600 g), 5.0 mL of DMA, 0.70 mmol of CuCl₂ (1 mol%), and 0.35 mmol of pyridine (0.5 mol%). The vial was introduced into the autoclave, which was sealed and charged with O₂ (0.7 MPa) and CO up to a total pressure of 4.0 MPa. The autoclave was heated at 130 °C for 5 h. After this time, the autoclave was cooled down to room temperature, evacuated from the residual gas and sampled for conversion and selectivity. Then, the mixture was recharged with a fresh mixture of CO/O₂ and allowed to react at 130 °C for other 5 h. This procedure was repeated nine times until the conversion remained constant indicative of the fact that the carbonylation process was stopped.

To verify if the incomplete conversion was due to the catalyst deactivation, the organic products were distilled out from the reaction mixture and the solid residue was tested for a new carbonylation experiment by adding fresh starting materials (glycerol, pyridine and DMA) under 4 MPa of CO/O₂. The carbonylation started again indicating that the catalyst is stable under the reaction conditions and that the apparent deactivation is due to the side-reaction of CO oxidation to CO₂ promoted by Cu(II) and water (by-product of carbonylation) which becomes predominant during the course of reaction (see Section 3.3).

2.5. Carbonylation mechanism: reductive step

A glass vial was charged with glycerol (280 mg, 3.7 mmol), an equimolar amount of CuCl₂ (496 mg, 3.7 mmol), K₂CO₃ (780 mg, 7.4 mmol) in DMA (5 mL). The vial was introduced into the autoclave, which was sealed, charged with 2.5 MPa of CO and allowed to react at 100 °C for 5 h. After this time, the autoclave was cooled to room temperature and evacuated, and the reaction mixture was treated with the silylating reagent and analyzed by GC–MS. A conversion of 50% ca. was detected. The reaction was repeated with

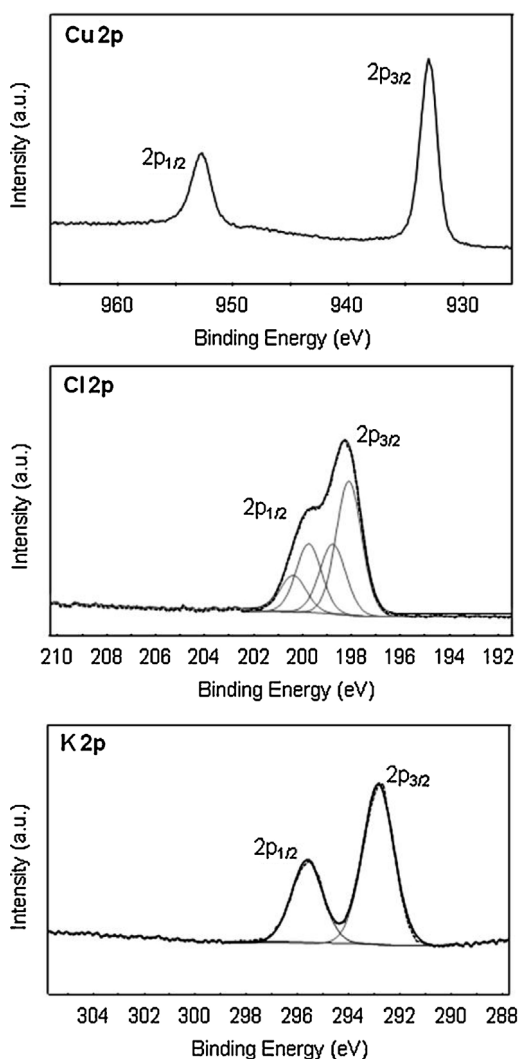


Fig. 1. High-resolution XPS spectra of Cu 2p, Cl 2p and K 2p core levels of the pale green solid.

the double molar amount of CuCl_2 (992 mg, 7.4 mmol) respect to glycerol (280 mg, 3.7 mmol) obtaining its complete conversion in carbonate according to the stoichiometry depicted in Eq. (7) (Section 3.3).

A copper containing pale green precipitate was formed during the reactions that was separated by centrifugation and immediately kept under nitrogen atmosphere to avoid oxidation. Then, the solid was quickly fixed on a piece of UHV compatible carbon tape (Agar Scientific) and immediately transferred into the XPS load lock chamber pumped down to 10^{-8} mbar. In order to remove any trace of organic solvents the sample was left to dry overnight.

2.6. XPS characterization of the copper based pale green precipitate

Analysis of the survey spectrum allowed for the qualitative atomic chemical composition of the sample. More specifically, signals attributed to Cu, Cl, K, C and O were identified. Atomic

Table 1
XPS atomic percentages.

Element	XPS atomic percentage (%)
Cu	17.0
O	10.3
Cl	26.3
K	17.0
C	29.4

percentages were then obtained from the high-resolution spectra and results are reported in Table 1.

Fig. 1 collects the high resolution spectra of Cu 2p, Cl 2p and K 2p. All these spectra show the spin-orbit splitting of the 2p level thus resulting in doublet features. The shape of the Cu 2p spectrum is indicative of copper (I) compounds, with the Cu $2p_{3/2}$ signal comprised of a single component at 932.9 eV, typical of CuCl [36–38].

This peak position was found to be the same of a standard CuCl sample analyzed for further validation.

Since some oxygen percent was found in the solid, it must be said that the presence of a certain amount of copper(I) oxide cannot be ruled out, due to the very low binding energy separation between chloride and oxide copper (I) compounds [37,38].

Curve-fitting of the Cl 2p spectrum reveals the presence of two doublets. The components of the Cl $2p_{3/2}$, centred at 198.1 eV and 198.8 eV can be assigned to KCl and CuCl, respectively. Correspondingly, the K $2p_{3/2}$ peak is centred at 292.8 eV matching with the presence of KCl [37,38].

In order to gain more insights into the possible presence of copper(I) oxide, based on the atomic percentages it has been tried to estimate the amount of oxygen bonded to copper. To this aim it is necessary first of all to subtract the percent of oxygen bonded to C to the overall percentage of oxygen. This amount has been determined from the curve-fitting of the C1s high resolution spectrum, which has been found to consist of three components at 284.5 eV (C–C/H), 286.2 eV (C–OH/R) and 288.1 eV (C=O) [39], and it has been found to be 25.9%. Then the amount of oxygen bonded to copper as Cu_2O is about 3.5%.

3. Results and discussion

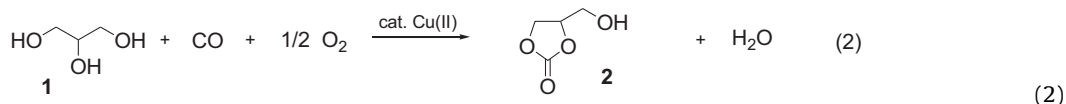
3.1. General

We recently reported that copper(II) salts catalyze the oxidative carbonylation of diols into the corresponding cyclic carbonates [22], and that catalytic efficiency (activity and stability) is affected by the nature of the solvent and the presence of bases and ligands.

We also demonstrated the importance of the co-catalytic role of the base, which could act as a proton shuttle from the diol to the molecular oxygen, which in turn should act as a copper re-oxidant closing the catalytic cycle (see Section 3.3).

The screening of bases showed the best activity for Na_2CO_3 , which at the same time caused the catalyst deactivation for prolonged reaction times. In addition, we also found that DMF, as already reported [21], can play the role of base avoiding the need for Na_2CO_3 and similar inorganic bases, and therefore prolonging the catalyst lifetime.

Extending the study to glycerol **1**, we have found that copper(II) catalysts promote the oxidative carbonylation into its cyclic carbonate **2** according to the stoichiometry of Eq. (2), and that catalytic efficiency is also affected by the reaction times and the temperature conditions.



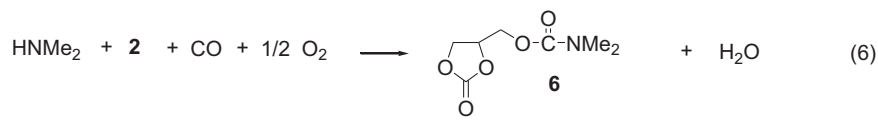
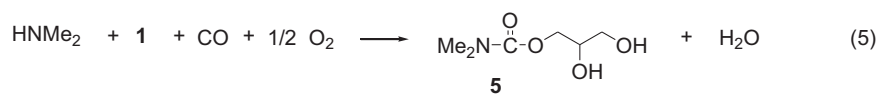
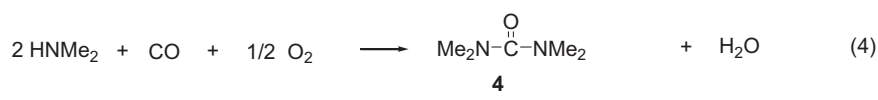
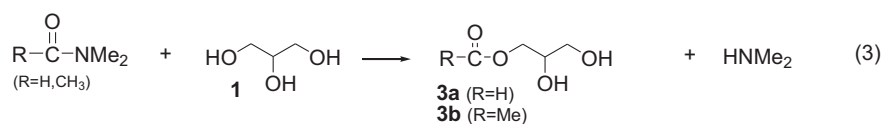
(2)

The optimization of the reaction conditions was started applying the protocol previously found for diols [22]: 6 mmol of glycerol, 0.6 mmol of CuCl₂ dissolved in 5 mL of solvent, at 100 °C for 4 h, under a CO/O₂ mixture (4 MPa, 5:1 ca. molar ratio, Table 2, entries 1–4). Preliminarily, the blank reaction showed that the presence of copper is necessary to promote the process (Table 2, entry 1).

In the absence of bases, acetonitrile (ACN) proved to be unsuccessful (Table 2, entry 2) [22], while other dipolar solvents like dimethylacetamide (DMA) and dimethylformamide (DMF) promoted the process, indicating that they can assume the role of proton acceptor (Table 2, entries 3 and 4). However, under these conditions conversions in carbonate were lower than 30%.

To improve the catalyst activity, we evaluated the opportunity of using pyridine which should exert the double role of ligand and base (Table 2, entries 5–13). In fact, this additive had a beneficial effect on the catalytic activity even in acetonitrile, confirming its co-catalytic role, but the positive influence was observed only with a Py/Cu molar ratio of 1:2 (Table 2, entries 5–7), whereas with higher Py amounts conversions dropped again in all the tested solvents (Table 2, entries 8–13). This trend could be explained with the good coordinating ability of pyridine towards copper that would lead to a catalyst inhibition in the presence of excess amounts of the ligand.

Interestingly, reactions carried out in acetonitrile occurred with selectivities in glycerol carbonate higher than 96% (Table 2, entries 5, 8, 11). On the contrary, reactions performed in DMF and DMA led in many cases to considerable amounts of by-products deriving mainly from side-reactions that involved the solvent (Table 2, entries 3, 4, 9, 10, 12, 13). In particular, the glycerolysis of DMF (or DMA) would account for the corresponding monoacylated glycerol derivatives **3a** (or **3b**) and dimethylamine (Eq. (3)). The latter, under the reaction conditions, might undergo an oxidative carbonylation affording tetramethylurea **4**, 2,3-dihydroxypropyl dimethylcarbamate **5** and (2-oxo-1,3-dioxolan-4-yl)methyl dimethylcarbamate **6** (Eqs. (4)–(6))



To limit these undesired side-reactions, the screening was also extended to other different types of solvents. To this aim, we tested a protic polar solvent like 1-butanol and the dipolar 1-methylimidazole, both possessing good solvent properties for glycerol and being totally inert towards glycerolysis. Disappointing results were obtained in both cases: dibutyl carbonate was observed as the main reaction product in butanol (Table 2, entry 14), whereas a complete catalysis inhibition occurred in 1-methylimidazole, probably due to the good coordinating ability of this solvent towards copper (Table 2, entry 15). The detrimental effect of water on this process [22] was confirmed by the addition

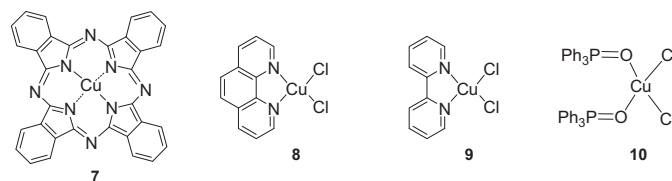


Fig. 2. Cu(II) complexes investigated.

of 0.5 mL of water to the initial reaction mixture (Table 2, entry 16, see Section 3.3).

Importantly, under the tested conditions ($T=100\text{ }^\circ\text{C}$, $t=4\text{ h}$), the catalytic activity proved to be low reaching 43% as maximum conversion value. In order to check whether the incomplete conversions observed in entries 1–16 ($t=4\text{ h}$) were due to catalyst deactivation or to an insufficient reaction time, we prolonged the time of reaction to 6, 8 and 10 h (Table 2, entries 17–19).

In these experiments conversions and selectivities gradually increased reaching the maximum values of 94% and 95%, respectively (Table 2, entry 19), indicating that: (i) the low conversions of entries 1–16 were not due to catalyst deactivation, and (ii) side-reactions listed in Eqs. (3)–(6) take place at the beginning of the process, when an induction period is required by copper to trigger catalysis. During this delay, probably due to the slow diffusion of carbon monoxide into the viscous solution, copper could act as a Lewis acid promoting the glycerolysis of the solvent [Eq. (3)].

These hypotheses were verified performing two appropriate experiments. In the first one, reaction was carried in DMA under inert atmosphere, which afforded to the formation of **3b** and dimethylamine as the sole reaction products, confirming that glycerolysis [Eq. (3)] is the main side-reaction which in turn generates the other by-products [Eqs. (4)–(6)].

In a second experiment, the initial DMA solution of glycerol was preliminarily saturated with CO/O₂ at 100 °C for 1 h before adding the catalyst. As expected, selectivity of carbonylation after 4 h increased respect to the analogous reaction performed without pre-saturation (Table 2, entry 6) reaching the value of 90%.

On these bases, being the oxidative carbonylation process controlled by the diffusion rate of the gases into the solution, better selectivities are expected adopting a more efficient stirring apparatus, preferably of mechanical type [17].

Differently to what found for diols [22], the temperature conditions proved to be crucial for the catalyst activity. Indeed, a

Table 2
Optimization of the reaction conditions.^a

Entry	Solvent	Py/Cu	T (°C)	Time (h)	Conv. ^b (%)	Sel. ^b (%)
1 ^c	DMA	–	100	10	–	–
2	ACN	0	100	4	–	–
3	DMA	0	100	4	25	66
4	DMF	0	100	4	27	59
5	ACN	0.5	100	4	18	96
6	DMA	0.5	100	4	40	80
7	DMF	0.5	100	4	43	75
8	ACN	1.0	100	4	10	96
9	DMA	1.0	100	4	20	50
10	DMF	1.0	100	4	21	46
11	ACN	2.0	100	4	8	99
12	DMA	2.0	100	4	18	47
13	DMF	2.0	100	4	20	44
14	1-Butanol	0.5	100	4	20	40
15	1-Methylimidazole	0.5	100	4	–	–
16 ^d	DMA	0.5	100	4	15	90
17	DMA	0.5	100	6	63	86
18	DMA	0.5	100	8	82	91
19	DMA	0.5	100	10	94	95
20	DMA	0.5	130	4	93	91
21 ^e	DMA	0.5	130	8	89	90
22	DMA	0.5	150	3	91	91

^a General reaction conditions: glycerol (6 mmol), CuCl₂ (0.6 mmol), pyridine (as reported) in 5 mL of solvent, heated under stirring under a gaseous mixture of O₂ (0.7 MPa) and CO (3.3 MPa).

^b Evaluated via GC–MS after silylation. Selectivities are referred to the moles of glycerol carbonate formed (see Section 2).

^c In the absence of CuCl₂ (blank test).

^d Performed by adding 0.5 mL of water to the reaction mixture.

^e Reaction carried out with a CO:O₂ = 15:1 molar ratio (see Sections 2.1 and 2.2).

remarkable shortening of the reaction times was observed by raising the temperature up to 150 °C, accompanied by only a slight lowering of selectivity (91%, Table 2, entry 22). However, the optimal conditions in terms of conversion were found working at 130 °C (Table 2, entry 20). This trend can be explained considering the two opposing effects exerted by the temperature increment: the lowering of viscosity that allows a better permeation of gaseous phase into the solution on one hand; the decreasing of the solubility of gaseous reactants into the liquid phase on the other [17].

The catalytic activity of other copper compounds was also investigated (Table 3). As far as copper halides are concerned, we found that catalytic performance decreased by passing from CuCl₂ to CuBr₂ and CuI (Table 3, entries 1–3). This latter salt was used on the base of our previous findings indicating that Cu(I) is also active in the oxidative carbonylation of diols through its preliminary oxidation in situ by molecular oxygen [22].

Copper(II) salts bearing anions other than halides, such as sulphate, acetate, triflate and perchlorate, were less efficient than CuCl₂ (Table 3, entries 4–7). Finally, we tested the Cu(II) complexes 7–10 listed in Fig. 2.

Three of them, the (phthalocyanine)copper(II) 7, the o-phenanthroline copper(II) dichloride 8 and bipyridyl copper(II) dichloride 9, bearing chelating N-ligands, proved to be totally inactive (Table 3, entries 8–10), while the last one, the bis(triphenylphosphine oxide) copper(II) dichloride 10, displayed a comparable activity with that of CuCl₂ (Table 3, entry 11).

The total inertness of complexes 7–9 can be explained taking into account that the presence of the good coordinating N-ligands impedes the dissociation rendering the copper coordination sites not accessible to reactants. This is in line with the inhibitory effect

Table 3
Screening of copper catalyst sources.^a

Entry	Cu catalyst	Time (h)	Conv. ^b (%)	Sel. ^b (%)
1	CuCl ₂	4	93	91
2	CuBr ₂	4	51	89
3	CuI	4	69	94
4	CuSO ₄	4	75	95
5	Cu(OAc) ₂	4	10	40
6	Cu(OTf) ₂	4	72	60
7	Cu(ClO ₄) ₂	4	41	40
8	(Phthalocyanine)Cu(II) (7)	4	–	–
9	(o-Phen)CuCl ₂ (8)	4	–	–
10	(Bipy)CuCl ₂ (9)	4	–	–
11	(Ph ₃ PO) ₂ CuCl ₂ (10)	3	92	94

^a General reaction conditions: glycerol (6 mmol), copper catalyst (0.6 mmol), pyridine (0.3 mmol), DMA (5 mL), heated under stirring under a gaseous mixture of O₂ (0.7 MPa) and CO (3.3 MPa).

^b Evaluated via GC–MS after silylation. Selectivities are referred to the moles of glycerol carbonate formed (see Section 2).

exerted by the excess of monodentate N-ligand pyridine as mentioned above (Table 3, entries 8–13).

A different behaviour is shown by complex 10, which can liberate easily the coordination sites because of the poor coordinating ability of triphenylphosphine oxide ligands (Table 3, entries 1 and 10).

3.2. Catalyst stability and scale-up

To evaluate the catalyst stability, we decided to perform the scale-up of the carbonylation process by reacting a tenfold amount of glycerol with the lower catalyst loading of 1 mol%. Reaction was monitored every 5 h recharging the reactor with fresh CO/O₂ until conversion remained constant over the time (see Section 2.4).

Data reported in Fig. 3 shows that the CuCl₂/pyridine/glycerol system (0.7 mmol, 0.35 mmol, 70 mmol), in DMA exhibited an overall turnover number of 82 (expressed as mole of substrate reacted per mole of catalyst).

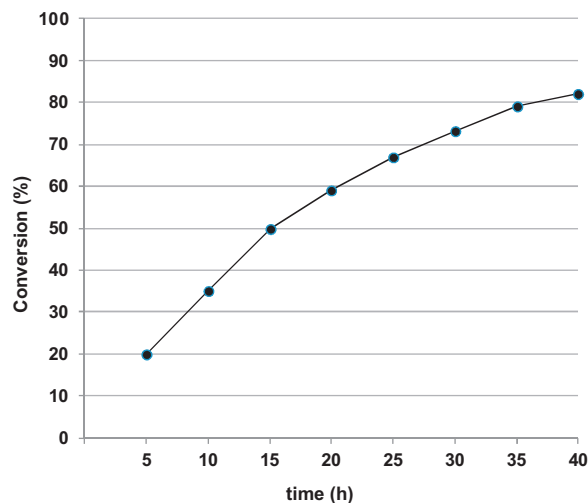


Fig. 3. Evaluation of the total turnover number of the catalyst. General reaction conditions: glycerol (70 mmol), CuCl₂ (0.7 mmol, 1%), pyridine (0.35 mmol, 0.5%), DMA (5 mL), O₂ (0.7 MPa) and CO (3.3 MPa), T = 130 °C. Selectivities for each run were higher than 92%.

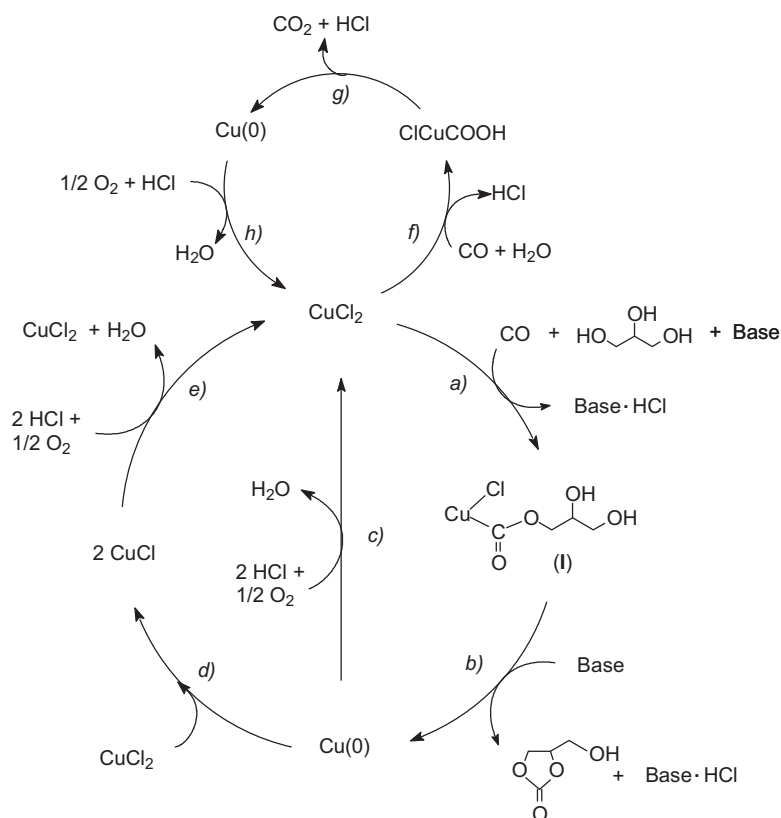


Fig. 4. The reaction mechanism.

Similarly to what found with diols [22], also the glycerol carbonylation reaches a maximum conversion (82%) after a 40 h time reaction.

Prolonging the reaction time, the oxidation of CO to CO₂ promoted by Cu(II) and water (the by-product of the oxidative carbonylation) becomes the dominant process (Fig. 4). This is evidenced monitoring the narrow IR signal of CO₂ at 2340 cm⁻¹ of the reaction mixture.

To verify whether the incomplete conversion was due to this side-reaction or to the catalyst deactivation, the organic products were distilled out from the reaction mixture and the solid residue was tested for a new carbonylation experiment by adding fresh starting materials (glycerol, pyridine and DMA) under 4 MPa of CO/O₂. As hypothesized, the carbonylation started again indicating that the catalyst is stable under the reaction conditions and confirming that the apparent deactivation is due to the above mentioned side-reaction (see also Section 2.4).

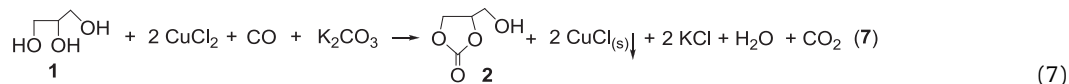
It is worth mentioning that, probably due to the presence of pyridine as ligand, CuCl₂ did not experience the decomposition

carbonylation. Concerning the catalyst, this process should proceed through a reduction of Cu(II) to Cu(0) [path (b)] followed by re-oxidation through path (c) and/or paths (d) and (e).

However, we have already postulated the involvement of Cu(I) as an intermediate in the re-oxidation of Cu(0) [paths (d) and (e)], but then this hypothesis was not supported by experimental evidences.

Therefore, to detect the intermediate species of copper, we carried out some reactions with stoichiometric amounts of CuCl₂ and in the absence of O₂ (see Section 2.5). Experiments carried out using potassium carbonate as the base allowed the formation of an insoluble green solid that was separated and analyzed by XPS technique resulting mainly composed by cuprous chloride (CuCl, see Section 2.6).

These carbonylation tests also revealed that a complete conversion of glycerol into the corresponding carbonate **2** requires twice molar amount of CuCl₂ respect to **1**, whereas equimolar quantities of copper(II) salt stopped the carbonylation process at 50%. All these data account for the stoichiometry of the reductive step depicted in Eq. (7).



promoted by water observed in the case of diols, when an inactive pale green solid, with a minimal formula of CuCl_{0.7}(OH)_{1.2}, precipitated from the reaction mixture during the last cycles of carbonylation.

3.3. Mechanistic insights

Based on our previous work on diols [22], we propose the reaction mechanism shown in Fig. 4 for the glycerol oxidative

This confirms the mechanism of Fig. 4 indicating that one of the two equivalents of CuCl₂ promotes the oxidative coupling between glycerol and CO [paths (a) and (b)], with the consequent reduction to Cu(0), while the second one reoxidises Cu(0) affording Cu(I) [path (d)]. Furthermore, as no detectable amounts of Cu(0) were observed by XPS analyses of the green solid in all the reductive experiments, these data also suggest that retro-dismutation step [path (d)] should be very fast.

4. Conclusions

We have reported here the first systematic study on the use of copper(II) catalysts in the synthesis of glycerol carbonate via oxidative carbonylation. Excellent conversions (>92%) and selectivities (>93%) are achieved in relatively short reaction times (4 h) using a catalyst system composed by CuCl₂/pyridine in a 1/0.5 molar ratio in DMA as the solvent, at 130 °C and 4 MPa of CO₂ (ca. 5:1 as molar ratio).

By prolonging the reaction times, the catalyst dosage can be reduced until 1 mol% reaching an overall TON value of 82 (Fig. 3) and without observing the catalyst inactivation. New experimental evidences are reported to support the postulated mechanism that involves copper(I) as intermediate species allowing significant advancements respect to the previous work in the comprehension of the catalytic cycle (Fig. 4).

This methodology to valorize glycerol is not only an attractive way to carry out its oxidative carbonylation, but is very important from economic point of view, being a valuable alternative to the protocol promoted by the more efficient but much more expensive palladium catalysts [17,18].

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