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N_2O-free single-pot conversion of cyclohexane to adipic acid catalysed by an iron(II) scorpionate complex

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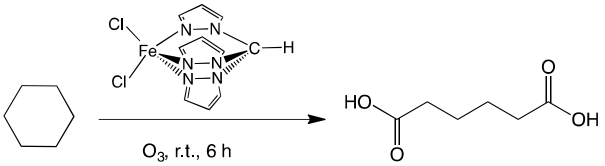
The highly efficient eco-friendly synthesis of adipic acid (96% yield, 98% selectivity, TONs up to 1.8 x 10^3) directly from cyclohexane is achieved by using ozone and $[FeCl_2\{\kappa^3\text{-}HC(pz)_3\}]$ (pz=pyrazol-1-yl) in a solvent-, heating-, radiation- and N_2O-free new protocol.

Due to its versatility as building block for several processes in the chemical, pharmaceutical and food industries, adipic acid is a relevant commodity chemical produced worldwide (over 3.5 millions of metric tons/year, growing *ca*. 5%/year) [1,2]. Its primary use is as a precursor for the synthesis of Nylon-6,6 polyamide although also widely used to produce polyester and polyurethane resins.

Adipic acid is industrially obtained [1,3] *via* a two-step process: *i*) oxidation of cyclohexane to KA oil (a mixture of cyclohexanol and cyclohexanone), and *ii*) oxidation of KA oil with an excess of nitric acid leading to an extensive liberation of the greenhouse gas N_2O (300 kg of N_2O per ton of adipic acid) [1,4]. Although alternative substrates and synthetic routes have been explored towards a future sustainable adipic acid production [4-10], the need for a procedure that meets those requirements remains.

A single-pot oxidation (from the alkane) would be especially useful for the adipic acid production, in view of the adopted industrial process. Moreover, it should also overcome the current undesirable emission of N_2O, thus avoiding the implementation of technologies for recovering and reuse this pernicious gas. From a synthetic and industrial viewpoint, such a single step procedure would also be economically favourable.

With the aim of developing a more efficient and eco-friendly process for the synthesis of the industrially most important dicarboxylic acid, herein we report the one-pot oxidation of neat cyclohexane, by ozone, to adipic acid catalysed by the bio-inspired C-scorpionate Fe(II) complex, $[FeCl_2\{\kappa^3\text{-}HC(pz)_3\}]$ (pz = pyrazol-1-yl) [11], as depicted in Scheme 1. This new catalytic system operates at room temperature, in solvent- and radiation-free conditions. Adipic acid precipitates from the reaction mixture, allowing a very simple procedure (by filtration, see experimental, ESI) for its isolation in a pure form (Figures S1 and S2).



Scheme 1. One-pot oxidation of cyclohexane to adipic acid catalysed by $[FeCl_2\{\kappa^3\text{-}HC(pz)_3\}]$.

As depicted in Figure 1 and Table S1 (ESI), a 6 h reaction time is required for the quantitative formation of adipic acid. Shorter reaction times (*e.g.,* 3 h) led to the formation of KA oil instead of this acid (entry 5, Table S1, ESI). The present reaction time is much shorter than the reported [5] for the non-catalytic ozonolysis of cyclohexane under UV irradiation (15 h).

The iron compound previously proved its catalytic activity in the selective peroxidative (with H_2O_2) oxidation of cyclohexane to a mixture of cyclohexanol and cyclohexanone [11-15], but neither adipic acid was formed under those conditions, nor the complex was tested with other oxidants.

Besides cyclohexane-1,2-diol, obtained in very low amounts (<2.5% Figure 2 and Table S1, ESI), no short-chain dicarboxylic acids or other products were detected under the optimized conditions, indicating a rather selective protocol for the adipic acid production (with improved waste minimisation).

The knowledge that acidic conditions (*e.g.*, aq. HCl solution [5]) could promote the adipic acid formation, prompted us to use pyrazine carboxylic acid (Hpca), a known promotor for the $[FeCl_2\{\kappa^3\text{-}$

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HC(pz)$_3$}] catalysed cyclohexane oxidation to KA oil [14]. At optimized reaction conditions Hpca notably improves the yield and selectivity of the reaction, leading to almost quantitative (>96%, Figure 1 and Table S1, ESI) formation of adipic acid with a turnover number, TON (moles of oxygenated products *per* mol of catalyst) of 1.8 x 10^3. Moreover, it is obtained in a much shorter reaction time (reduction from 15 [5] to 6 h) than when HCl is used.

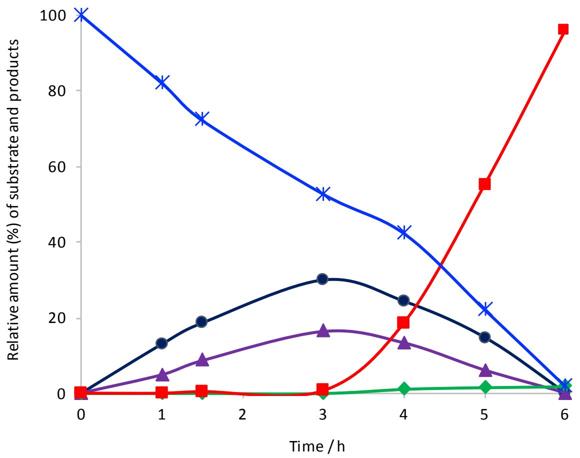

Figure 1. Effect of the reaction time on the relative amount (molar %) of cyclohexane (*) and of products, cyclohexanol (●), cyclohexanone (▲), cyclohexane-1,2-diol (◆) and adipic acid (■), obtained by one-pot oxidation of cyclohexane with O_3 catalysed by [FeCl$_2${κ^3-HC(pz)$_3$}].

The effect of Hpca is also clearly more pronounced than the observed with the inorganic nitric acid (Figure 2 and entries 8 and 9, Table S1, ESI). The same behaviour was found for the peroxidative (with H_2O_2) oxidation of cyclohexane to KA oil [14].

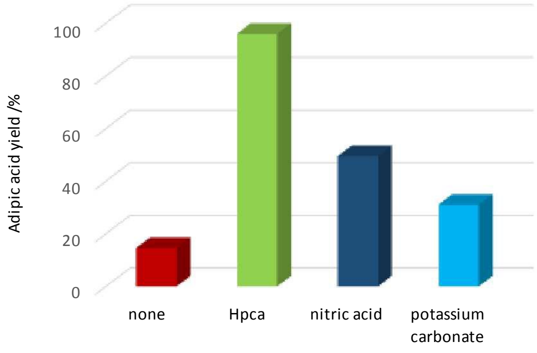

Figure 2. Effect of additives on the yields of adipic acid obtained by one-pot oxidation of cyclohexane with O_3 catalysed by [FeCl$_2${κ^3-HC(pz)$_3$}].

Thus, the reported [5] non-catalytic ozonolysis of neat cyclohexane (affording 12 mol% of adipic acid) or of cyclohexane – 8 vol% aq. 0.5 M HCl (leading to 45 mol% of adipic acid) are now notably improved by the action of catalytic amounts of [FeCl$_2${κ^3-HC(pz)$_3$}] and Hpca. Our catalytic system is also advantageous relative the reported photochemical one [5] affording higher yields of adipic acid (96% and 75% [5], respectively).

Other advantages of this new catalytic protocol are *i*) very low catalyst load (0.05 mol% *vs*. cyclohexane, Table S1, ESI), *ii*) mild and environmental benign conditions, such as the solvent-, heating-, radiation- and N_2O-free protocol (no N_2O abatement required), *iii*) the short reaction time required, increasing atomic and energetic efficiency, *iv*) the use of a non-toxic, biologic and cheap metal as catalyst and *v*) a facile work-up; significant features towards the development of a sustainable chemical process.

Control experiments under the same conditions but in the absence of [FeCl$_2${κ^3-HC(pz)$_3$}] (leading to up to 15% cyclohexane conversion with a selectivity of 20, 60 and 20%, for cyclohexanol, cyclohexanone and adipic acid, respectively, Table S1, ESI) confirmed the crucial role of the scorpionate iron(II) complex to efficiently catalyse the cyclohexane conversion to adipic acid. Moreover, the use of Fe(II) or Fe(III) chlorides affords a maximum of 27 or 21% conversion of cyclohexane, respectively, but without the formation of adipic acid (entries 14-17, Table S1, ESI).

Although the detailed mechanistic pathway is still to be established, the oxidation of cyclohexane by ozone is believed to proceed by a mechanism related to that reported for the oxidation of cyclohexane by dioxygen catalysed by a mononuclear Fe(II) porphyrin complex [16,17]. It is likely that the active catalytic species is a formally Fe(IV)=O one, resulting from the oxidation of the Fe(II) complex by O_3. The mechanism consists of three major oxidative steps (Scheme S1, ESI): *i*) cyclohexane oxidation to cyclohexane-1,2-diol (involving two consecutive hydroxylation steps, each initiated by a hydrogen-atom transfer from the substrate to Fe(IV)=O); *ii*) cyclohexane-1,2-diol conversion to hexane-1,6-dial (by intradiol C-C bond cleavage); and iii) hexane-1,6-dial oxidation to adipic acid (*via* hydroxylation of the carbonyl groups) [17]. The absence of cyclohexane-1,2-diol in our reaction solution (Figure 1) would be in accord with the very rapid ring-opening of the diol in the second main oxidative step of the proposed mechanism [17].

Our new protocol is also advantageous relative to the so far patented [7-9] alternative methods to produce adipic acid from cyclohexane: *i*) by catalytic air oxidation of cyclohexane, requiring high temperatures to yield a maximum of 70% of adipic acid and thus purification operations [9]; *ii*) by oxidation of cyclohexane dissolved in a halogenated hydrocarbon (*e.g.*, CCl_4) with an ozone-containing gas while heating up to 65 ºC [7]; or *iii*) by using a bimetallic catalyst supported on a transition metal oxide in an autoclave at up to 300 ºC, leading to a cyclohexane conversion of only 21% with an adipic acid selectivity of 34% [8].

In summary, a new N_2O-free simple method for the adipic acid synthesis *via* the one-pot oxidation of cyclohexane with ozone has

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been developed. Green metrics (Table S1) such as atom economy (molecular weight of desired product per combined molecular weight of starting materials) or carbon efficiency (amount of carbon in product *per* total carbon in reactants) highlight the need of a careful synthetic evaluation, especially on the use of co-catalysts. Further optimization studies will be attempted in view of the interesting preliminary results achieved.

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Notes and references

1 *Ullmann's Encyclopedia of Industrial Chemistry*, 6th ed., Wiley-VCH, Weinheim, Germany, 2002.
2 Adipic acid (ADPA): 2016 world market outlook and forecast up to 2020, Merchant Research and Consulting, Birmingham, UK, 2016.
3 I. Hermans, P.A. Jacobs, J. Peeters, *Chem. Eur. J.,* 2006, 12, 4229-4240.
4 S. Van de Vyver, Y. Román-Leshkov, *Catal. Sci. Technol*., 2013, **3**, 1465-1479.
5 K.C. Hwang, A. Sagadevan, *Science*, 2014, **346**, 1495-1498.
6 F. Cavani, S. Alini, in *Sustainable Industrial Processes*, F. Cavani, G. Centi, S. Perathoner, F. Trifiró (eds.), Wiley-VCH, Weinheim, 2009, Ch.7, pp. 367-425.
7 Miyazaki Shiyouji, JPS565374 (B2), 1981.
8 A.S. Alshammari, A.A. Bagabas, A. Kockritz, V.N. Kalaveru, US 2013/0296604 A1, 2013.
9 S. Liu, X. Qingli, L. Weiping, G. Cancheng, CN101337879, 2011.
10 D. Bonnet, T. Ireland, E. Fache, J-P. Simonato, *Green Chem*., 2016, **8**, 556-559.
11 T.F.S. Silva, E.C.B.A. Alegria, L.M.D.R.S. Martins, A.J.L. Pombeiro, *Adv., Synth. Cat*., 2008, **350**, 706-716.
12 L.M.D.R.S. Martins, A. Martins, E.C.B.A. Alegria, A.P. Carvalho, A.J.L. Pombeiro, *Appl. Cat. A: Gen.,* 2013, **464-465**, 43-50.
13 L.M.D.R.S. Martins, M.P. Almeida, S.A.C. Carabineiro, J.L. Figueiredo, A.J.L. Pombeiro, *ChemCatChem*, 2013, **5**, 3847-3856.
14 L.M.D.R.S. Martins, A.J.L. Pombeiro, *Coord. Chem. Rev.,* 2014, **265**, 74-88.
15 L.M.D.R.S. Martins, A.J.L. Pombeiro, *Eur. J. Inorg. Chem*., 2016, 2236-2252.
16 Y. Yuan, H. Ji, Y. Chen, Y. Han, X. Song, Y. She, R. Zhong, *Org. Process Res. Dev.* 2004, **8**, 418–420.
17 H. Noack, V. Georgiev, M.R.A. Blomberg, P.E.M. Siegbahn, A.J. Johansson, *Inorg. Chem*. 2011, **50**, 1194–1202.

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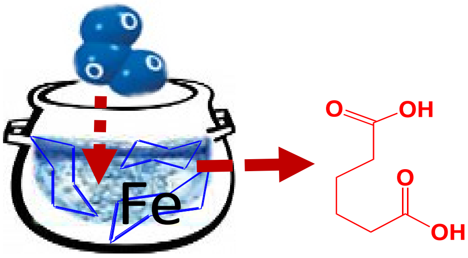

Iron catalysed efficient single-pot adipic acid synthesis by cyclohexane oxidation with ozone in a solvent-, heating-, radiation- and N_2O-free protocol.