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Efficient and selective oxidation of aldehydes with dioxygen catalysed by vanadium-containing heteropolyanions



Oxydation catalytique des aldéhydes par les hétéropolyacides à base de vanadium en présence de dioxygène

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ABSTRACT

The heteropolyacids “ $H_{3+n}[PMo_{12-n}V_nO_{40}] \cdot aq$ ” (denoted as HPA- n ; $n = 2, 3, 8$) catalyse the oxidation of aldehydes to carboxylic acids in the presence of dioxygen with very good yields. The effect on the catalytic activity of various parameters such as the precursors, solvent, temperature or catalyst/substrate ratio was examined. The process is particularly selective for linear and aromatic aldehydes. The oxidation of adipaldehyde with dioxygen in mild conditions, in the presence of HPA-2 as a catalyst, leads to the formation of adipic acid together with a significant amount of other byproducts. Thus, several modifications of the catalytic systems have been carried out to improve their selectivity. The effect of co-catalysts was investigated and, among the species tested, complex $Ni(acac)_2$ was found to be the most efficient yielding 60% of adipic acid.

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R E S U M É

Les hétéropolyacides, du type “ $H_{3+n}[PMo_{12-n}V_nO_{40}] \cdot aq$ ” (noté HPA- n ; $n = 2, 3, 8$), catalysent l'oxydation des aldéhydes en acides carboxyliques, en présence du dioxygène, avec de très bons rendements et des sélectivités élevées. Différents paramètres, comme les précurseurs, le solvant, la température ou le rapport catalyseur: substrat ont été examinés. Ce processus catalytique est particulièrement sélectif dans le cas des aldéhydes linéaires et aromatiques. L'adipaldéhyde est oxydé en acide adipique, mais aussi en d'autres sous-produits, en présence d'une quantité catalytique d'HPA-2 et de dioxygène, dans des conditions peu exigeantes. Plusieurs modifications des systèmes catalytiques ont été définies afin de limiter les oxydations subséquentes. Ainsi, l'effet des co-catalyseurs sur l'activité

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catalytique a été étudié dans ce dernier cas. Parmi les co-catalyseurs testés, nous avons montré que le complexe Ni(acac)₂ était le plus efficace, donnant ainsi de l'acide adipique avec un rendement de 60%.

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1. Introduction

Heteropolyacids presenting the Keggin structure, “H_{3+n}[PMo_{12-n}V_nO₄₀]·aq” (denoted as HPA-*n*, with *n* = 2, 3, 4 or 5), have been attracting considerable interest over recent years for acid- or redox-catalysed reactions [1–9]. These HPA-*n* species are easy to prepare from cheap reagents as MoO₃/V₂O₅/H₃PO₄/H₂O₂ [10–12] and display high thermal stability. They are soluble in aqueous media and in organic solvents such as MeCN or AcOH among others.

Regarding their chemical behaviour, HPA-*n* present a noticeable Brønsted acidity and are efficient oxidants, exhibiting fast reversible multielectron redox transformations under rather mild conditions. These properties make HPA-*n* appropriate bifunctional catalysts in both homogeneous and heterogeneous phases. In particular, heteropolyacids are highly suitable catalysts for the oxidative cleavage of cycloalkanones, and protocols for the preparation of keto acids or diacids involving oxidation of α -substituted cycloalkanones (including cyclohexanone) in the presence of dioxygen along with HPA-*n* (*n* = 2, 3, 4 or 5) or copper(II) salts have been described [6,8,10–21]. Treatment of cyclohexanone with HPA-2/O₂/AcOH/H₂O in different solvents leads to the formation of adipic acid as a main product, together with minor amounts of glutaric and succinic acids [10,15]. In addition to oxidative ring opening, gas chromatography-mass spectrometry (GC-MS) coupling experiments indicate the formation of intermediates such as adipaldehyde acid (6-oxohexanoic acid) [15].

Although some oxovanadium complexes are suitable catalysts for such oxidations [13], heteropolyacids display better performances because of the redox properties of the VO₂⁺ species and also to their Brønsted acidity, which is essential for the enolisation process. Here, we develop the transformation of aldehydes into the corresponding carboxylic acids under nearly identical experimental conditions with the idea of exerting some control on the aforementioned side reaction, and we also explore novel properties of HPA-*n* in the oxidation of aldehydes, as these species are important intermediates in synthetic chemistry and widespread pollutants in the human environment [22–24], reason why the development of fast and efficient protocols for their removal is a subject of increasing interest.

Various oxidants such as *t*-BuOOH, H₂O₂ [25–27] and molecular oxygen [28–31] have been used in the catalytic oxidation of aldehydes to the corresponding carboxylic acids. In particular, the oxidation with molecular oxygen is highly attractive because of its low cost/effectiveness ratio and environmentally friendly nature.

Oxidation of aldehydes to carboxylic acids catalysed by polyoxometalates has scarcely been investigated as a

synthetically useful transformation. Hill et al. [32] have studied this process using formaldehyde as a substrate. Formaldehyde constitutes one of the main targets for aerobic oxidation under ambient conditions, as it is suspected of being a carcinogenic agent fairly ubiquitous in indoor air. Its easy, O₂-driven oxidation to the far less toxic formic acid is a process of remarkable interest. Also, some aldehydes can be used for the epoxidation of alkenes and for the Baeyer–Villiger oxidation of ketones to esters. This has been carried out for instance using (NH₄)₅H₄PV₆W₆O₄₀ as a catalyst, with isobutyraldehyde as acylperoxy/peracid precursor [33].

Simple linear aliphatic aldehydes can be selectively oxidised with molecular oxygen but, in contrast, 2- and 4-methoxybenzaldehydes constitute a family of substrates that is difficult to oxidise in homogeneous catalytic systems. As an example, a study performed by Shi and Ji [34] on the oxidation of these types of substrates leads to low yield (<7%) of the corresponding carboxylic acids and demonstrate that strong electron-donating groups induce the formation of the corresponding phenols instead through the migration of the aromatic group.

Other groups have also recently reported the oxidation of aromatic aldehydes to the corresponding carboxylic acids by aqueous H₂O₂ catalysed by VO(acac)₂ [35] or H₅PV₂Mo₁₀O₄₀ [36]. Nevertheless, from an industrial point of view the use of oxovanadium together with H₂O₂ is highly dangerous as the reaction is exothermic and, in some cases, it becomes explosive. Thus, new polyoxometalates of the ϵ -Keggin structure, with formula [Mo₁₂O₃₉(μ -2-OH)₁₀H₂{X^{II}(H₂O)₃}]₄ (X = Ni, Co, Mn and Cu), have been synthesised and used as heterogeneous catalysts for the aerobic oxidation of aldehydes into the corresponding carboxylic acids. For linear aliphatic and benzylic aldehydes the reactions are selective but some substrates display low selectivity because of the formation of formate esters through Dakin-type reactions or also to allylic oxidations that can lead to decarboxylation and formation of ketones or allylic alcohols depending on the specific substrate [37].

In this article, we report the ability of heteropolyacids to catalyse the transformation of aldehydes into carboxylic acids in the presence of molecular oxygen, and we also investigate the role of novel low-cost triggers. The effects of solvent, temperature, reaction times and the presence of other precursors are considered.

2. Experimental section

2.1. Chemicals

The heteropolyacids HPA-*n* (*n* = 2, 3, 8) were prepared according to previously described oxoperoxy procedures [10–12] and were soluble in all solvents.

All reagents and solvents used in this work were purchased from Aldrich, Merck, Prolabo or Janssen Chimica, and they were used without further purification.

2.2. Catalytic tests

All catalytic tests were carried out using Schlenk flasks (20 mL), which were attached to a vacuum line with a manometer and a gas inlet. In a typical experiment, the Schlenk was charged with 5.0 mL of the corresponding solvent (CH₃CN, H₂O, CH₃OH, CH₃COOH or a mixture of CH₃COOH/H₂O) and HPA-*n* (0.02 mmol). The substrate (5.0 mmol) was then added and the vessel was immersed in an oil bath preheated at 70 °C. O₂ was introduced at atmospheric pressure and the mixture was stirred magnetically for the time indicated in the tables. Three parallel catalytic experiments were carried out for each test.

The addition of biphenyl as an internal standard at the end of the experiment (except for adipaldehyde and its ester, for which we used methyl heptanoate) permitted to quantify the products using a Shimadzu GC-2010 gas chromatograph equipped with a Chiraldex G-TA column (30 m length × 25 mm diameter) and a flame ionisation detector. GC conditions: initial temperature, 60 °C for 5 min; ramp rate, 10 °C min⁻¹; final temperature, 170 °C; injection temperature, 250 °C (split mode); detector temperature, 250 °C (detector FID); carrier gas, He, hydrogen and air.

3. Results and discussion

3.1. Influence of the type of catalyst

In this section, we considered first the oxidation of heptanal along with the oxidation of adipaldehyde acid and its corresponding ester. Finally, we carried out the study of the effect exerted by different cocatalytic systems in the oxidation of 6-oxohexanoic acid.

The results obtained for the oxidation of heptanal with selected precursors and/or reaction times are summarised in Table 1. As can be observed, the heteropolyacids of the series “H_{3+n}[PMo_{12-n}V_nO₄₀]·aq” (HPA-*n*, *n* = 2, 3, 8; entries 1–4) show an excellent catalytic behaviour in the oxidation of heptanal with dioxygen. For instance, the use of HPA-2 as a catalyst (Table 1, entries 1 and 2) leads to almost quantitative conversion and excellent yield of heptanoic acid even when using 0.02 mmol of a catalyst. The systems based on HPA-3 (Table 1, entry 3) and HPA-8 (Table 1, entry 4) display similar performance, with excellent selectivity values for the corresponding acid.

Furthermore, we can observe that the use of HPA-8 instead of HPA-*n* (*n* = 2, 3) increases the reactivity as the reaction is completed within only 4 h. This improved performance can be correlated with the higher Brønsted acidity of the HPA-8 catalyst.

It must be noticed here that the work of Matveev et al. [38] on polyanions “H_{3+n}[PW_{12-n}V_nO₄₀]·aq” emphasises that the reduced forms of HPA-*n* with *n* = 1, 2 would be very difficult to reoxidise by molecular oxygen, whereas those with *n* ≥ 4 are rapidly reoxidised even at 0 °C. To our knowledge, no similar studies on molybdenum analogues

Table 1

Oxidation of heptanal promoted by various precursors.^a

Entry	Precursor (mmol)	Time (h)	Conversion ^b (%)	Acid yield ^b (%)
1	HPA-2 (0.075)	12	99	98
2	HPA-2 (0.020)	12	99	98
3	HPA-3 (0.020)	8	99	98
4	HPA-8 (0.020)	4	99	98
5	H ₃ [PMo ₁₂ O ₄₀]·aq (0.062)	24	82	80
6	H ₃ [PW ₁₂ O ₄₀]·aq (0.062)	24	82	78
7	MoO ₂ (acac) ₂ (0.062)	24	98	98
8	VO(acac) ₂ (0.020)	24	97	97
9	VOSO ₄ ·5H ₂ O (0.020)	24	98	98
10	VOSO ₄ ·5H ₂ O/H ₃ PO ₄ (0.075)/(0.150)	24	90	90
11	V ₂ O ₅ /H ₃ PO ₄ (0.075)/(0.15)	24	80	70
12	MoO ₃ /H ₃ PO ₄ (0.375)/(0.150)	24	63	60
13	VOSO ₄ ·5H ₂ O/MoO ₃ /H ₃ PO ₄ (0.075)/(0.375)/(0.150)	24	98	96
14	V ₂ O ₅ /MoO ₃ /H ₃ PO ₄ (0.075)/(0.375)/(0.150)	24	80	70
15 ^c	“Q ₅ [PMo ₁₀ V ₂ O ₄₀]·aq” (0.020)	24	0	0
16	–	24	0	0

^a General procedure: heptanal (5 mmol), AcOH/H₂O (4.5 mL/0.5 mL), *T* = 70 °C, *p*(O₂) = 0.1 MPa, HPA-2 = “H₃[PMo₁₀V₂O₄₀]·aq”.

^b Conversions and yields were determined by GC analysis.

^c Q = (*n*-Bu)₄N⁺, C₅H₅N⁺(CH₂)₁₅CH₃.

have been carried out in the solvents that we use, but a parallel behaviour can be expected for the series of HPA-*n* catalysts. The initial solutions undergo a colour change from orange to blue-green and finally orange-brown that is consistent with the variation in the oxidation state of vanadium [V(V)/V(IV)] and, consequently, the overall reaction can be interpreted in terms of a vanadium-catalysed process assisted by dioxygen [15]. Blank experiments under the same conditions, in the absence of the catalyst, did not display any substrate conversion.

Vanadium(IV) acetylacetonate or vanadyl sulphate (Table 1, entries 8 and 9) also display catalytic activity under aerobic conditions leading to high yields of heptanoic acid, although after longer reaction times. These observations clearly show that precursors based on vanadium species simpler than HPA-*n* might be used in the oxidation of aldehydes in the presence of dioxygen but, dissimilarly to the case of the heteropolyacid species, vanadium in entries 8 and 9 is introduced at an intermediate degree of oxidation. Consequently, the latter must be oxidised to generate an active catalytic species in accordance with the HPA-*n* mechanism in solution (vide infra).

Two molybdenum-based precursors (Table 1, entries 5 and 7) were tested and display catalytic activity, although the recycling of the Mo(VI) species for both of them was difficult because of the formation of reduced heteropolyanions [1–8] or “insoluble molybdenum(V) blues”. The comparison of the catalytic activity of heteropolyacids versus their onium salts (Table 1, entry 15) shows that the former are active catalysts whereas the latter do not show any activity. Thus, the Brønsted acidity of the HPA-*n* seems to be a key parameter of the catalytic system, probably favouring in some way the reoxidation of the reduced catalyst. The lack of activity when using the corresponding salts can also be explained by the well-known decrease in

the redox potential of vanadium(V) in parallel with a reduction in the Brönsted acidity of the species [15].

The binary V(IV) and V(V)/PO₄³⁻ systems (Table 1, entries 10 and 11) are also able to activate molecular oxygen, whereas the molybdenum-based MoO₃/H₃PO₄ binary system (Table 1, entry 12) is less active. The addition of molybdenum trioxide to the vanadium binary mixtures improves the performance of the VOSO₄·5H₂O/H₃PO₄ catalytic system (compare entries 13 and 10), whereas the V₂O₅/H₃PO₄ system does not display significant modifications. These data suggest that, in the case of the VOSO₄·5H₂O/H₃PO₄ system, the HPA-*n* species can be formed in situ from the VOSO₄·5H₂O//MoO₃/H₃PO₄ mixture thus avoiding the tedious preparation of heteropolyacids with ether extraction.

We describe next additional studies performed using the HPA-2 heteropolyacid as it is most commonly used in our catalytic tests, and it will also allow us to compare the results with those obtained for the oxidation of cyclohexanone.

3.2. Effect of the solvent

Preliminary studies with analogous catalytic systems have emphasised the key role of the solvent in this type of process [15,16,39]. Thus, the influence of various solvents on the oxidation path of heptanal was tested using pure dioxygen as an oxidant and HPA-2 as a catalyst, and the results are presented in Table 2. When using toluene (Table 2, entry 1), the yield of acid obtained was up to 91%. However, the best conditions leading to heptanoic acid were found using THF as a solvent at 40 °C (Table 2, entry 2), yielding almost quantitative conversion (99%) and excellent selectivity (99%) for the acid product. It seems that THF facilitates the oxidation of V(IV) to V(V) and also increases the solubility of dioxygen, hence improving the catalytic activity even at relatively low temperatures. Nevertheless, we shall note that the α -positions of ethers can be attacked by dioxygen and, besides, THF is damaging from an environmental point of view and must be handled under strict safety conditions.

Table 2

Effect of a solvent on the catalytic oxidation of heptanal using HPA-2 as a catalyst.^a

Entry	Solvent (mL)	T (°C)	Conversion ^b (%)	Yield ^b (%)
1	Toluene (5)	70	91	78
2 ^c	THF (5)	40	99	99
3	CH ₃ CN (5)	70	99	97
4 ^d	MeOH (5)	60	13	12
5	–	rt	100	95
6	AcOH (5)	70	100	95
7	H ₂ O (5)	70	49	46
8	AcOH/H ₂ O (4.5/0.5)	70	99	98
9	AcOH/H ₂ O (4/1)	70	45	43
10	AcOH/H ₂ O (3/2)	70	43	42
11	AcOH/H ₂ O (2.5/2.5)	70	42	37

^a Heptanal (5 mmol), HPA-2 (0.02 mmol), *t* = 12 h, *p*(O₂) = 0.1 MPa.

^b See Table 1.

^c Four hour.

^d Twenty-four hour, the product is identified as methyl heptanoate.

Good conversions of heptanal to heptanoic acid (99%) were afforded in acetonitrile (Table 2, entry 3), whereas in methanol (entry 4) the system only reaches 13% conversion in 24 h. This could be because of the ability of MeOH to form hydrogen bonds that may suppose a drawback for the catalytic activity.

In the absence of a solvent (entry 5) complete conversion was obtained without a considerable reduction in the yield of the reaction, which was around 95%. In pure acetic acid (entry 6), excellent yields of heptanoic acid (95%) were also obtained. We note that, in this latest case, the reaction was highly exothermic. On the other hand, when using water as a solvent (entry 7), only moderate activity with 49% conversion and 46% yield is obtained, which is a very interesting result. From an environmental point of view the use of water is always desirable because it fulfils both environmental and safety requirements. However, heptanal and water are immiscible at room temperature, and this can be partially responsible for the moderate degree of conversion obtained.

On the basis of the previous studies [15,16,39], we have carried out the catalytic oxidation of heptanal in AcOH/H₂O mixtures, which are among the most convenient media for controlling these reactions. The best result has been obtained for the AcOH/H₂O = 4.5/0.5 (v/v) composition (Table 2, entry 8), with a 98% yield of heptanoic acid after 12 h. Even if the initial rates are higher for compositions with a lower AcOH/H₂O ratio (4/1, 3/2 or 2.5/2.5 (v/v), see entries 9–11), the final conversions after 12 h drop dramatically to values less than half of that obtained with the AcOH/H₂O = 4.5/0.5 system.

In these assays, the solvent effect could probably be explained by the distinct solubility of dioxygen, with the best performance displayed by systems with solvents having higher O₂ mole fraction [40].

Encouraged by the remarkable results obtained with the previously mentioned reaction conditions, and to generalise this new protocol, we used the HPA-2/O₂ catalytic system in the oxidation of other aldehydes as discussed subsequently. The tests were carried out using an AcOH/H₂O = 4.5/0.5 (v/v) mixture as a solvent.

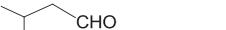
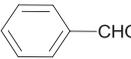
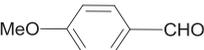
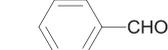
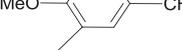
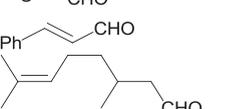
3.3. Oxidation of other aldehydes

HPA-2 was found to be highly active towards the oxidation of both aliphatic and aromatic aldehydes to the corresponding acids with dioxygen in AcOH/H₂O = 4.5/0.5 (v/v) mixtures. The results obtained for the different substrates are gathered in Table 3.

The performance observed for linear aldehydes (Table 3, entry 1) is not conditioned by the chain length as complete conversion is obtained for octanal, with a selectivity of 99%. Among the aliphatic aldehydes tested, those with branched carbon chains were found to react at a slower rate than aldehydes with linear carbon chains (compare for instance entries 2, 9 or 10 with entry 1).

The oxidation of *iso*-valeraldehyde (Table 3, entry 2) afforded *iso*-valeric acid as the main product. Under these conditions, benzaldehyde (entry 3) also leads to almost quantitative conversion and excellent yield of benzoic acid. However, for substituted aromatic substrates containing

Table 3Oxidation of aldehydes to carboxylic acids by HPA-2/O₂/AcOH–H₂O system.^a

Entry	Aldehyde	Time (h)	Conversion ^b (%)	Acid yield ^b (%)
1		12	99	98
2		24	99	98
3		24	97	97
4		48	30	26
5		48	26	22
6		48	20	20
7		48	36	34
8		12	98	97
9		24	99	88
10		24	72	50

^a Aldehyde (5 mmol), HPA-2 (0.02 mmol), AcOH/H₂O (4.5 mL/0.5 mL), 70 °C, p(O₂) = 0.1 MPa.^b Conversions and yields were determined by GC analysis. Products were identified by GC-MS.

electron-donating substituents (entries 4–7) the reaction rate dramatically decreases, reaching up to 36% conversion in 48 h. These observations clearly show that such strong electron-donating groups do not favour the oxidation of aldehydes to carboxylic acids but rather lead to the generation of the corresponding phenols through the migration of the aromatic group [34]. The heteroatom-containing aldehyde furan-2-carboxaldehyde produced the furan-2-carboxylic acid in good yield (entry 8).

On the other hand, the oxidation of *trans*-cinnamaldehyde and citronellal (3,7-dimethyl-6-octenal) was evaluated under the oxidative conditions of our catalytic system (Table 3, entries 9 and 10) with the aim of exploring the chemoselectivity of HPA-2, as these substrates contain an aldehyde functionality together with an epoxidisable olefinic double bond. The results obtained show that the oxidation of *trans*-cinnamaldehyde (Table 3, entry 9) is selective towards the formation of *trans*-cinnamic acid (88%), but oxidative scission of the conjugated carbon–carbon double bond takes place in parallel, resulting in the generation of minor side products, which were identified as benzaldehyde (4%) and benzoic acid (6%). The oxidation of citronellal displayed only a moderate selectivity for the corresponding citronellic acid (Table 3, entry 10).

In the catalytic oxidation by dioxygen, one of the main uncertainties is whether oxidation proceeds via a non-radical reaction mechanism or, alternatively, via a radical-mediated pathway. To shed some light on the mechanism followed, the oxidation of heptanal was carried out in the presence of 2,6-di-*tert*-butyl-*p*-cresol as a radical scavenger. The reaction was inhibited and only 18% of heptanoic

acid was obtained within 24 h, clearly confirming the occurrence of a radical mechanistic pathway. The poor effectiveness on the oxidation of substituted aromatic aldehydes is also in agreement with such a radical mechanism because these types of aldehydes can also act as radical scavengers.

The high selectivity observed in the reaction with heptanal and the stability of the product obtained led us to test this aldehyde as a substrate to evaluate the recyclability of the HPA-2 catalytic system. It is known that the recovery of

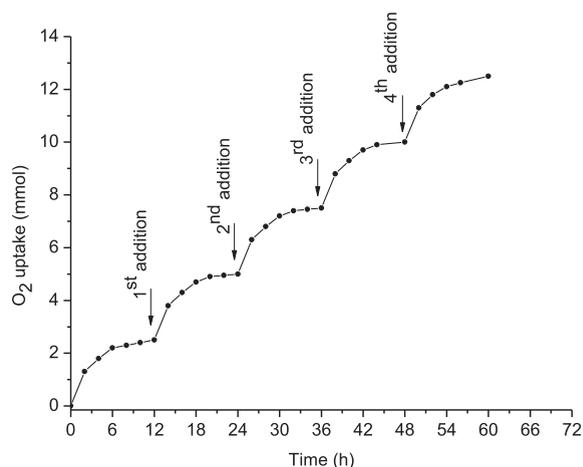
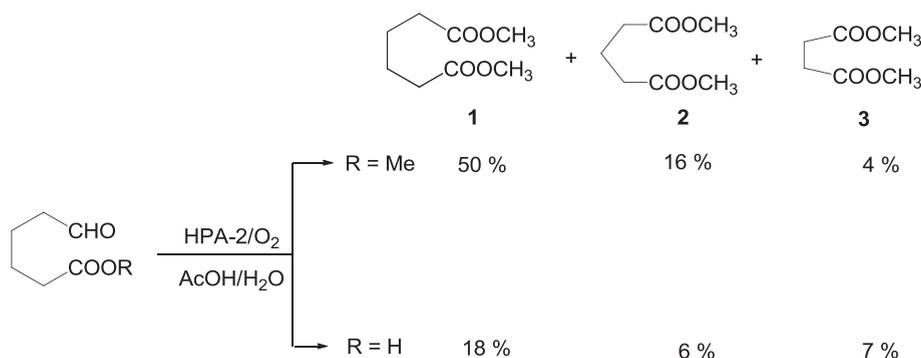


Fig. 1. Reuse of the HPA-2 catalyst in the oxidation of heptanal by dioxygen through five successive runs. Conditions: heptanal (5 mmol), AcOH/H₂O (4.5 mL/0.5 mL), $t = 12$ h per run, p(O₂) = 0.1 MPa.



Scheme 1. Catalytic oxidation of 6-oxohexanoic acid and methyl 6-oxohexanoate.

the catalyst in a homogeneous medium is challenging, and the solubility of HPA-2 either in organic solvents or in the mixture of acetic acid and water makes difficult the design of a procedure to extract it from the reaction medium. Thus, we carried out successive catalytic runs by sequential addition of substrate loads at the reaction vessel, without isolating the catalyst or the heptanoic acid product at the end of each run (Fig. 1).

Under these conditions, we have shown that the uptake of dioxygen resumes as soon as a new load of substrate is introduced. Throughout consecutive additions, the consumption profiles of the oxidant $n(\text{O}_2) = f(\text{time})$ and the amount of O_2 consumed are relatively reproducible. The average dioxygen uptake/substrate ratio consumed was 0.5 mmol/mmol. It should be noted that after four successive reuses, the amount of heptanoic acid is four times that obtained after the first test, then evidencing that the catalyst is stable through the whole experiment. A major approach to HPA- n reuse shall be based on chemical immobilisation of the catalyst in organic or inorganic support. This work is in progress.

We have reported that, during the oxidation of cyclohexanone, adipaldehyde acid was formed as intermediate, and we suggest that the byproducts formed in the reaction arise predominantly from the degradation of this intermediate. Thus, 6-oxohexanoic acid and its corresponding methyl ester were prepared [41] and oxidised under the same reaction conditions by the HPA-2/ O_2 system (Scheme 1).

Comparative studies of the reactivity of 6-oxohexanoic acid ($\text{R}=\text{H}$) and its corresponding ester, methyl 6-

oxohexanoate ($\text{R}=\text{Me}$), show that, in all experiments, the oxidation reaction leads to the formation of dimethyl adipate (**1**) as main product, together with dimethyl glutarate (**2**) and dimethyl succinate (**3**).

To complement the previous assays, the use of other metal complexes as inorganic redox cocatalysts was carried out with the idea to prevent or minimise the formation of byproducts **2** and **3**, and the results are given in Table 4. Reactions were carried out in an $\text{AcOH}/\text{H}_2\text{O}$ mixture as reaction medium.

The cocatalysts tested are tris-acetylacetonate $\text{M}(\text{acac})_3$ species with $\text{M}=\text{Fe}$, Co and Ru , and also nickel(II) acetylacetonate. As can be observed, only two of the catalytic systems, HPA-2/ $\text{Co}(\text{acac})_3$ and HPA-2/ $\text{Ni}(\text{acac})_2$ (entries 2 and 5, respectively), improve the yield of dimethyl adipate in a significant amount when compared to the HPA-2 system itself (Table 4, entry 1), whereas HPA-2/ $\text{Fe}(\text{acac})_3$ and HPA-2/ $\text{Ru}(\text{acac})_3$ (entries 3 and 4) exert only a slight effect on the yield of adipic acid.

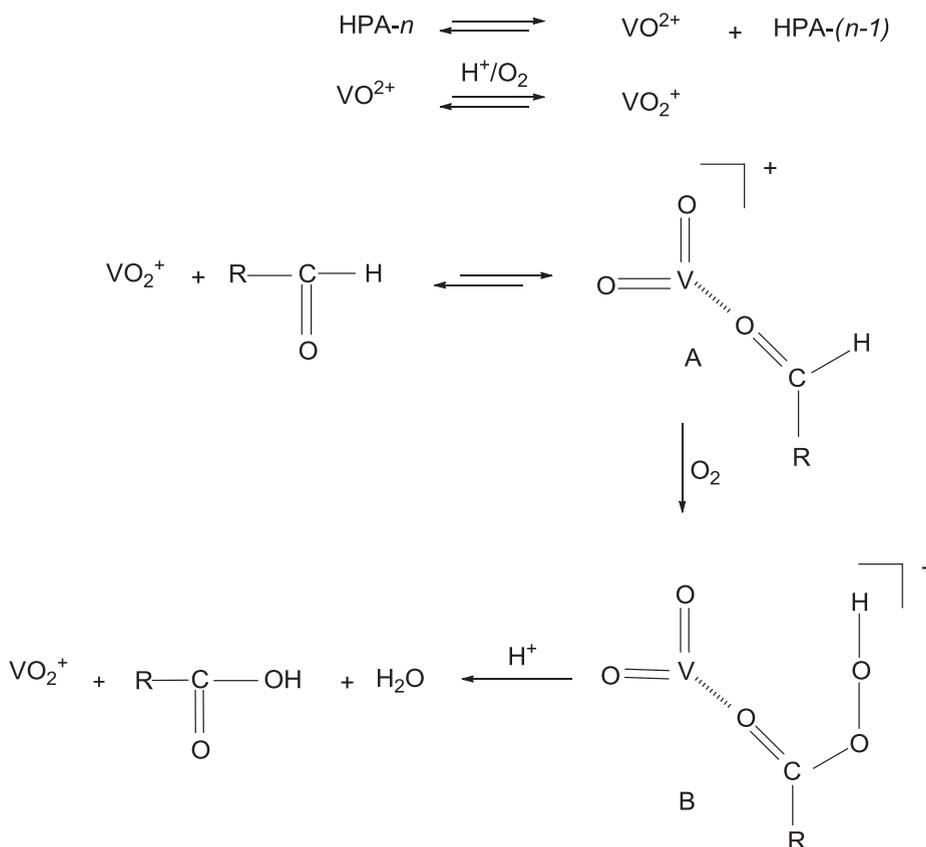
The HPA-2/ $\text{Ni}(\text{acac})_2$ system is one of the best catalysts for the oxidation of 6-oxohexanoic acid, with 60% yield of **1** after only 8 h of the reaction (Table 4, entry 5). The presence of Ni^{2+} results in the enhancement not only of the selectivity for dimethyl adipate but also of the overall catalytic performance, with 98% conversion within half of the time needed for the HPA-2 catalytic system. These results probably suggest that there is a synergistic effect between $\text{Ni}(\text{acac})_2$ and the P–Mo–V containing heteropolyacid to reoxidise the reduced catalyst under the conditions used. Thus, Ni^{2+} could assist the regeneration of the V(V) species with high efficiency. This synergistic effect was much less

Table 4
Aerobic oxidation of adipaldehyde acid catalysed by HPA-2 with different cocatalysts.^a

Entry	Cocatalyst (mmol)	Time (h)	Conversion ^b (%)	Yield ^b (%)		
				1	2	3
1	—	16	99	50	16	4
2	$\text{Co}(\text{acac})_3 \cdot 4\text{H}_2\text{O}$	16	90	56	11	3
3	$\text{Fe}(\text{acac})_3 \cdot 4\text{H}_2\text{O}$	24	72	52	16	4
4	$\text{Ru}(\text{acac})_3 \cdot 4\text{H}_2\text{O}$	24	70	52	20	4
5	$\text{Ni}(\text{acac})_2$	8	98	60	9	2

^a Adipaldehyde acid (5 mmol), HPA-2 (0.02 mmol), cocatalyst (0.03 mmol), $\text{AcOH}/\text{H}_2\text{O}$ (4.5 mL/0.5 mL), 70 °C, $p(\text{O}_2) = 0.1$ MPa.

^b Conversion and yields were determined by GC analysis after the addition of an ether solution of diazomethane to the crude mixture using methyl heptanoate as internal standard. Products were identified by GC-MS.



Scheme 2. Proposed mechanism for the oxidation of aldehydes catalysed by HPA-2.

significant when a combination of HPA-2 and $\text{M}(\text{acac})_3$ cocatalyst ($\text{M}=\text{Fe}$, Co or Ru) was used. It is still unclear which is the role of $\text{Ni}(\text{acac})_2$ in the catalytic process. Moreover, the catalytic performance of “HPA-2/ $\text{Ni}(\text{acac})_2/\text{AcOH}-\text{H}_2\text{O}/\text{O}_2$ ” is influenced by the pressure of dioxygen. Presumably, in the presence of an excess of dioxygen adipaldehyde acid undergoes oxidative dehydrogenation at a faster rate than that of its conversion to adipic acid. The effect of this parameter over the conversion and selectivity values is now under study to further improve the catalytic performance of the HPA-2/ $\text{Ni}(\text{acac})_2/\text{O}_2$ system.

3.4. Proposed mechanism for the oxidation of aldehydes

We would attempt to rationalise the different results by proposing a valid general mechanism for all the types of aldehydes tested (Table 3), taking into account the different experimental facts and data already gathered in the bibliography. A plausible reaction path is drawn up in Scheme 2.

HPA- n in solution is an extremely complex system. Many studies have shown that, at low pH, HPA- n solutions contain a solvated *cis*-dioxo cation $[\text{VO}_2(\text{H}_2\text{O})_4]^+$, usually written as VO_2^+ [5,6,42–45]. In the presence of an organic substrate, the V(V)/V(IV) redox process takes place unavoidably. In acidic medium and in the presence of dioxygen, the major part of V(IV) is converted to V(V). The final mechanism proposed by Brégeault et al. [17] in the

case of 2-hydroxycyclohexanone, and regardless of the vanadium precursor(V) tested including HPA-3 [16], suggests a purely homolytic mechanism with the involvement of vanadium(IV) and (V) forms. In our case, we also believe that VO_2^+ is the key species in the oxidation of aldehydes to their corresponding acids under dioxygen atmosphere.

The results suggest that (i) VO_2^+ is bound to the aldehyde substrate to form the intermediate cationic complex (A), which could interact with O_2 , in a vanadium-assisted pathway, to afford (B); (ii) the peracid intermediate undergoes vanadium-assisted decomposition to yield the carboxylic acid together with H_2O , and restoring the vanadium cation VO_2^+ .

4. Conclusion

We have shown that the catalytic systems “HPA- n ($n=2, 3, 8$)/ $\text{O}_2/\text{solvent}$ ” can efficiently induce the oxidation of aldehydes and adipaldehyde acid to the corresponding carboxylic acids or diacids respectively, with improved performances in comparison to other precursors. When using linear and aromatic aldehydes the reactions are selective for the acid product. This homogeneous catalytic process is the first example of aldehyde oxidation in solution using Keggin-type heteropolyacids. Furthermore, the catalyst can be reused for at least four times without any loss of catalytic activity. We suggest that the high

effectiveness of HPA-*n* is primarily because of the formation of VO₂⁺ species and also to its strong Brønsted acidity, with the selectivity and conversion values depending on the solvent. On the other hand, the catalytic oxidation of adipaldehyde acid was slightly improved via the addition of Ni²⁺ as a cocatalyst into the reaction mixture. This method offers several advantages including excellent yields of the products, safe handling, experimental simplicity and environmentally friendly conditions. Further applications of this catalytic system to other oxidation processes are under investigation, with a particular focus on prochiral aldehydes. Research will also be addressed towards the development of clays-supported HPA-*n* heterogeneous catalysts and the comparison of their performances with those of the described homogeneous systems with “PMoV” species.

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