Selective oxidation of glycerol to formic acid catalyzed by iron salts

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ABSTRACT

Glycerol is oxidized by hydrogen peroxide to formic acid with excellent selectivity in the presence of iron salts. The oxidation takes place at room temperature in water; at the end of the reaction the catalytic system is still active and available to restart the oxidation.

1. Introduction

In recent years the blooming business of biodiesel fuels has led to an increasing surplus of glycerol as the main by-product of transesterification of biomass-derived triglycerides with methanol. As a consequence, studies regarding the development of feasible and convenient ways to transform glycerol in higher value products have proportionally increased in number. Such valorization would make the biofuels production significantly cheaper and therefore affordable in comparison to traditional fossil fuels.

From several points of view glycerol is a versatile molecule, however its high number of functional groups - which is a valuable characteristic for its use as chemical building block - causes at the same time the hardest difficulties in the set-up of selective reactions. Among the possible glycerol valorization routes oxidation is one of the most studied, since the potentially obtainable products are all commercially relevant (Scheme 1) [1,2]. However, some of the most appealing products obtainable by glycerol oxidation, *e.g.* dihydroxyacetone (DHA), are themselves rather reactive compounds: therefore, selective oxidation of glycerol often leads to poor yields due to subsequent decomposition of the oxidation products [3].

The difficulties experienced in developing selective routes for a partial oxidation of glycerol would be overcome by pushing the oxidation process to its end, for example to formic acid (FA) as final product. Few studies report glycerol oxidation to FA in the past literature [4], but their number has been growing in very recent years [5–8]. Most of the reported systems are based on heterogeneous catalysts and the oxidant agent can be hydrogen peroxide as well as molecular oxygen.

The rising interest in efficient FA production lies in its use as hydrogen carrier. With its 4.4% hydrogen content and several well-known systems able to decompose it in mild conditions to hydrogen and carbon dioxide [9–12], FA might provide a supply for the hydrogen fuel cells [13], as well as for the hydrogenation process of biomasses [14] and even directly as automotive alternative fuel [15] which would perfectly fit with the biofuel production above cited. On the other hand, FA is also a convenient source of C1 raw material for the chemical industry, as it can be easily transformed into carbon monoxide [16].

The pushing requirements of the twelve Green Chemistry principles [17] urge to shift towards more sustainable reactions and the use of iron catalysts in place of rarer and more expensive transition metals [18] meets such expectations, as demonstrated by the growing interest in their applications [19]. Iron compounds have been known to promote alcohols and diols oxidation by hydrogen peroxide since nineteenth century and even glycerol oxidation was briefly described in 1899 [20], but also in the last years both iron salts [21–24] and iron complexes [25–28] were reported to catalyze alcohol oxidation by either molecular oxygen or hydrogen peroxide.

Our group has recently described glycerol oxidation by hydrogen peroxide catalyzed by iron complexes with the tridentate ligand bis(2-pyridinylmethyl)amine (BPA) [29]; these studies have shown that by careful tuning of the experimental setup a remarkably selective formation of DHA can be obtained: on the other hand, in some cases we also detected a significative amount of FA as by-product.

Here we present our results in the oxidation of glycerol by hydrogen peroxide catalyzed by iron salts to give FA with high selectivities and in very mild conditions.

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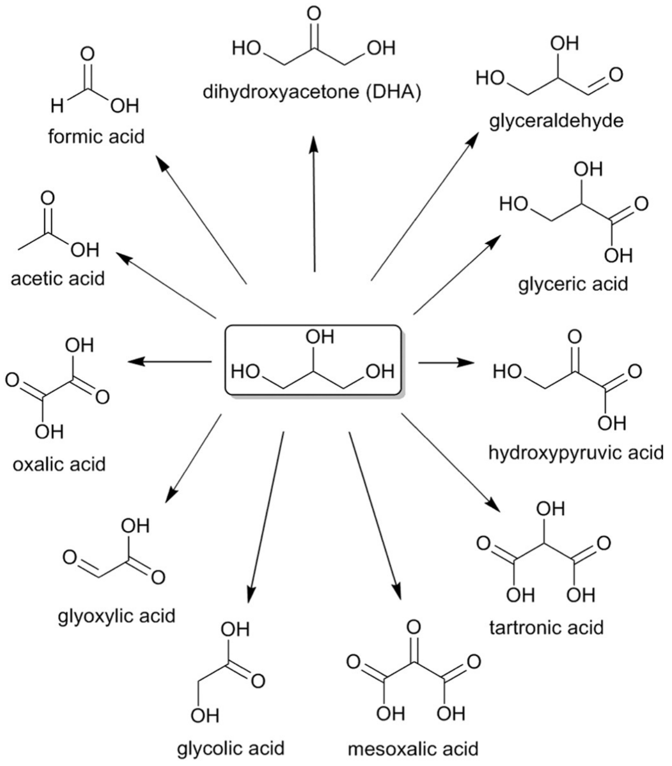


Scheme 1. Possible products of glycerol oxidation.

2. Results and discussion

The oxidation of glycerol by hydrogen peroxide catalyzed by $Fe(OTf)_2$ (Tf = trifluoromethanesulfonate) and BPA in acetonitrile/water 2:1 gave a 25% selectivity of FA besides the main product DHA (Table 1 entry 1). The reaction was carried out at r.t. with a 2.8 hydrogen peroxide/glycerol ratio and three equivalents of BPA with respect to the iron salt. Similar results were obtained using the preformed complex $[Fe(BPA)_2(OTf)_2]$ in the presence of added BPA as catalytic system (entry 2): all these findings are consistent with those reported in our previous paper [29].

In order to push the oxidation further, we increased the total amount of H_2O_2 to 11 equivalents, which were added in 1.1 eq portions at intervals of 30 min (entry 3 and Fig. 1). GC analysis of the reaction mixture after each addition showed that the first two equivalents of hydrogen peroxide caused partial oxidation of glycerol to a mixture of DHA and glyceraldehyde; upon addition of further amounts of hydrogen peroxide we detected the formation of FA which rapidly became the main product of the reaction. In the course of the addition of H_2O_2, initially formed glyceraldehyde disappeared and besides FA only traces of DHA were detected in solution, together with minor amounts of a new product which was identified as glycolic acid (GA) (see Scheme 2). After ten additions (11 equivalents of hydrogen peroxide), the oxidation of glycerol was almost complete to produce FA and GA; no other products were detected. Further addition of H_2O_2 caused no modifications to the reaction mixture. On the other hand, no significative differences were observed when the same overall amount of hydrogen peroxide was added in a single step (entry 4).

When a catalytic test was performed replacing glycerol with FA as substrate no reaction was observed, as opposed to the results reported by Walton [4] on the iron catalyzed oxidation of FA to carbon dioxide and water.

The use of $Fe(OTf)_2$ as catalyst in the absence of BPA gave even better results, with an almost complete glycerol conversion to FA and only traces of DHA and glycolic acid as by-products (entry 5). We repeated several times the catalytic cycle by adding new loads of fresh glycerol and hydrogen peroxide, obtaining comparable yields of FA: thus, at the end of the reaction the catalytic system was still active and available to restart the oxidation without significative loss of activity.

We repeated the reaction reported in entry 5 by adding hydrogen peroxide in 1.1 eq portions at intervals of 30 min (entry 6 and Fig. 2) and we verified that the evolution of the reaction catalyzed by

Table 1
Oxidation of glycerol with H_2O_2 catalyzed by iron compounds[a].

Entry	Catalyst	[BPA(tot)]/[Fe]	Solvent	$[H_2O_2]/[glycerol]$	t (min)	Conv.[b] (%)	DHA Sel. (%)	GA Sel. (%)	FA Sel. (%)
1	$Fe(OTf)_2$ + BPA	3	$MeCN:H_2O$[c]	2.8	90	25	72	3	25
2	$[Fe(BPA)_2(OTf)_2]$ + BPA	3	$MeCN:H_2O$[c]	2.8	90	18	74	4	22
3	$Fe(OTf)_2$ + BPA	3	$MeCN:H_2O$[c]	11.2[d]	280	99	Traces	6	93
4	$Fe(OTf)_2$ + BPA	3	$MeCN:H_2O$[c]	11.2[e]	36	96	2	6	92
5	$Fe(OTf)_2$	0	$MeCN:H_2O$[c]	11.2[e]	36	99	Traces	Traces	99
6	$Fe(OTf)_2$	0	$MeCN:H_2O$[c]	4.4[d]	106	100	Traces	1	98
7	$Fe(OTf)_2$	0	$MeCN:H_2O$[c]	4.2[e]	6	97	Traces	Traces	96
8	$Fe(OTf)_2$	0	H_2O	4.2[e]	6	99	Traces	4	94
9	$Fe(OTf)_2$ + BPA	3	H_2O	4.2[e]	36	82	24	12	63
10[f]	$Fe(OTf)_2$	0	H_2O	4.2[e]	6	99	1	3	95
11[g]	$Fe(OTf)_2$	0	H_2O	4.2[e]	6	99[h]	Traces[h]	3[h]	95[h]
12[i]	$Fe(OTf)_2$	0	H_2O	4.2[e]	6	98[h]	0[h]	5[h]	95[h]
13[j]	$Fe(OTf)_2$	0	H_2O	4.2[e]	16	98	Traces	2	97
14[k]	$Fe(OTf)_2$	0	H_2O	4.2[l]	60	0	0	0	0
15	$Fe(OTf)_3$	0	H_2O	4.2[e]	6	99	Traces	1	99
16	$FeCl_2$	0	H_2O	4.2[e]	6	99	Traces	4	95
17	$FeCl_3$	0	H_2O	4.2[d]	6	99	Traces	3	97

[a] Experimental conditions: [Fe] = 1.0×10^{-2} M; [glycerol]/[Fe] = 35. Isolated yields could not be provided, since all efforts to separate FA from reaction mixture were unsuccessful; therefore all yields are based on GC analyses (see Experimental section in Supplementary data).
[b] Calculated as % of glycerol reacted.
[c] $MeCN:H_2O$ ratio = 2:1.
[d] Addition of H_2O_2 in portions of 40 μl (1.1 equivalents) each.
[e] Addition of H_2O_2 in a single portion.
[f] Reaction carried out in closed and thermostatted vessel.
[g] A second load of fresh glycerol was added after the end of the first reaction and a second addition of H_2O_2 was repeated.
[h] Overall results.
[i] A third load of fresh glycerol was added after the end of the second reaction and a third addition of H_2O_2 was repeated.
[j] [glycerol]/[Fe] = 100.
[k] Reaction carried out with *t*-BuOOH as oxidant.
[l] [*t*-BuOOH]/[glycerol] (*t*-BuOOH 70% w/w).

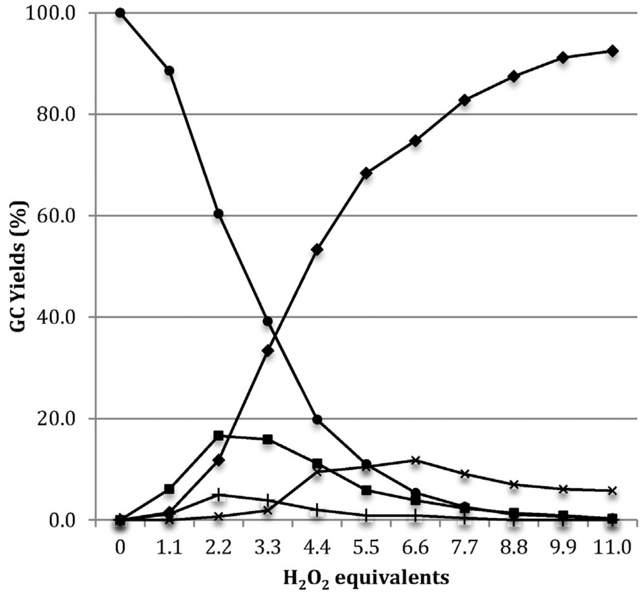


Fig. 1. Glycerol oxidation by H_2O_2 in MeCN:H_2O (2:1) catalyzed by Fe(OTf)$_2$ + BPA (1:3). Exp. conditions: [Fe] = 1.0 × 10–2 M; [glycerol]/[Fe] = 35; (-●-): glycerol; (-◆-): formic acid; (-■-): DHA; (-+-): glyceraldehyde; (-×-): glycolic acid.

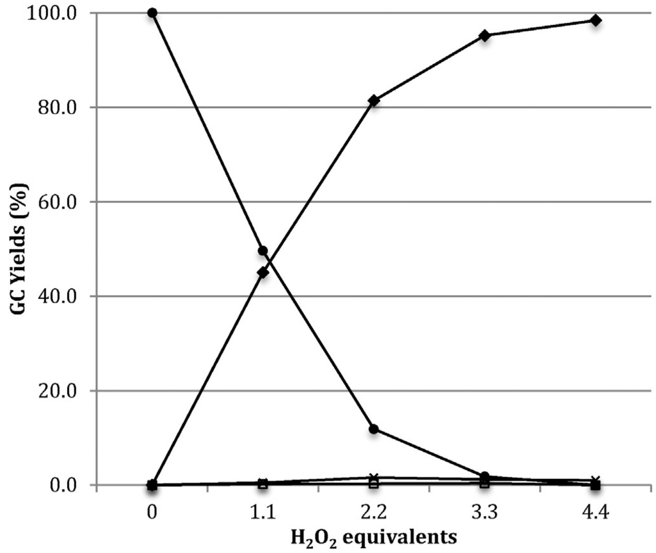
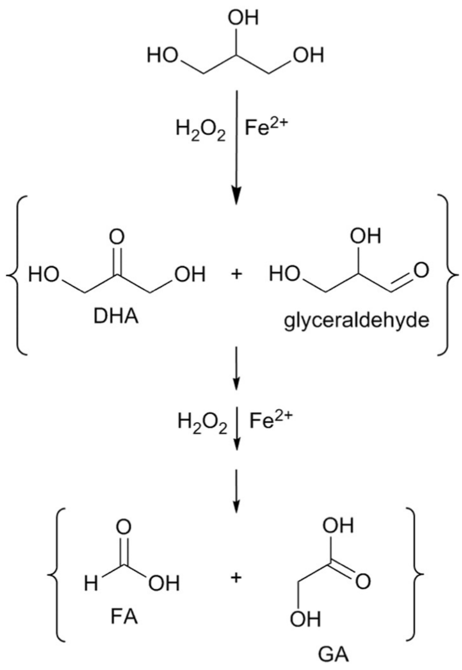


Fig. 2. Glycerol oxidation by H_2O_2 in MeCN:H_2O (2:1) catalyzed by Fe(OTf)$_2$. Exp. conditions: [Fe] = 1.0 × 10–2 M; [glycerol]/[Fe] = 35; (-●-): glycerol; (-◆-): formic acid; (-■-): DHA; (-×-): glycolic acid.

Fe(OTf)$_2$ was the same either in the presence or in the absence of the co-catalyst BPA (compare entries 3 and 6); the main differences in the latter case were a lower production of DHA and glyceraldehyde and the use of fewer equivalents of hydrogen peroxide to obtain a complete glycerol oxidation.

In several reports of heterogeneously catalyzed glycerol oxidation, the reaction was proposed to occur *via* formation of intermediates such as DHA, glyceraldehyde, glycolic acid, glyceric acid and oxalic acid [30–32]. In the present case, the results shown in Figs. 1 and 2 indicate that the initial glycerol oxidation products were DHA and glyceraldehyde, which upon further addition of hydrogen peroxide were in turn oxidized to FA; in contrast, formation of glycolic acid was not followed by further oxidation. Notably, other possible oxidation products were never detected in the reaction mixture.



Scheme 2. Glycerol oxidation to formic acid (FA) and glycolic acid (GA).

The results of entry 6 and Fig. 2 evidence that after addition of 4.4 equivalents of H_2O_2 oxidation of glycerol to FA was complete under these experimental conditions, in agreement with the stoichiometry of the oxidation from glycerol to formic acid. Therefore, we carried out a reaction by slow addition of 4.2 equivalents of H_2O_2 to the reaction mixture (one drop every 15 s, 6 min altogether): glycerol oxidation was completed immediately after the last H_2O_2 addition, with no further reaction occurring afterwards (entry 7). A faster addition of hydrogen peroxide gave rise to somewhat lower conversion, probably due to partial hydrogen peroxide decomposition which is known to occur in the presence of iron salts [21,25].

We tested water as solvent to improve the sustainability of the reaction; the catalytic reactions performed in water gave similar results to those in acetonitrile/water, with only a slight decrease in FA selectivity (entry 8), thus confirming the full feasibility of the reaction in environmentally friendly setting. As already observed in acetonitrile/water mixture (see entries 4 and 5), also in water in the presence of BPA the reaction was less selective, giving mixtures of DHA, glycolic acid and formic acid (compare entries 8 and 9). These results can be interpreted in terms of formation of two catalytically active species, *i.e.* a free cationic iron species which promotes glycerol oxidation to formic acid on one hand, and on the other a Fe/BPA complex which is responsible for the glycerol oxidation to DHA.

In order to minimize the effects of temperature variations, we performed the reaction in a vessel closed by a serum cap and kept at constant temperature (21 °C) in a thermostatted oil bath: the results of such experiment (entry 10) were comparable to those obtained in an open vessel. At the end of the reaction a second catalytic cycle with a new glycerol load and subsequent oxidation by H_2O_2 addition was performed, followed by an analogous third cycle. The results, reported in entries 11 and 12 respectively, show for both catalytic cycles a remarkable selectivity in FA, with no apparent loss of catalytic activity. The only detectable side effect was the absence of DHA and a moderate increase of glycolic acid yield. The high catalytic activity was confirmed by increasing the catalytic ratio [glycerol]/[Fe] to 100 (entry 13), without significative variation on both glycerol conversion and FA selectivity.

The effect of choice of the oxidizing agent was tested by replacing hydrogen peroxide with another peroxide: use of *tert*-butyl hydroperoxide, a frequently employed oxidant in iron promoted alcohol oxidation [25,27] was totally ineffective in the catalytic reactions under investigation (entry 14).

We also tested the effect on the catalytic activity of both catalyst counterion and iron oxidation state (entries 15–17): the results were not affected by replacing either triflate with chloride, or Fe(II) with Fe(III) salts. Our findings on the catalytic activity of iron(III) salts, although not in agreement with those reported by Fenton [20], are however coherent with other literature reports of oxidation by hydrogen peroxide catalyzed by Fe(III) salts [21,22,24,26]. On the other hand, it is known that Fe^{2+} could be easily oxidized to Fe^{3+} in air or when exposed to oxidizing agents; that might account for the similar activity showed by $FeCl_2$, $FeCl_3$, $Fe(OTf)_2$ and $Fe(OTf)_3$.

In fact the underlying chemistry in Fenton- or Gif-type reactions, *i.e.* the oxidation systems based on Fe^{n+} with H_2O_2, is very complex and still subject of studies and discussions [24,33,34], one of the most debated points being the iron oxidation states throughout the catalytic cycle. The two proposed mechanisms, *i.e.* a free radical mechanism as opposed to H_2O_2 nucleophilic addition to the metal centre, have been supported by mechanistic studies and it was shown that the actual reaction pathway depends on several experimental parameters, one of which is the pH of the reaction medium [24,34]. Although we do not have any positive proof indicating the actual mechanism of the reaction here described, the high selectivity and the absence of tar polymers might be both evidences (see Supplementary data) in favour of a non-radical pathway [24,35]; at the same time, the neat changes of colours during the first stages of the H_2O_2 addition - from orange to deep purple to clear yellow - might indicate fast variations through different iron oxidation states.

Further studies are presently in progress to shed light on the influence of the various experimental parameters – including the presence of added ligands – on the course of the catalytic reactions: all evidences obtained by us as well as by other groups may contribute to a better understanding of Fenton-type chemistry.

3. Conclusions

Glycerol was oxidized by hydrogen peroxide to formic acid with excellent selectivity in the presence of iron salts; the only by-product present in the final reaction mixture was glycolic acid. The reaction was carried out at r.t. either in acetonitrile/water or in water; at the end of the reaction the catalytic system was still active and oxidation of another glycerol load took place with comparable reaction rate and selectivity.

The catalytic reactions here described fully comply the requirements for a green process, from the point of view of metal, oxidant, reaction medium, experimental conditions as well as excellent selectivity and overall high atom efficiency.

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