Pergamon

SCIENCE DIRECT®

Tetrahedron 59 (2003) 1823–1830

TETRAHEDRON

Oxidation of mandelic acid derivatives catalysed by Bi(0)/O_2 systems: mechanistic considerations

Isabelle Favier[a] and Elisabet Duñach[b,*]

[a]*Laboratoire Arômes Synthèses et Interactions, Université de Nice-Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 2, France*
[b]*Laboratoire de Chimie Bioorganique, UMR CNRS 6001, Université de Nice-Sophia Antipolis, 06108 Nice Cedex 2, France*

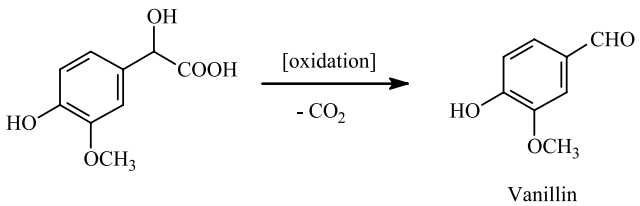
Received 4 October 2002; revised 12 December 2002; accepted 6 January 2003

Abstract—Mandelic acid and some aryl substituted derivatives were oxidised under molecular oxygen and a catalytic amount of Bi(0). The corresponding aldehydes and/or the carboxylic acids were obtained selectively depending on the nature of the substituent. Aldehydes and α-keto acids were oxidised under the same Bi(0)/O_2 system and α-keto acids were proposed as intermediates in the formation of benzoic acid derivatives.

1. Introduction

The most general utilisation of mandelic acid and its derivatives in industrial applications concerns their oxidation, which allows the access to aromatic aldehydes.[1] In particular, hydroxy- and alkoxy-substituted aldehydes constitute important products, used in the field of flavours and perfumes.[2,3] Mandelic acid derivatives are also used as intermediates in the field of agrochemicals, pharmaceuticals and in cosmetology.[4–6] Thus, piperonal (heliotropin) or vanillin are obtained from the oxidation of 3,4-methylenedioxymandelic acid[7] or 4-hydroxy-3-methoxymandelic acid (or VMA), respectively, (Scheme 1).[1,8,9]

The oxidation of mandelic acids can afford different oxidation products: the corresponding aldehyde, the carboxylic acid and the α-keto acid. A large variety of stoichiometric oxidation systems have been reported for this decarboxylative oxidation of mandelic acids to the corresponding aldehydes.[10] Among the catalytic reactions, Fe(II) and Cu(II) systems with H_2O_2 or $S_2O_8^{2-}$ as the oxidants,[11,12] Cr(V)[13] or $KMnO_4$[14] with $HClO_4$, or Cu(II)/O_2 systems have been described.[15]



Scheme 1. Oxidative decarboxylation of VMA.

The oxidation of mandelic acids can also afford the corresponding benzoic acids or the arylglyoxylic acids. Thus, phenylglyoxylic acid has been obtained from the O_2 oxidation of mandelic acid in the presence of Cu(II),[16] Pd/C, or Pt/C catalytic systems.[17] The oxidation to benzoic acid derivatives has been reported with Ce(IV) or Mn(II) in the presence of bromide ions, with Ru(VI)/Fe(III) or with Co(III)/O_2 systems.[18–20]

Despite these numerous studies, there has been no systematic study undertaken concerning the oxidation of mandelic acids. We present here systematic mechanistic considerations of this reaction with a bismuth-based catalytic system.

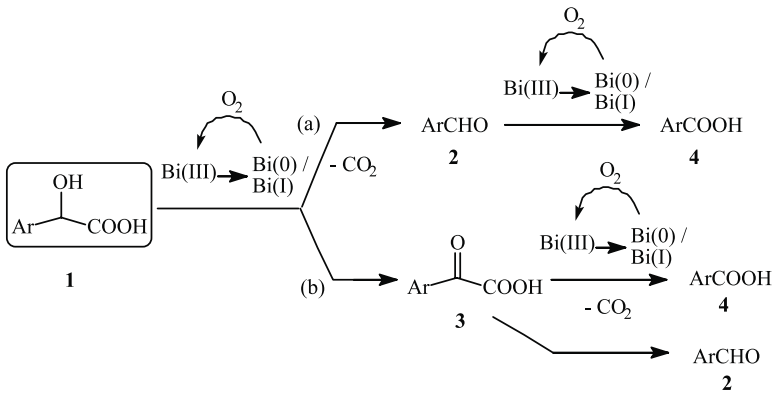
We have shown that some Bi(III) complexes such as Bi(III)-mandelate, in the presence of molecular oxygen, presented an interesting catalytic activity towards the oxidation and the oxidative C–C bond cleavage of epoxides and α-ketols.[21–23] More recently, metallic bismuth powder has also been reported as an efficient catalyst for the oxidation of these families of compounds, including the oxidation of α-hydroxy acids.[24]

The use of other bismuth derivatives in the oxidation of mandelic acids has been limited to the stoichiometric utilisation of sodium bismuthate[25] and of bismuth nitrate[26] leading to benzaldehydes and benzoic acids, respectively.

Keywords: mandelic acid; oxidation; bismuth; molecular oxygen; substituent effects.

* Corresponding author. Tel.: +33-4-92-07-61-42; fax: +33-4-92-07-61-51; e-mail: dunach@unice.fr

0040–4020/03/$ - see front matter
doi:10.1016/S0040-4020(03)00083-8



Scheme 2. Pathways for the oxidation of mandelic acid derivatives catalysed by Bi(0)/O_2 system.

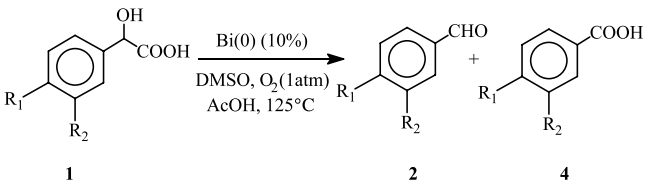
On the other hand, bismuth (III) derivatives have been described in the last years as possessing interesting Lewis acid character, able to catalyse, for example, the deprotection of acetals[27] and *S*,*S*-acetals,[28] the isomerisation of epoxides,[29] the sulfonylation reaction,[30] the acetylation and benzoylation of alcohols[31] the Mukaiyama aldol reaction,[32] the Diels–Alder reaction,[33,34] as well as other organic transformations.[35]

In the present study, we summarise our results on the bi-catalysed oxidation of differently substituted mandelic acids, benzaldehydes and phenylglyoxylic acids, in order to get a better understanding of the factors that govern the reaction chemoselectivity, and in order to propose plausible mechanistic pathways and intermediates for the oxidation of the various substrates examined.

2. Results and discussion

The oxidation of mandelic acids (or one of its aryl derivatives), **1**, can afford benzaldehydes, **2**, arylglyoxylic acids, **3**, and/or the benzoic acid derivatives, **4**. As shown in Scheme 2, the oxidative decarboxylation of **1** may directly afford **2**, which, in turn can be oxidised to **4** (path (a)). In an alternative pathway (path (b)), the alcohol oxidation of **1** may lead to keto acid **3**, which can be either decarboxylated to **2** or undergo an oxidative decarboxylation to **4**.

During the oxidation of differently substituted mandelic acids in the presence of Bi(0)/O_2 as the catalytic system, we observed that the nature of the substituents on the aryl ring was chemoselectively influencing the outcome of the reaction (Eq. (1)).



(1)

As shown in Table 1, whereas the oxidation of unsubstituted mandelic acid, **1a** led to the selective formation of benzoic acid, **4a**, the oxidation of 4-hydroxy-3-methoxymandelic acid, **1d**, afforded the corresponding aldehyde, **2d**, in high selectivity. In a recent study,[36] we could distinguish between two types of substitution on the aryl ring able to strongly influence the reactivity and the selectivity of the oxidation of mandelic acid derivatives. Thus, the presence of electron-withdrawing substituents allowed the selective formation of benzoic acids, **4**. In contrast, mandelic acid derivatives possessing an hydroxy substituent at the 2- or 4-positions of the aryl group tended to favour the formation of the corresponding benzaldehydes, **2**.

To complete this study, we examined the reactivity of four model compounds, differently substituted in the aromatic ring, under oxidative catalytic conditions, using the system Bi(0) under molecular oxygen. The oxidations were carried out in DMSO/AcOH as the reaction medium at 125°C, with 10 mol% of catalyst with respect to the substrate. Under these conditions, the commercially available and non-toxic Bi(0) powder could be dissolved and an homogeneous yellow solution was obtained. A Bi(III)/Bi(0) redox couple was operating as the catalytic system, able to activate O_2 at

Table 1. Oxidation of mandelic acid derivatives catalysed by Bi(0)/O_2 system

Substrate	R_1	R_2	Time	Conversion (%)	Yields (%) /conversion **2**+**4**	Selectivity **2/4**
1a	H	H	24 h	54	81[a]	7:93
1b	OMe	H	6 h	77	100	38:62
1c	CF_3	H	24 h	97	100	1:99
1d	OH	OMe	40 min	97	100	87:13
1e	OH	H	6 h	100	98	77:23

[a] Phenylglyoxylic acid **3a** was also obtained in 19% yield.

Table 2. Oxidation of mandelic acid, **1a**, benzaldehyde, **2a** and phenylglyoxylic acid, **3a**, catalysed by Bi(0)/O_2 system for 24 h reaction

Substrate	Conversion (%)	Products formed and selectivity		
		2a	**3a**	**4a**
1a	54	6	19	75
2a	15	–	–	100
3a	85	–	–	100

atmospheric pressure. Model compounds chosen were mandelic acid, **1a**, 4-methoxymandelic acid, **1b**, 4-trifluoromethylmandelic acid, **1c**, and 4-hydroxy-3-methoxymandelic acid, **1d**. We examined as well, the oxidation of the corresponding benzaldehydes, **2a**–**d**, and arylglyoxylic acids, **3a**–**c**. The oxidation of 4-hydroxy mandelic acid **1e** was also examined, for comparison.

2.1. Oxidation of mandelic acid, benzaldehyde and phenylglyoxylic acid

Under the standard reaction conditions, the oxidation of mandelic acid, **1a**, led, after 24 h to a 54% conversion. Among the compounds formed, the major product was benzoic acid, **4a**, obtained with a selectivity of 75%. Benzaldehyde, **2a** and phenylglyoxylic acid, **3a** were obtained in 6 and 19% selectivity, respectively, (Table 2).

Both **2a** and **3a** being possible intermediates in the formation of **4a**, their oxidation was run under the same conditions. Benzaldehyde was converted into benzoic acid in only 15% after 24 h. In contrast, the oxidation of phenylglyoxylic acid, **3a** afforded, under the same conditions, 85% conversion with exclusive formation of **4a**.

These results indicated that benzaldehyde **2a** is not a plausible intermediate in the oxidation of **1a** to **4a** (Scheme 2). However, the keto acid, **3a**, constitutes an intermediate compatible with the oxidation kinetics. The kinetic evolution of the oxidation of a 1:1 mixture of **1a** and **3a** is presented in Figure 1. The reaction was followed by NMR, after treating aliquot samples from the reacting mixture.

As shown in Figure 1, the keto acid **3a** is oxidised at a higher rate than **1a**. This is in agreement with a mechanism following path (b) in Scheme 2.

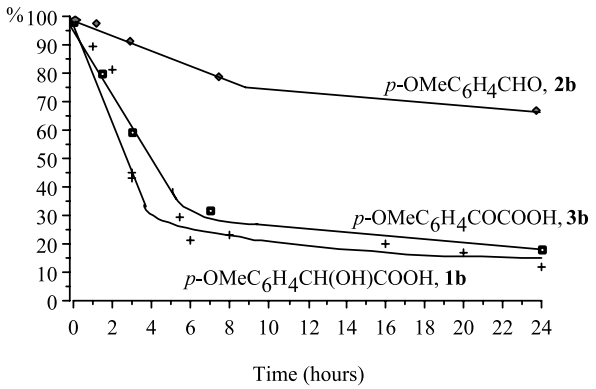


Figure 2. Oxidation of *p*-methoxymandelic acid, *p*-methoxybenzaldehyde and *p*-methoxyphenyglyoxylic acid catalysed by Bi(0)/O_2.

2.2. Oxidation of 4-methoxymandelic acid, 4-methoxybenzaldehyde and 4- methoxyphenylglyoxylic acid

The kinetics of the Bi(0)/O_2 oxidation reactions of 4-methoxymandelic acid, **1b**, 4-methoxybenzaldehyde, **2b**, and 4-methoxyphenylglyoxylic acid, **3b**, are presented in Figure 2. Both 4-methoxymandelic acid and 4-methoxyphenylglyoxylic acid reacted at similar rates, and faster than the aldehyde, **2b**. Conversions and selectivities in 4-methoxybenzoic acid, **4b**, are presented in Table 3.

The oxidation of **1b** led, after 6 h, to a 77% conversion into a mixture of aldehyde **2b** and carboxylic acid **4b** with a selectivity **2b**:**4b** of 38:62. It is to be noted that **3b** was not isolated from the oxidation of **1b**. The oxidation of **3b** afforded selectively **4b** in 98%.

The aldehyde **2b** being only slowly oxidised to **4b**, the formation of **4b** from **1b** is essentially due to its oxidation

Table 3. Oxidation of *p*-methoxymandelic acid, *p*-methoxybenzaldehyde and *p*-methoxyphenyglyoxylic acid catalysed by Bi(0)/O_2

Substrate	Time (h)	Conversion (%)	Products formed and selectivity		
			2b	**3b**	**4b**
1b	6	77	38	–	62
2b	24	32	–	–	100
3b	24	80	2	–	98

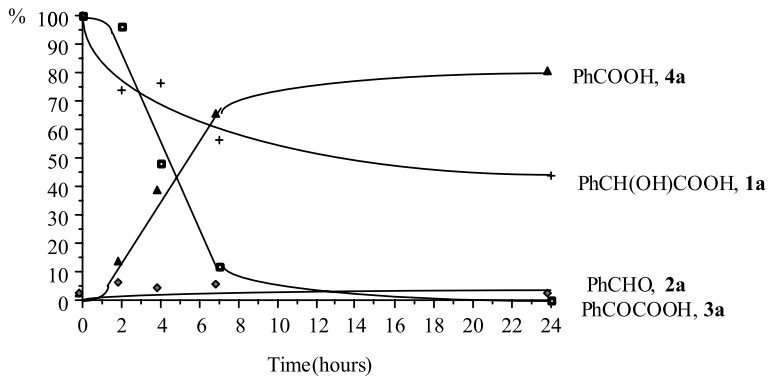


Figure 1. Oxidation of a mixture of mandelic acid and phenylglyoxylic acid (1:1) catalysed by Bi(0)/O_2.

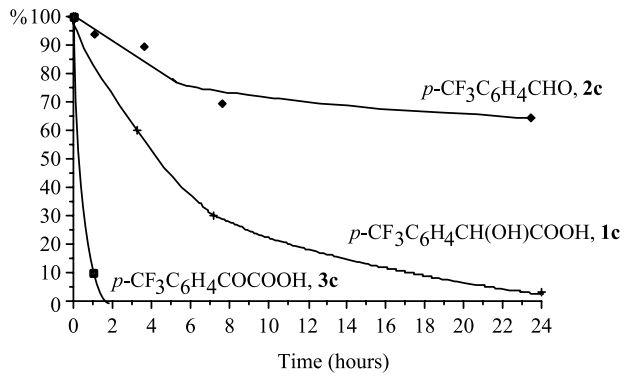


Figure 3. Oxidation of *p*-trifluoromethylmandelic acid, *p*-trifluoromethylbenzaldehyde and *p*-trifluoromethylphenylglyoxylic acid catalysed by $Bi(0)/O_2$.

via the keto acid **3b**, following path (b) in Scheme 2, according to the data in Table 3.

In the oxidation of **1b**, the aldehyde **2b**, present with a selectivity of 38%, is not issued from the keto acid intermediate. The aldehyde should be directly formed from **1b** by an oxidative decarboxylation reaction, as shown by path (a) of Scheme 2. In the case of the oxidation of **1b**, the two possible oxidation pathways (a) and (b) of Scheme 2 seem to be operating simultaneously, with an approximate ratio of 1:2.

2.3. Oxidation of 4-trifluoromethylmandelic acid, 4-trifluoromethylbenzaldehyde and 4-trifluoromethylphenylglyoxylic acid

Figure 3 presents the kinetic evolution of the Bi(0)-catalysed oxidation of 4-trifluoromethylmandelic acid, **1c**, 4-trifluoromethylbenzaldehyde, **2c**, and 4-trifluoromethylphenylglyoxylic acid, **3c**. The results indicate that the oxidation of the keto acid **3c** occurs at a much higher rate than that of **1c**, and a relatively slow oxidation of aldehyde **2c** can be observed.

It can be concluded that **3c** is an intermediate in the oxidation of **1c** to **4c**, and **3c** is not isolated in the reaction. Table 4 indicates the results of the oxidations of **1c**–**3c**. After 1 h reaction, the keto acid **3c** is almost completely converted and the carboxylic acid **4c** is formed with a selectivity of 98%. This result is compatible with the oxidation of **1c** to **4c** via **3c** as the intermediate.

The aldehyde **2c** is practically not formed in the oxidation of either **1c** or **3c**. The aldehyde is only slowly oxidised to **4c**,

Table 4. Oxidation of *p*-trifluoromethylmandelic acid, *p*-trifluoromethylbenzaldehyde and *p*-trifluoromethylphenylglyoxylic acid catalysed by $Bi(0)/O_2$

Substrate	Time (h)	Conversion (%)	Products formed and selectivity		
			2c	**3c**	**4c**
1c	24	97	1	–	99
2c	24	37	–	–	95
3c	1	90	2	–	98

Table 5. Oxidation of VMA and vanillin catalysed by $Bi(0)/O_2$

Substrate	Time	Conversion (%)	Products formed and selectivity		
			2d	**3d**	**4d**
1d	20 min	69	99	–	1
	40 min	97	87	–	13
	24 h	100	61	–	31
2d	24 h	25	–	–	68

and it does not constitute an intermediate in the oxidation of **1c** to **4c**. Thus, the oxidation of 4-trifluoromethylmandelic acid, **1c** follows almost exclusively path (b) in Scheme 2.

2.4. Oxidation of 4-hydroxy-3-methoxymandelic acid and 4-hydroxy-3-methoxybenzaldehyde

The oxidation of 4-hydroxy-3-methoxymandelic acid or vanillic mandelic acid, **1d**, and of 4-hydroxy-3-methoxybenzaldehyde or vanillin, **2d**, was carried out by the $Bi(0)/O_2$ system. In the case of the 4-hydroxy-3-methoxy substituted derivatives, several attempts to prepare the keto acid derivative, **3d**, were unsuccessful.

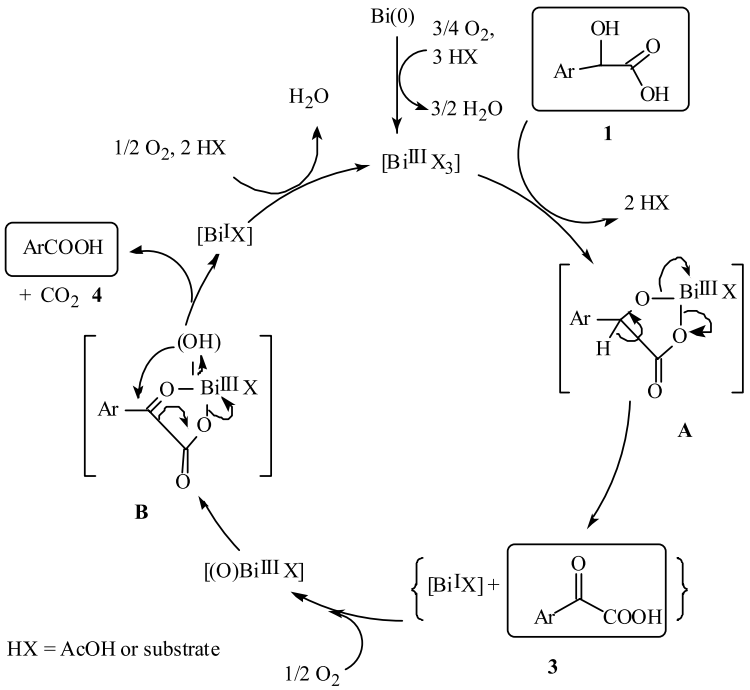
The oxidation of **1d** was completed in 1 h and occurred at a much higher rate than that of **2d**. The oxidation of **2d** afforded a conversion of only 25% after 24 h. As shown in Table 5, the oxidation of **1d** to **2d** occurs very selectively at the first stages of the reaction. However, in the reaction medium, **2d** undergoes a slow oxidation to **4d**, and therefore the aldehyde selectivity decreases with time.

The oxidation of **1d** led selectively to the aldehyde **2d**. However, and in the absence of intermediate **3d**, we cannot conclude weather **2d** is formed by a direct oxidative decarboxylation of **1d** (path (a), Scheme 2) or by the decarboxylation of the keto acid intermediate (path (b)). The carboxylic acid **4d** is formed from the slow oxidation of aldehyde **2d**. As in the case of **1d**, 4-hydroxymandelic, **1e**, led to the preferential formation of aldehyde **2e** in 77% selectivity (Table 1).

2.5. Proposed mechanisms

The above results indicate that in the case of the oxidation of **1a**–**c**, the formation of the corresponding carboxylic acid **4** is issued from a first oxidation of the α-hydroxy acid, **1** to the corresponding α-keto acid, **3**, followed by a second step of oxidative decarboxylation to **4**. These successive oxidation steps are catalysed by the system $Bi(0)/O_2$ in DMSO/AcOH. It has been recently reported, that under the reaction conditions, the initial Bi(0) is dissolved in the medium and forms a Bi(III) complex, which constitutes the active oxidation species.[24] In each oxidation step, the redox couple Bi(III)/Bi(I) should be operating. The recycling of the Bi(III) species is effected by molecular oxygen.

A proposed catalytic cycle for the transformation of mandelic acids **1** to their corresponding benzoic acids **4** is shown in Scheme 3. The nature of the intermediates Bi(III) or Bi(I) species, or the mode of coordination of O_2 are not yet known.

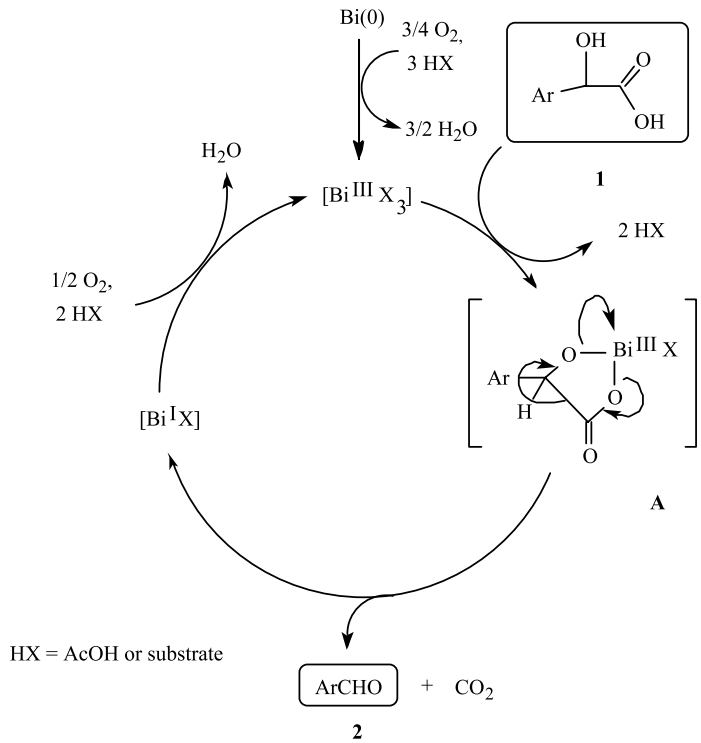


Scheme 3. Catalytic cycle proposed for the oxidation of mandelic acids, **1** to their corresponding benzoic acids, **4**.

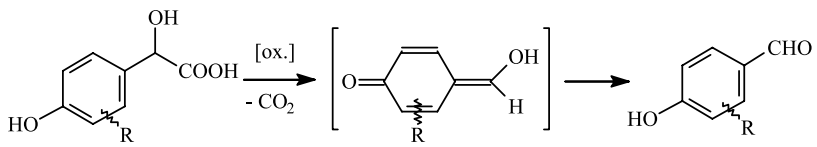
According to Scheme 3, a first oxidation of Bi(0) to Bi(III) is followed by the coordination of **1** to form a proposed intermediate **A**. Other mechanisms are also possible for the alcohol oxidation reaction, either concerted or non-concerted. A redox reaction of **A** affords Bi(I) and the keto acid **3**. Further Bi(I) reoxidation to Bi(III) allows the oxidative decarboxylation of the carboxylate intermediate **B** to form the carboxylic acid **4** and CO_2. The proposed mechanism involving the passage **3** to **4** in Scheme 3 has some similarities with the α-keto acid oxidation mechanisms proposed by dioxygenase enzymes and their iron synthetic models.[37]

This type of catalytic cycle is selectively operating in the case of mandelic acid and of mandelic acids substituted by electron-withdrawing substituents in the aryl ring.

The kinetic and preparative-scale results also indicated the



Scheme 4. Catalytic cycle proposed for the oxidation of mandelic acids, **1** to their corresponding benzaldehydes, **2**.



C

Scheme 5. Proposed quinoid-type intermediates for mandelic acids possessing hydroxyl substituents on 2- or 4-positions of the aryl ring.

possibility, for substrates such as **1b** and **1d** to undergo a direct oxidative decarboxylation to the corresponding aldehydes **2**. A catalytic cycle for the aldehyde formation is proposed in Scheme 4.

In this case, intermediate **A** does not undergo alcohol oxidation, but the cleavage of the C–C bond with loss of CO_2 and direct formation of derivatives **2**, with recycling of the Bi(III) species.

This catalytic cycle is preferred in the case of mandelic acids possessing hydroxy substituents on the 2- or 4-positions of the aryl ring. The possible participation of quinoid-type intermediates of type C (Scheme 5) can also be considered and has already been proposed.[38] The mechanism shown in Scheme 4 should be partially operating in the case of electron-donating substituents, such as the methoxy group, as in the oxidation of **1b**.

Two different mechanistic pathways are therefore operating in the oxidation of differently substituted mandelic acids. To complete this study, a Hammett-type correlation was obtained from the kinetic data with the Bi(0)/O_2-catalysed oxidation of mandelic acid substrates. The results are presented in Table 6 and in Figure 4.

Table 6. Reaction half-time, rate constants and σ values[39] for mandelic acid oxidations (see Eq. (1))

R	Substrate	$t_{1/2}$ (h)	K (s^{-1})×10^{5a}	log (k/k_0)	σ
H	**1a**	22	0.88 (k_0)	0	0
p-OMe	**1b**	3	6.42	0.86	−0.28
p-CF_3	**1c**	5	3.85	0.64	0.53
p-OH	**1e**	2	9.63	1.04	−0.38
p-Cl	**1f**	15	1.28	0.16	0.24
m-Cl	**1g**	7	2.75	0.49	0.37

[a] The rate constant was taken as: k=ln 2/$t_{1/2}$.

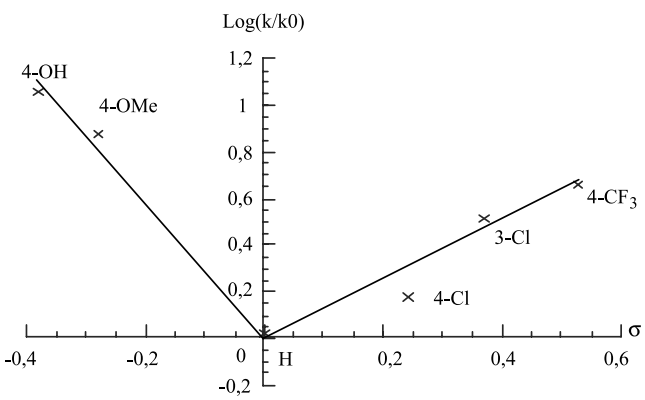


Figure 4. Hammett representation for the oxidation of *p*-substituted mandelic acid derivatives (Eq. (1)).

A different slope in the Hammett correlation was obtained for electron-rich and for electron-poor substrates, in agreement with different operating mechanisms.

On the other hand, parallel competitive reaction studies were carried out on the oxidation of some *p*-substituted mandelic acid derivatives. In a first competition experiment a 1:1 mixture of 4-trifluoromethylmandelic acid and unsubstituted mandelic acid were reacted under the standard reaction conditions for 24 h. The results are shown in Figure 5. It could be observed that mandelic acid under these competitive conditions reacted slightly faster than alone, no keto acid was present after 24 h (see Table 1 for comparison) and the selectivity towards benzoic acid was of 85%.

A slightly lower reactivity was observed for 4-trifluoromethylmandelic acid in this competitive experiment, with a final selectivity in 4-trifluoromethylbenzoic acid of 88%. Overall, the oxidation of a mixture of the two derivatives afforded the same products with slight kinetic differences, but in a less selective process.

A second competitive experiment was carried out with a 1:1 mixture of 4-trifluoromethylmandelic acid and 4-hydroxymandelic acid for 5 h, and the results are presented in Figure 6. In this reaction, an electron-poor substrate reacting through path (b) in Scheme 2, according to the mechanism proposed in Scheme 3 was reacted together with a 4-OH substituted mandelic derivative, that was mainly affording the corresponding aldehyde according to Schemes 4 or 5.

The results obtained indicated that the rate of conversion of the 4-hydroxymandelic acid slowed down, and that of 4-trifluoromethylmandelic acid slightly increased. For both compounds the selectivity towards the corresponding aldehydes increased. Thus, the conversion of 4-hydroxymandelic acid was of 57% after 6 h with a ratio **2e**:**4e** of 89:11. For 4-trifluoromethylmandelic acid a conversion of 57% was reached after 5 h and the ratio **2c/4c** was of 35:65. This competitive experiment with two substrates reacting through differently reaction pathways indicated that there is a strong influence of the presence of one substrate on the reactivity and the selectivity of the other one.

3. Conclusions

We report for the first time a systematic study on the oxidation of differently substituted mandelic acid derivatives, **1** with a Bi(0)/O_2 catalytic system. The oxidation of **1** can afford either the corresponding carboxylic acids **4** or the aldehydes **2**. We could show that the formation of acids **4** could involve the intermediate passage through the

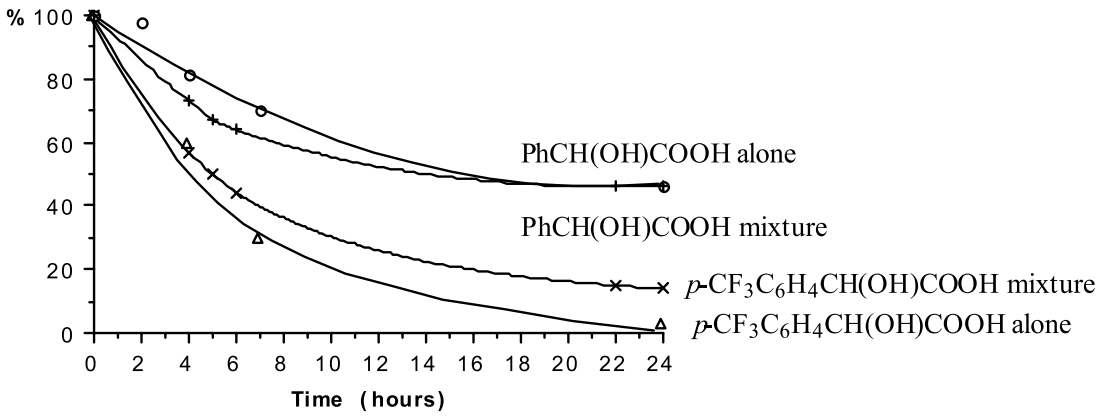


Figure 5. Oxidation of a 1:1 mixture of *p*-trifluoromethylmandelic acid and mandelic acid catalysed by $Bi(0)/O_2$.

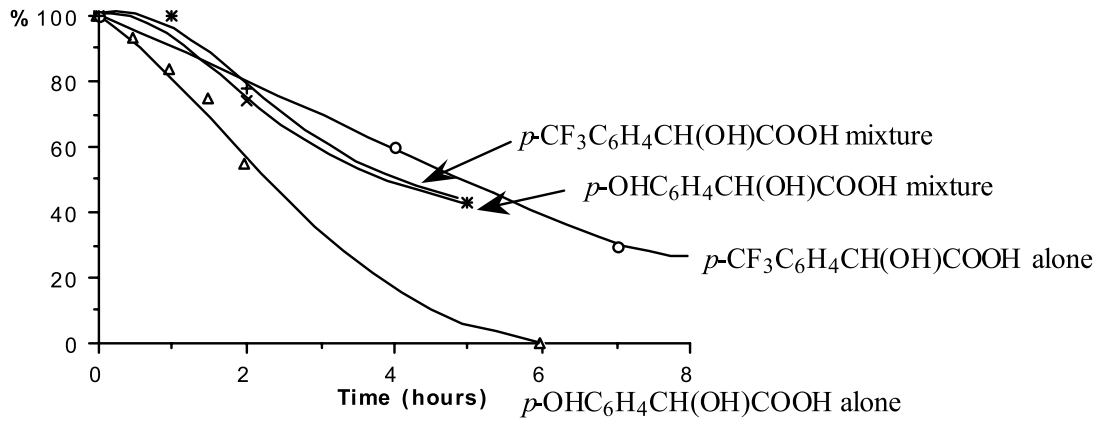


Figure 6. Oxidation of a 1:1 mixture of *p*-trifluoromethylmandelic acid and 4-hydroxymandelic acid catalysed by $Bi(0)/O_2$.

corresponding keto acid intermediates, **3**. Aldehydes **2** are obtained through a different mechanism, the direct oxidative decarboxylation. With the $Bi(0)/O_2$ catalytic system, the choice of one or other mechanism is essentially governed by the nature of the substituent on the aryl ring of **1**. Thus, electron-withdrawing groups in the aryl moiety selectively orientate towards the formation of the corresponding carboxylic acids, via the keto acid intermediates. In sharp contrast, when –OH or other electron-donating groups are present as aryl substituent(s), particularly at the 2- and 4-positions, the formation of the aldehyde **2** is preferred and the reaction rates are increased.

4. Experimental

The commercially available products were used without further purification. The reactions were carried out under atmospheric pressure of molecular oxygen. Mandelic acid or its derivatives (**1a**–**d**) (2 mmol), was dissolved in DMSO (5 mL) in the presence of Bi(0) powder (0.2 mmol) and 3 mmol of AcOH (50% aqueous solution). The mixture was stirred at 125°C for 24 h or until the complete consumption of the starting material, which was followed by HPLC and/or by ^{1}H NMR. The crude reaction mixture was hydrolysed with 5 mL aqueous 1 M HCl solution saturated with NaCl, and extracted with ethyl acetate (5×10 mL). Organic phases were collected and washed twice with an aqueous 0.1 M HCl solution saturated with NaCl, dried over $MgSO_4$ and filtered off. The products were analysed by HPLC and ^{1}H NMR and their spectral data compared to those of authentic samples.

References

1. (a) Hodny, I.; Krob, V.; Smidrkal, J.; Bouskova, O. Czech. CS 277365 B6 (Cl. C07C47/575), 13 Jan 1993; *Chem. Abstr.* **1994**, *121*, 82716s. (b) Soucek, J.; Hora, A.; Kluger, A.; Hedrlin, I.; Krob, V. Czech. CS 265937 B1 (Cl. C07C47/575), Avr 13 1990; *Chem. Abstr.* **1992**, *116*, 83373m. (c) Maggioni, P.; Minisci, F. Neth. Appl. NL 7905900 (Cl. C07C47/52), Fév. 03 1981; *Chem. Abstr.* **1981**, *95*, 42661h. (d) Ube Industries, Ltd. Jpn. Kokai Tokkyo Koho JP 82,112,346 (Cl. C07C47/565); *Chem. Abstr.* **1982**, *97*, 181970n. (e) Umemura, Y.; Enomiya, T.; Shiraishi, H.; Nakamura, T. Jpn. Kokai Tokkyo Koho JP 8022614 (Cl. C07C49/245); *Chem Abstr.* **1980**, *93*, 114140w. (f) Umemura, S.; Takamitsu, N.; Enomiya, T.; Shiraishi, Y.; Nakamura, T.; Harada, K.; Hashino, Y. Jpn. Kokai Tokkyo Koho JP 7922334 (Cl. C07C47/56); *Chem Abstr.* **1979**, *90*, 186590d.
2. Teissere, P. *Chimie des Substances Odorantes*. Lavoisier Tec & Doc, Paris, 1991.
3. Boelens, H. *Indian Perfum.* **1968**, *12*, 28–32.
4. (a) Barthel, W. F.; Leon, J.; Hall, S. A. *J. Org. Chem.* **1954**, *19*,

485–489. (b) Tsantrizos, Y. S.; Ogilvie, K. K. *Can. J. Chem.* **1991**, *69*, 772–778.
5. (a) Cooper, R. D. G.; Jose, F.; McShane, L.; Koppel, G. A. *Tetrahedron Lett.* **1978**, *26*, 2243–2246. (b) Rosenheim, M. L. *Lancet* **1935**, *1*, 1032–1037.
6. Roeding, J.; Teichmueller, E.; Seigfried, B. G. Ger. Offen. 1995 GWXXBX DE 4420727 A1 19951221 *Chem. Abstr.* **1995**, *124*, 185169.
7. Sidot, C.; Christidis, Y. Eur. Pat. Appl. EP 429,316 (Cl. C07D317/54); *Chem Abstr.* **1991**, *115*, 92249g.
8. (a) Kalikar, R. G.; Deshpande, R. S.; Chandalia, S. B. *J. Chem. Technol. Biotechnol.* **1987**, *106*, 49713f. (b) Bauer, K.; Grabe, P. *Common Fragance and Flavor Materials, Preparation, Properties and Uses*; VCH: Lausanne, 1985.
9. (a) Wuthrick, M. F.; Maliverney, C. *Industrial Chemistry Library*; Desmurs, J. R., Ratton, S., Eds.; Elsevier: Amsterdam, 1996; Vol. 8, pp 343–349. (b) Perrin, R.; Scharff, J. P. *Chimie Industrielle*; Masson: Paris, 1993; Vol. 2. pp 841–842.
10. (a) Santaniello, E.; Manzocchi, A.; Farachi, C. *Synthesis* **1980**, 563–565. (b) Nwaukwa, S. O.; Keehn, P. M. *Tetrahedron Lett.* **1982**, *23*, 3135–3138. (c) Beebe, T. R.; Adkins, R. L.; Belcher, A. I.; Choy, T.; Fuller, A. E.; Morgan, V. L.; Sencherey, B. B.; Russell, L. J.; Yates, S. W. *J. Org. Chem.* **1982**, *47*, 3006–3008. (d) Firouzabadi, H.; Sardarian, A. R.; Naderi, M.; Vessal, B. *Tetrahedron* **1984**, *40*, 5001–5004. (e) Sen Gupta, K. K.; Banerjee, A.; Chatterjee, H. *Tetrahedron* **1992**, *48*, 5323–5330. (f) Rigby, W. *J. Chem. Soc.* **1950**, 1907–1913. (g) Stange, H.; Matschiner, H.; Mendow, E.; Schunke, D.; Nauwald, G. Ger. (East) DD 289516 A5 (Cl. C07C47/58, C07C47/565, C07C45/32); *Chem Abstr.* **1991**, *115*, 158717s.
11. Mahapatro, S. N.; Panigrahi, A. K.; Panda, R.; Patro, D. M. *Inorg. Chem.* **1984**, *23*, 4119–4120.
12. Walling, C.; Amarnath, K. *J. Am. Chem. Soc.* **1982**, *104*, 1185–1189.
13. Krumpolc, M.; Rocek, *J. Inorg. Chem.* **1985**, *24*, 617–621.
14. Banerjee, K. K. *Tetrahedron* **1973**, *29*, 1401–1403.
15. Higuchi, M.; Ikeda, I.; Hirao, T. *J. Org. Chem.* **1997**, *62*, 1072–1078.
16. Schouteeten, A.; Christidis, Y.; Vallejos, J. C. EP 47693 A1, Mar. 17 1982; *Chem. Abstr.* **1982**, *96*, 217481z.
17. Fiege, H.; Wedemeyer, K.; Bauer, K.; Mollenken, R. Ger. Offen. 2,824,407 (Cl. C07C65/20), Déc. 13 1979, Appl.; *Chem. Abstr.* **1980**, *92*, 180833e.
18. Singh, C. M.; Dutt, D. K.; Singh, S. B. *J. Indian Chem. Soc.* **1993**, *70*, 190–192.
19. Gupta, K. C.; Kumar, P.; Behari, K. *Bull. Soc. Chim. Fr.* **1987**, *2*, 232–236.
20. Blay, G.; Fernandez, I.; Formentin, P.; Pedro, J. R.; Rosello, L. A.; Ruiz, R.; Journaux, Y. *Tetrahedron Lett.* **1998**, *39*, 3327–3330.
21. Zevaco, T.; Duñach, E.; Postel, M. *Tetrahedron Lett.* **1993**, *34*, 2601–2604.
22. Le Boisselier, V.; Duñach, E.; Postel, M. *J. Organomet. Chem.* **1994**, *482*, 119–123.
23. Le Boisselier, V.; Coin, C.; Postel, M.; Duñach, E. *Tetrahedron* **1995**, *51*, 4991–4996.
24. Coin, C.; Le Boisselier, V.; Favier, I.; Postel, M.; Duñach, E. *Eur. J. Org. Chem.* **2001**, 735–740.
25. Rigby, W. *J. Chem. Soc.* **1950**, 1907–1913.
26. Tymonko, S. A.; Nattier, B. A.; Mohan, R. S. *Tetrahedron Lett.* **1999**, *40*, 7657–7659.
27. Eash, K. J.; Pulia, M. S.; Wieland, L. C.; Mohan, R. S. *J. Org. Chem.* **2000**, *65*, 8399–8401.
28. Komatsu, N.; Taniguchi, A.; Uda, M.; Suzuki, H. *Chem. Commun.* **1996**, 1847–1848.
29. Bhatia, K. A.; Eash, K. J.; Leonard, N. M.; Oswald, M. C.; Mohan, R. S. *Tetrahedron Lett.* **2001**, *42*, 8129–8132.
30. Le Roux, C.; Dubac, J. *Synlett* **2002**, 181–200.
31. Mohammadpoor-Baltork, I.; Aliyan, H.; Khosropour, A. R. *Tetrahedron* **2001**, *57*, 5851–5854.
32. Le Roux, C.; Ciliberti, L.; Laurent-Robert, H.; Laporterie, A.; Dubac, J.; Desmurs, J. R. *Synlett* **1998**, 1249–1251.
33. Robert, H.; Garrigues, B.; Dubac, J. *Tetrahedron Lett.* **1998**, *39*, 1161–1164.
34. Sabitha, G.; Venkata Reddy, E.; Yadav, J. S. *Synthesis* **2002**, 409–412.
35. For a review see for example Suzuki, H.; Ikegami, T.; Matamo, Y. *Synthesis* **1997**, 249–267.
36. Favier;, I.; Giulieri, F.; Duñach, E.; Hébrault, D.; Desmurs, J. R. *Eur. J. Org. Chem.* **2002**, 1984–1988.
37. Chiou, Y. M.; Que, Jr. L. *Angew. Chem.* **1994**, *106*, 1969–1971.
38. Taran, F.; Renard, P. Y.; Bernard, H.; Mioskowski, C.; Frobert, Y.; Pradelles, P.; Grassi, J. *J. Am. Chem. Soc.* **1998**, *120*, 3332–3339.
39. March, J. *Advanced Organic Chemistry*, 3rd ed., Wiley: New York, 1985; p 244.