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# Mohr's salt catalyzed oxidation of aldehydes with *t*-BuOOH

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Various aromatic, aliphatic and conjugated aldehydes were transformed to the corresponding carboxylic acids with 70% *t*-BuOOH solution (water) in the presence of catalytic amounts (10 mol%) of Mohr's salt. This method possesses functional group compatibility, does not involve cumbersome work-up, exhibits chemoselectivity since other functional groups remain intact and proceeds under mild conditions. The resulting products are obtained in good yields within reasonable times. Copyright © 2011 John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: oxidation; aldehyde; Mohr's salt; t-BuOOH; kinetics

# Introduction

The oxidation of aldehydes is of interest owing to their potential in organic synthesis and industrial manufacturing, and is recognized as one of the fundamental reactions.<sup>[1-5]</sup> The most popular and widely used reagent for such a transformation is Jones's reagent.<sup>[6-11]</sup> However, the reaction is stoichiometric and is performed under highly acidic conditions. Substrates with acid-sensitive functionalities may not tolerate such acidity. In addition, the generation of Cr-based side products may be considered as a potential environmental hazard.<sup>[12]</sup>

Other reagents that have been used successfully include oxone,<sup>[13]</sup> calcium hypochlorite<sup>[14]</sup> and 2-hydroperoxyhexafluoro-2-propanol.<sup>[15]</sup> Catalytic methods using metals have been developed using oxidation reactions.

Interesting methodologies for metal-mediated transformation of the aldehyde functionality to carboxylic acid have been reported recently.<sup>[16–27]</sup> The above reagents and the methods involved have one or more limitations that include the use of superstoichiometric amounts of expensive compounds and employment of highly basic or acidic reaction conditions. The search for catalytic processes involving environmentally benign reagents remains an attractive avenue in this area.

It is reported that, in the presence of O<sub>2</sub>, Cu(I) salts catalyze the oxidation of alcohols to aldehydes and ketones.<sup>[28]</sup> Our recent results highlight the oxidation of aldehydes to carboxylic acids in the presence of catalytic amounts of AgNO<sub>3</sub> and Bi<sub>2</sub>O<sub>3</sub>.<sup>[29,30]</sup> Our continued interest in studying catalytically active and environmentally benign processes led us to investigate the capability of Fe(II) reagents to oxidized Mohr's salt [(NH<sub>4</sub>)<sub>2</sub>(Fe)(SO<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O]; a popular redox indicator was used as a stable Fe(II) source.

# **Results and Discussion**

#### **Oxidation of Aldehydes**

Initial attempts to optimize the reaction conditions for the oxidation of aldehydes to the corresponding carboxylic acids were done using 2-methoxybenzaldehyde as a suitable substrate

in the presence of different solvents, oxidants and 10 mol% Fe(II) salts (Table 1).

The conversion of 2-methoxybenzaldehyde to 2-methoxybenzoic acid is facile in dimethyl sulfoxide at 80 °C in the presence of 10 mol% Mohr's salt and 5 equiv. 70% *t*-BuOOH (water) as oxidant (Table 1, entry 6). Large-scale reactions must be avoided since *t*-BuOOH may spontaneously detonate at high temperatures.<sup>[37,38]</sup> At room temperature, the reaction is sluggish.

Oxidation with *t*-BuOOH (water) alone in DMSO was found to be negligible (<5%). In the presence of 5 mol% Mohr's salt and 5 equiv. 70% *t*-BuOOH (water) as the oxidant in DMSO, the reaction required 5 h for completion with 80% isolated yield of the product. In DMSO, with 10 mol% Mohr's salt and 5 equiv. 70% *t*-BuOOH (water) as the oxidant, the reaction went to completion in a shorter time. With 5 equiv. 5 m *t*-BuOOH (decane), the reaction was found to complete in 3.5 h with 85% isolated yield. We did not use this reagent further since the results are not as good as for the water solution and it is much more expensive.

The reaction took 9 h when performed with 5 equiv. 30% H<sub>2</sub>O<sub>2</sub> in DMSO and yielded 87% of product. The other solvents used for optimization (Table 1, entries 1–9) were used under conditions of reflux. DMSO yielded the best results (Table 1, entry 6). The other Fe(II) salts (Table 1, entries 10 and 11) were found to be inferior. Having determined the correct conditions for oxidation, we continued our studies with a variety of aromatic and aliphatic substrates (Table 2).

The scope of our catalytic system is applicable for a wide range of aromatic, conjugated and aliphatic substrates. These aldehydes were converted to the corresponding carboxylic acids in good isolated yields in reasonable time (Table 2).

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**Table 1.** Optimization of the reaction conditions for the conversion of 2-methoxybenzaldehyde to 2-methoxybenzoic acid with different solvents,5 equiv. 70% t-BuOOH (water) and 10 mol% Fe(II) salts

|   |                   | H Fe(II) salt, <i>t</i> -BuOOH solvent | → OH<br>OH<br>OMe     |                        |  |  |
|---|-------------------|--|-----------------------|------------------------|--|--|
| Entry   | Catalyst          | Solvent                                | Time (h) <sup>a</sup> | Yield (%) <sup>b</sup> |  |  |
| 1   | Mohr's salt       | EtOAc                                  | 4                     | 93                     |  |  |
| 2   | Mohr's salt       | MeCN                                   | 4                     | 89                     |  |  |
| 3   | Mohr's salt       | toluene                                | 15                    | 87                     |  |  |
| 4   | Mohr's salt       | $CH_2CI_2$                             | 22                    | 80                     |  |  |
| 5   | Mohr's salt       | DMF                                    | 10                    | 91                     |  |  |
| 6   | Mohr's salt       | DMSO                                   | 3                     | 95                     |  |  |
| 7   | Mohr's salt       | THF                                    | 19                    | 85                     |  |  |
| 8   | Mohr's salt       | EtOH                                   | 17                    | 80                     |  |  |
| 9   | Mohr's salt       | CH <sub>3</sub> NO <sub>2</sub>        | 15                    | 82                     |  |  |
| 10  | FeCl <sub>2</sub> | DMSO                                   | 30                    | 71                     |  |  |
| 11  | FeBr <sub>2</sub> | DMSO                                   | 27                    | 80                     |  |  |
| $^{\rm a}$ Reactions performed at 80 $^{\circ}$ C and monitored using TLC until all the aldehyde was found to have been consumed. |                   |  |                       |                        |  |  |

<sup>a</sup> Reactions performed at 80 °C and monitored using TLC until all the aldehyde was found to have been consumed <sup>b</sup> Isolated yield after column chromatography of the crude product with 2% standard deviation.

It is pertinent to mention here that mild halogenic oxidants like hypochlorites,<sup>[14,31,32]</sup> chlorites<sup>[33,34]</sup> and NBS<sup>[35,36]</sup> are not suitable for substrates with electron-rich aromatic rings, olefinic bonds and secondary hydroxyl groups, since these functional groups also react. Substitutions at different positions on the phenyl ring do not hinder the reaction, although the reaction time is affected.

Our catalytic system is mild and shows sufficient selectivity in carrying out the expected oxidation without affecting other functionalities like phenol and amine (Table 2, entries 7 and 8). Oxidation of  $\alpha$ - and  $\beta$ -unsaturated derivatives (Table 2, entry 15) resulted in the formation of the expected acid in very good yield.

# **Kinetic Studies**

Kinetic studies of the oxidation with 3,4-dimethoxybenzaldehyde, 2-nitrobenzaldehyde and crotonaldehyde were carried out next. High-pressure liquid chromatography (HPLC) was used to determine the various starting materials and products present as a function of time. The concentrations of reactant and product for the oxidation of 3,4-dimethoxybenzaldehyde are shown in Fig. 1. The concentration of the aldehyde decreased while that of the carboxylic acid increased.

We calculated the rate of such reactions. As an example, let us consider the conversion of 3,4-dimethoxybenzaldehyde to 3,4dimethoxybenzoic acid. The Van't Hoff differential method was used to determine the order (n) and rate constant (k) (Fig. 2). From Fig. 1, the rate of the reaction at different concentrations can be estimated by evaluating the slope of the tangent at each point on the curve corresponding to that of 3,4-dimethoxybenzaldehyde.

With these data,  $\log_{10}(\text{rate}) \text{ vs } \log_{10}(\text{concentration})$  is plotted. The order (*n*) and rate constant (*k*) are given by the slope of the line and its intercept on the  $\log_{10}(\text{rate})$  axis, respectively. From Fig. 2, it is clear that this reaction proceeds with second-order kinetics (n =2.17) and the rate constant  $k = 0.2 \text{ L mol}^{-1} \text{ min}^{-1}$ . For the other substrates, namely 2-nitrobenzaldehyde and crotonaldehyde, the order of the reaction  $n \approx 2$  with rate constants (*k*) 6.7 ×  $10^{-3}\ mol^{-1}\ min^{-1}$  and 6.9  $\times\ 10^{-2}\ L\ mol^{-1}\ min^{-1},$  respectively, (see Supporting Information for details).

# Conclusions

In summary, we have developed a simple, efficient, chemoselective and inexpensive catalytic method for the oxidation of aldehydes to carboxylic acids with a common laboratory reagent such as Mohr's salt. It is noteworthy that this method does not use ligands and other additives.

# **Experimental Section**

# **General Reagents and Equipment**

All the substrates used in this study, along with *t*-BuOOH, were purchased from Aldrich and used as received. The solvents used were purchased from Ranchem, India and purified using standard methods. <sup>1</sup>H and <sup>13</sup>C spectra were recorded with a Bruker Avance 400 instrument. Chemical shifts (in ppm) were referenced to residual solvent resonances and are reported as parts per million relative to SiMe<sub>4</sub>. A 0.5 ml aliquot of CDCl<sub>3</sub> was used for every NMR spectral measurement. HPLC analysis was carried out using a Waters HPLC instrument fitted with a Waters 515 pump and a Waters 2487 dual  $\lambda$  absorbance detector. Suitable mehtods were developed with different proportions of MeCN and alcohol.

# Typical Procedure for the Oxidation of Aldehyde to Carboxylic Acid

To a stirred solution of  $[(NH_4)_2(Fe)(SO_4)_2 \cdot 6H_2O]$  (39 mg, 0.10 mmol) and aldehyde (1 mmol) in 2.5 ml DMSO was added 70% *t*-BuOOH (water; 0.90 ml, 5 mmol). The reaction mixture was heated to 80 °C. The progress of the reaction was monitored using TLC until all aldehyde was found to have been consumed. The crude

| Table 2. Mohr's salt-catalyzed oxidation of aldehydes to carboxylic acids <sup>a</sup>  |   |                  |                       |                        |  |  |  |
|---|---|------------------|-----------------------|------------------------|--|--|--|
| O<br>H<br>H<br>10 mol% Mohr's salt<br><u>5 equiv. 70% <i>t</i>-BuOOH (water)</u><br>R<br>O<br>H<br>O<br>DMSO<br>R<br>O<br>O<br>O<br>H |   |                  |                       |                        |  |  |  |
| Entry   | Aldehyde                                | Acid             | Time (h) <sup>b</sup> | Yield (%) <sup>c</sup> |  |  |  |
| 1   | СНО                                     | Соон             | 4                     | 93                     |  |  |  |
| 2   | МеО-СНО                                 | МеО-СООН         | 3.5                   | 90                     |  |  |  |
| 3   | СНО                                     | Соон             | 3                     | 95                     |  |  |  |
|   | OMe                                     | OMe              |                       |                        |  |  |  |
| 4   | СНО                                     | Соон             | 5                     | 90                     |  |  |  |
| 5   | MeO                                     | MeO              | 2                     | 02                     |  |  |  |
| 5   | МеО-СНО                                 | МеО-СООН         | 2                     | 92                     |  |  |  |
| <i>.</i>  | MeÓ                                     | MeÓ              | 1 5                   | 01                     |  |  |  |
| 6   | OMe                                     | OMe              | 1.5                   | 91                     |  |  |  |
|   | МеО-СНО                                 | МеО—СООН         |                       |                        |  |  |  |
|   | MeO                                     | MeO              |                       |                        |  |  |  |
| 7   | но-Сно                                  | ноСоон           | 4.5                   | 90                     |  |  |  |
| 8   | NСНО                                    | Л-СООН           | 6.5                   | 88                     |  |  |  |
| 9   | СІ—СНО                                  | СІСООН           | 5                     | 91                     |  |  |  |
| 10  | СІ————————————————————————————————————— | СІСООН           | 7.5                   | 93                     |  |  |  |
|   | CI′                                     |                  |                       |                        |  |  |  |
| 11  | СНО                                     | Соон             | 3.5                   | 89                     |  |  |  |
| 12  | NO <sub>2</sub>                         | NO <sub>2</sub>  | -                     | 00                     |  |  |  |
| 12  | Сно                                     | Соон             | 5                     | 90                     |  |  |  |
|   | O <sub>2</sub> N                        | O <sub>2</sub> N |                       |                        |  |  |  |
| 13  | O <sub>2</sub> N-CHO                    | 02N-СООН         | 6.5                   | 90                     |  |  |  |
| 14  | СНО                                     | Соон             | 3.5                   | 92                     |  |  |  |
| 15  | Ph                                      | Ph               | 3                     | 93                     |  |  |  |
| 16  | СНО                                     | СООН             | 7                     | 87                     |  |  |  |
| 17  | СНО                                     | СООН             | 4                     | 90                     |  |  |  |

<sup>a</sup> Reactions performed in DMSO with 10 mol% Mohr's salt and 5 equiv. 70% *t*-BuOOH at 80  $^{\circ}$ C.

<sup>b</sup> Monitored using TLC until all the aldehyde was found to have been consumed. <sup>c</sup> Isolated yield after column chromatography of the crude with 2% standard deviation.



Figure 1. Concentration vs time in the oxidation of 3,4-dimethoxybenzaldehyde with 10 mol% Mohr's salt and 5 equiv. 70% t-BuOOH (water) in DMSO at 80 °C with 2% standard deviation.



Figure 2. Van't Hoff differential plot for the oxidation of 3,4dimethoxybenzaldehyde with 10 mol% Mohr's salt and 5 equiv. 70% *t*-BuOOH (water) in DMSO at 80  $^{\circ}$ C with 2% standard deviation.

product was treated with saturated NaHCO<sub>3</sub> solution. This was extracted with ethyl acetate. Finally, the aqueous layer was acidified using 2 M HCl and extracted with ethyl acetate. The organic layer was concentrated under vacuum and subjected to column chromatography using ethyl acetate and hexane. The spectral data of the various carboxylic acids were found to be satisfactory in accordance with the literature (see Supporting Information for details).

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#### Supporting information

Supporting information may be found in the online version of this article.

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