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Allylic oxofunctionalization of cyclic olefins with homogeneous and heterogeneous catalysts

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Abstract

Heterogeneous catalysis and heterogenization of homogeneous catalysts are catch phrases of modern chemistry. Here we attempt to trace the development from homogeneous to heterogeneous catalysis in the allylic oxofunctionalization of cyclic olefins. The utility of this oxidative conversion is highlighted succinctly in the allylic oxidation of isophorone to ketoisophorone, which is a useful intermediate in the synthesis of carotenoids and fragrances. Competitive allylic oxidation and epoxidation are discussed briefly for the structurally simpler cyclohexene. Allylic oxidation of bicyclic α-pinene to verbenone is used as an example to illustrate that upon progressing to more complex cyclic olefins, competitive isomerization and structural rearrangements often result in very poor selectivity to the desired α,β-unsaturated ketone. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: Cyclic olefins; Allylic; Oxofunctionalization; Isopherone

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1. Introduction

Awareness of environmental issues has proven a potent driving force in the development of environment friendly processes and technologies in the chemical industry [1,2]. This has manifested itself in a determined effort, on behalf of the industry, to develop catalytic processes which obviate waste production, i.e. solving the problem at the beginning and not dealing with waste disposal later [3]. As a consequence of the inherent advantages of heterogeneous reagents, much effort has been directed towards the development of heterogeneous processes and the heterogenization of known active homogeneous catalysts [4]. For similar reasons, selective catalytic oxidation of organic compounds utilizing heterogeneous catalysts is proving more important in organic synthesis [5].

2. Scope of article

2.1. Allylic oxidation versus epoxidation

Allylic oxofunctionalization is defined, for the purpose of this article, as the preparation of α,β-unsaturated ketones of cyclic olefins using primarily dioxygen as oxidant. Allylic oxidation and epoxidation are two competing processes both in vivo and in vitro [6]. Typically, allylic oxidation products are found when hydrogen abstraction is the dominant reaction. Electrophilic attack at the double bond of the cyclic olefin leads to epoxidation or ring cleavage [7]. In contrast to epoxidation, allylic oxidation

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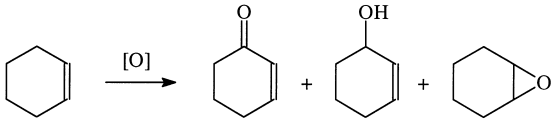
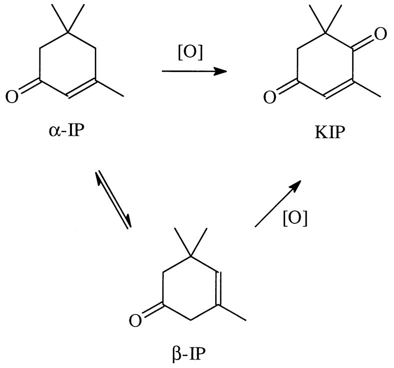


Scheme 1.

retains the olefinic functionality in the product allowing further useful transformations. Allylic oxidation is a process involving free radicals and is most likely to occur in the presence of low oxidation state transition metal species [6]. On the other hand, epoxidation is generally associated with oxometallic species such as Ru(VIII), Cr(VI), and Mn(V) [8]. In practice, however, allylic oxidation and epoxidation are often competitive processes in the oxidation of cyclic olefins and frequently both processes occur simultaneously. The dominance of one or the other process is also heavily dependent on the nature of olefin used and the relative stability of the intermediate allylic radical formed [6].

2.2. Choice of cyclic olefin

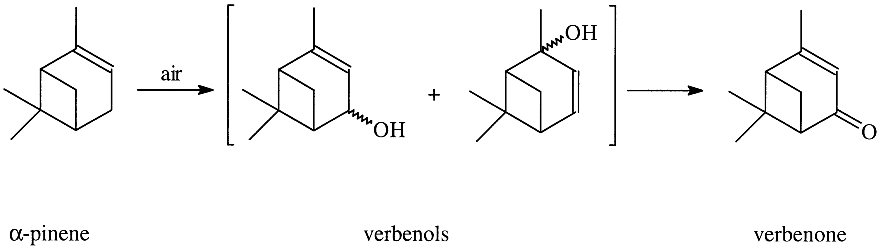
Cyclohexene, one of the structurally simpler cyclic olefins, provides the opportunity to study the effects of catalyst, oxidant and solvent, which lead to allylic oxidation and/or epoxidation (Scheme 1). This article refers only briefly to recent new developments with regard to cyclohexene oxidation. More specifically, we will concentrate on the industrially relevant oxidation of isophorone (IP) to ketoisophorone (KIP) (Scheme 2) which falls within the confines of the fine chemicals industry. KIP is known as a key intermediate for the synthesis of carotenoids [9–11] and flavoring substances [12–15]. Catalytic systems which facilitate the direct oxidation of α-IP to KIP are particularly attractive since they offer a “single-step” synthesis, avoiding the need for the isomerization of α- to β-IP [16]. Isomerization of α-IP to β-IP is a thermodynamically unfavorable process involving disruption of the conjugated alkene–ketone system in α-IP and thereby increasing the energy of the β-IP molecule. Despite this disadvantage the greatest success has been achieved in liquid phase oxidations of β-IP. Oxidation of cyclic olefins is often accompanied by double bond isomerization, oligomerization and non-selective reactions, which are exemplified here in the oxidation of isophorone.



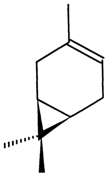
Scheme 2.

To illustrate the effects of ring size and number of rings in the allylic oxidation of more complicated cyclic olefins we briefly describe allylic oxidations of the readily available terpene, α-pinene (Scheme 3). Oxidations of such bicyclic systems clearly demonstrate how heavily the product distribution depends on the nature of the olefin. Historically, the autoxidation of pinenes has been known for two centuries [17], however, high selectivity to a single product in the catalytic oxidation of pinenes has alluded the chemist. Verbenone, an important allylic oxidation product from pinenes, is considered a suitable precursor in the preparation of taxol, which has recently been introduced as a therapeutic agent. In theory therefore, a judicious choice of the appropriate pinene enantiomer, both chiral forms being available, should lead to a suitable intermediate for the asymmetric synthesis of taxol [18,19].

While the influence of ring strain in oxidation has not been directly investigated for α-pinene, a comparative study of the oxidation of carene and α-pinene has appeared [20]. Autoxidation of carene and α-pinene in the presence of homogeneous transition metal catalysts yielded allylic oxidation and epoxidation products, respectively. It was proposed that molecular flexibility of the cyclic skeleton in carene allowed the molecule to align the allylic hydrogen and double bond in the same plane, thus facilitating hydrogen abstraction and leading to allylic oxidation products. The authors concluded that allylic oxidation of α-pinene was hindered by the lack of conformational flexibility of this molecule in accommodating the transition state necessary for H-abstraction.



Scheme 3.


carene

2.3. Choice of oxidant

Utilizing molecular oxygen as oxidant is particularly attractive for economic reasons. In addition, air and oxygen/nitrogen mixtures as oxidants in the presence of true heterogeneous catalysts fulfill the demands of non-polluting oxidizing reagents. When such systems can be employed, replacing for example highly toxic chromium oxidizing reagents [21], the benefits to the community are clear. Several excellent books describing the activation of molecular oxygen [22], details of structurally characterized dioxygen-metal complexes [23] and autoxidation [24] are available. Alternative, and still attractive, oxidants are hydrogen peroxide and *tert*-butylhydrogen peroxide (TBHP). In the production of commodity chemicals the price of oxidant may determine the economic viability of the entire process. In the synthesis of fine, specialty or pharmaceutical chemicals the value of reactant and product are often orders of magnitude higher than that of hydrogen peroxide or TBHP, and the crucial parameter in optimizing a process is usually the yield (or selectivity at reasonably high conversion).

2.4. Recent trends in catalyst development for liquid phase oxidations

Recent trends in liquid phase oxidations fall into two broad categories: (i) development of new transition metal substituted redox molecular sieves (silicalites, zeolites, aluminophosphates and silicoaluminophosphates) [25,26] and (ii) immobilization of known homogeneous oxidation catalysts on the surface and in the cavities of suitable hosts such as zeolites and structurally tailored sol–gel materials [27–29]. Heterogenized systems usually display lower activities in comparison with their homogeneous counterparts, which is partly due to diffusion limitations in the solid material. However, in some cases higher activities have been achieved as a result of site isolation phenomena (i.e. avoiding catalyst deactivation) [4].

It must be kept in mind, however, that the development of truly heterogeneous catalysts has been troublesome and leaching of metal ions/metal complexes from the solid in liquid phase oxidations has often led to competing homogeneous and heterogeneous processes [30]. Heterogeneous gas phase oxidation, although technically more demanding, provides a unique and convenient solution to many of the current challenges encountered in liquid phase oxidations. Unfortunately, the limited volatility and thermal stability of complex molecules hinders the general application of gas/solid type reactors for oxidation in fine chemistry.

3. Oxofunctionalization of cyclic olefins in the liquid phase

3.1. Homogeneous first row transition metal salts and transition metal salt/pyridine systems

Previous studies of the allylic oxidation of olefins have generally focused on the use of transition metal compounds [6]. In particular, cobalt and manganese are commonly used in autoxidation catalysis. In in-

Table 1
Oxidation of β-IP to KIP using various catalysts and molecular oxygen as oxidant

Catalyst	Catalyst/β-IP ratio (wt.%)	Time (h)	Temperature (°C)	KIP yield (%)	Reference
Co, Mn, Pb acetates and V, Cr(III), Cu, Fe(III)(acac) complexes with pyridine	2.5–10	1–3.5	40–70	68–91	[36]
$Cu(acac)_2$ py	–	7	75	84	[40]

dustrial processes, cobalt and manganese acetates with bromide as modifier have been used for the partial oxidation of methyl-substituted aromatics, as in the conversion of *p*-xylene to terephthalic acid [31]. Cobalt acetate (cobalt acetate/modifier system) has been the basis for patents describing the oxidation of pinenes and to a lesser extent isophorone.

With a few exceptions the literature concerning oxidation of α- and β-IP to KIP is limited to patents describing liquid phase oxidation mediated by first row transition metal and molybdenum based catalysts. Liquid phase oxidations of α-IP employing simple salts of first row transition metals as catalysts typically gave KIP in poor yields (ca. 21%) [32,33]. Long reaction times (i.e. days rather than hours) at high temperatures (>100°C) are characteristic of these autoxidations. Oxidation of α-IP mediated by transition metal salts (Cr, Mn, Fe, Co, Cu) at more moderate temperatures in the presence of pyridine and H_2O_2 afforded ca. 50% yields of KIP [34]. Extended reaction times did not dramatically improve KIP yields in these systems.

Oxidation of β-IP is considered indirectly as oxidation of α-IP involving a two-step process, isomerization followed by oxidation, leading to the desired allylic oxidation product KIP (Scheme 2). KIP is more readily available via oxidation of β-IP, probably as a result of deconjugation of the eneone system in β-IP (Table 1). Oxidation of β-IP, mediated by cobalt and manganese acetates in the presence of pyridine and under mild conditions gave KIP in good yields (68–85%). A vanadium catalyst, $V(acac)_3$ with pyridine, showed enhanced activity and provided KIP in 91% yield [35,36]. As in the case of α-IP oxidation, pyridine has a very positive influence, increasing yields by ca. 45% and significantly reducing reaction times over comparable first row transition metal systems in the absence of pyridine [37,38]. Oxidation of β-IP by copper(II) salts in the presence of amines depended heavily on amine type. An increase from 30 to 84% yield of KIP was achieved on replacing *tert*-amines [39] with pyridine [40]. Attempts to heterogenize these systems for the oxidation of β-IP (manganese and cobalt on silica at 50°C) gave KIP in 28–41% yields [37]. An interesting exception to this trend and an attractive route to KIP involves the use of activated carbon in the presence of an amine and in the absence of any transition metal. This process afforded KIP in good yield (75.5%) with almost complete conversion of β-IP [41].

Verbenone is an important intermediate in the preparation of taxol and allylic oxidation of α-pinene opens an avenue to this intermediate (Scheme 3). The patent literature concerning oxidation of pinenes is limited to three Czech patents, from 1992, based on cobalt and palladium catalyst systems. A water insoluble cobalt salt supported on activated carbon has been used to catalyze atmospheric oxidation of α-pinene to verbenone. Trace amounts of soluble chromium salts were employed as promoters and it can be debated if catalysis is only due to soluble chromium species [42]. Oxidation of α-pinene with atmospheric oxygen, catalyzed by Pd/C promoted with salts of Co, Mn, Bi, Cd or Zn gave verbenol and verbenone [43]. Verbenone was also obtained by oxidation of α-pinene with oxygen in the presence of dipyridyl cobalt dibromide as catalyst with chromium or cobalt salts of fatty acids as cocatalysts [44].

Autoxidation is typically difficult to control and the question arises if there is any possibility to improve these systems in order to achieve greater conversions while maintaining high selectivity. In many cases substituting manganese for cobalt gives no change in conversion. Addition of sodium bromide to cobalt acetate increased conversions in autoxidation, by dioxygen, of α-pinene to myrtanal, verbenone and *trans*-verbenyl acetate. Unfortunately, high conversions in this system were accompanied by very poor selectivities. Substitu-

Table 2
Heterogenized chromium based catalysts for oxofunctionalization of cyclic olefins

Catalyst	Substrate	Product	Oxidant	Conditions	Yield (%)	Reference
Cr-pillared montmorillonite	Methylcyclohexenes	Methylcyclohexenones	TBHP	36–39 h, RT	68–76	[52]
CrY	Cyclohexene	2-Cyclohexen-1-one	O_2 and NMP	24 h, 65°C	35	[55]
Cr-pillared montmorillonite	α-Pinene	Verbenone	TBHP	42 h, RT	76	[52]
Cr–APO-5	α-Pinene	Verbenone	TBHP	24 h, 80°C	66	[53]
Cr-pillared montmorillonite	Ionone	Oxoionone	TBHP	46 h, RT	68	[52]

tion of manganese for cobalt in pinene oxidation also shifted selectivity towards alcohols and acetates [45].

In the case of cyclohexene oxidation, Alper and Harustiak [46] have shown that for the cobalt chloride diglyme system selectivity could be switched to the alkenone product by addition of *N*-methylpyrrolidinone (NMP) to the reaction mixture. NMP played the role of radical initiator and also effectively increased solvent polarity [47,48].

In the oxidation of α-pinene, cobalt(II) pyridine complexes tend to increase the degree of allylic oxidation to verbenone. $Co(C_5H_5N)_2Br_2$ [49] and $Co(4\text{-}MeC_5H_4N)_2Br_2$ [50] proved to be promising catalysts for the aerobic oxidation of α-pinene. Complete conversion of α-pinene afforded verbenone as the major product in 76% yield. It was suggested that α-pinene is first oxidized to a mixture of alcohols which is further oxidized to verbenone (Scheme 3).

3.2. Heterogenized chromium based catalysts

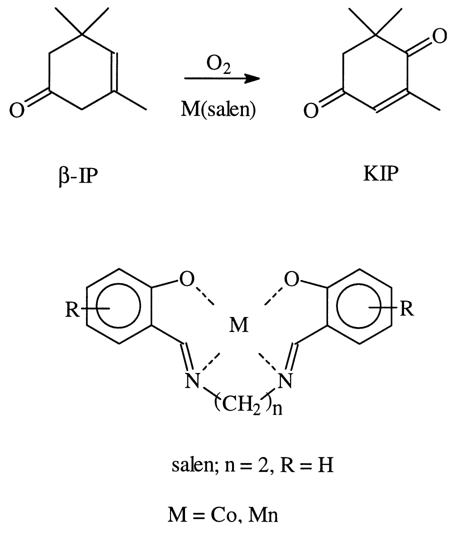
The use of chromia and chromium based oxidizing reagents has pervaded synthetic organic chemistry for many years [21]. The synthetic utility of these reagents is, however, outweighed by the stoichiometric (and often excess) amounts necessitated and the toxicity of the waste produced. Heterogenization of these versatile chromium reagents is an attractive approach to eliminate such problems.

Heterogeneous chromium catalysts, mainly in combination with TBHP as oxidant, provide α,β- unsaturated ketones in the allylic oxofunctionalization of a variety of cyclic olefins (Table 2). In a development of Muzart's successful chromium(VI) catalyzed oxidations [51] chromium-pillared clays have been applied in the allylic oxidation of a broad range of cyclic olefins, including ionone and α-pinene [52]. Using equimolar quantities of TBHP at room temperature, the alkenone products were isolated in 68–76% yields. Working under anhydrous conditions the catalyst could be reused without any loss in activity and selectivity. The presence of water reportedly resulted in significant leaching of chromium, however, water is a coproduct of the oxidation reaction and minimizing chromium loss in this system may be a difficult task. Chromium substituted aluminophosphates also catalyze the liquid phase oxidation of terpenes with TBHP to the corresponding α,β-unsaturated ketones. The oxidation of α- and β-pinene to verbenone and pinocarvone, respectively, in high conversions with good selectivities was described [53]. Leaching of chromium during oxidation begged the question as to whether it is possible to heterogenize chromium containing reagents via this strategy [54].

Combination of a chromium-exchanged zeolite NaY catalyst and NMP gave a 20% yield of oxygenated products from cyclohexene with ca. 90% selectivity to 2-cyclohexen-1-one product. Increasing the amount of NMP had no effect on the product distribution but served to increase the conversion and yield [55].

3.3. First row transition metal salen based catalysts

Manganese, iron, cobalt and copper salen catalysts in the presence of a tertiary amine, water, and solvent give excellent conversions and selectivities in the aerobic oxidation of β-IP to KIP (Scheme 4). Manganese based catalysts have proven particularly attractive and provide almost quantitative yields under very mild conditions (ca. 30°C) in 4 h [56–58]. Recently, studies of the influence of β-IP concentration on selectivity to KIP have shown that the addition of an organic acid to the Mn(II)(salen) system provides



Scheme 4.

improved space–time yields [59]. Oxidation of β-IP with oxygen and TBHP at 30°C in the presence of Mn(II)(salen), ethylenediamine, and triethylamine afforded KIP in excellent yield (93.4%) without epoxide formation [60]. Interestingly, while Schiff base complexes of manganese and cobalt(II) catalyze the aerobic oxidation of β-IP to KIP, α-IP is inert under the same reaction conditions [61].

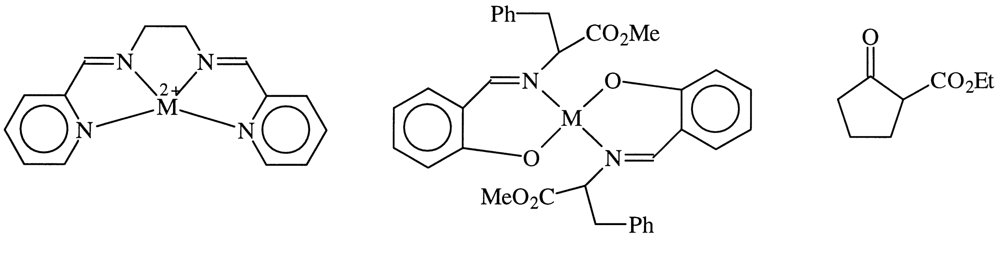
Ligand tuning, as demonstrated here for cobalt Schiff base catalysts, can play a significant role in determining the outcome of alkene oxidation. Autoxidation of α- and β-pinene in the presence of oxygen and 2-methylpropanal using Schiff base complex **1** (Scheme 5) afforded the corresponding epoxides in 64–70% yields, whereas **2** promotes formation of allylic oxidation products (alcohols and enones) [62]. Further developments which show how selectivity barriers may be overcome are illustrated by allylic oxidations catalyzed by **2** with dioxygen in the presence of ethyl 2-oxocyclopentanecarboxylate. This system provides allylic oxidation products from cyclo-pentene, -hexene and -octene, no epoxidation products are observed. The reaction is believed to proceed via formation of a cobalt(III) superoxide species, which forms only in the presence of ethyl 2-oxocyclopentanecarboxylate, followed by transfer of oxygen to ethyl 2-oxocyclopentanecarboxylate and the cyclic alkene [63].

Constantini [61] showed that effective oxidation catalysis using M(salen) complexes depended heavily on the metal (M), metal oxidation state, subtituents (R) on the phenyl ring of salen, and the number of carbons in the chain linking the two halves of the ligand (Scheme 4). Mn(II)(salen) was the most active catalyst with R = H, and $n = 2$. Pre-oxygenation of the Mn(II)(salen) catalyst has to be avoided by adding the catalyst to the oxidation reaction as the final step. Stoichiometric amounts of the brown oxygenated complex (salen)Mn(III)–O–O–(III)Mn(salen) did not oxidize β-IP in acetone/H_2O in the presence of base. Thus, attempts to identify the active metal complex show only that it is an intermediate between Mn(II)(salen) and (salen)Mn(III)–O–O–(III)Mn(salen).

$$\mathrm{LMn(II)} + \mathrm{O_2} \leftrightharpoons \mathrm{(III)–O_2} \qquad (1)$$

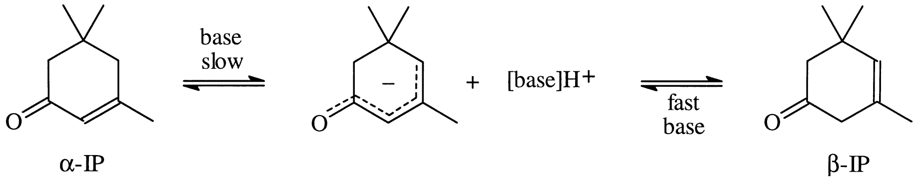
$$\mathrm{LMn(III)–O_2} + \mathrm{LMn(II)} \leftrightharpoons \mathrm{(III)–O–O–Mn(III)L} \qquad (2)$$

Mn(II)(salen) catalyzed oxidations depend heavily on the solvent system, base additive and the presence



1 **2** **3**

Scheme 5.

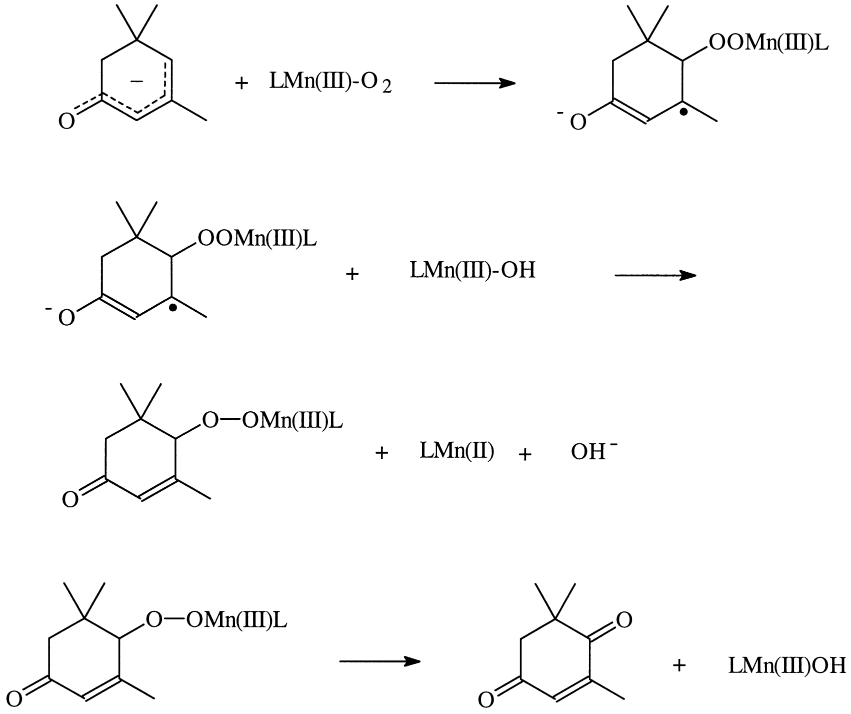


Scheme 6.

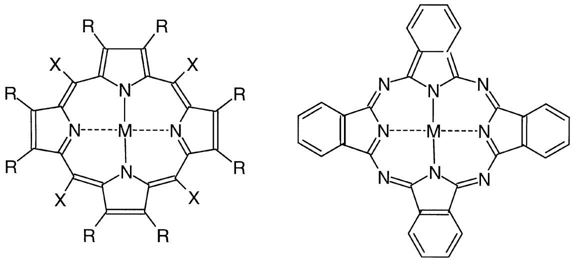
of small amounts of water. Only aprotic solvents are suitable since in protic solvents back isomerization of β- to α-IP, which is unreactive under these conditions, is observed. Reaction rates, but not selectivities, increased with increasing polarity and basicity of the solvent system. Strong organic bases, in particular tertiary amines, afforded the best results. Mineral bases lead mainly to back-isomerization of β-IP. In the absence of water an inhibition period was observed during which small amounts of water were produced in the oxidation reaction. It was shown by kinetic studies that the reaction is first order in organic base [61].

Constantini et al. [61] proposed that isophorone enolization is the rate determining step in the oxidation to KIP, the enol being the likely active species in the oxidation reaction (Scheme 6). From the available literature, and catalytic systems studied, β-IP is more readily oxidized to KIP than α-IP. Consequently, since it appears that upon enolization α- and β-IP afford the same intermediate, the greater reactivity of β- over α-IP may reflect the difficulty involved in enolization of the latter.

It was proposed in oxidations catalyzed by salen complexes that the key step involved radical addition of the oxygenated complexes $M(L)_nO_2$ to enolized β-IP (Scheme 7). A second electron transfer is followed by regeneration of the catalyst and production of KIP.



Scheme 7.



porphyrin M(TPP); R = H, X = Ph phthalocyanine M(ptc)

Scheme 8.

In the copper salt catalyzed oxidation of isophorone, the proposed mechanism involves electron transfer between copper(II) and the dienolate anion followed by coupling of the formed radical with molecular oxygen [64]. This mechanism is similar to the generally accepted mechanism for the oxidation of ketones in basic media [65].

3.4. Transition metal porphyrins

The subject of metalloporphyrins in oxidation catalysis has been extensively reviewed [66,67]. Oxidation of β-IP to KIP (93% yield, 12 500 turnover number) with molecular oxygen is catalyzed by metal phthalocyanines (ptc) and tetraphenylporphyrins (TPP) including Mn(II,III), Fe(II,III), Co(II), Cu(II) and Ru(II) in the presence of triethylamine and water, in dimethoxyethane (Scheme 8) [68]. The mechanism of catalytic oxidation by molecular oxygen and metal porphyrins [69] is similar to that suggested for salen based catalysts [61]. Among the complexes studied TPPMn(III)Cl proved to be the most effective for the oxidation of β-IP to KIP. Interestingly, the same result was obtained for the TPPMn(II) analog [68,70], indicating that divalent metal complexes are the active species in these catalytic cycles [61].

Immobilization of TPP and ptc systems has been the focus of much attention [67]. Recently, iodonated polysiloxane-supported metalloporphyrin complexes (manganese and tin) have been found to exhibit excellent selectivity (100%) to 2-cyclohexen-1-one in the aerobic oxidation of cyclohexene. In addition, the heterogenized systems showed increased activity over their homogeneous analogs [71]. Polymer-bound copper-2,2-bipyridine complexes have also been employed in cyclohexene oxidation, affording allylic oxidation products in good selectivity (85.2–95.7%) at reasonable conversions (15–40%) [72]. Birnbaum et al. [73] described the catalytic aerobic oxidation of cyclohexene to epoxide and allylic oxidation products using halogenated iron porphyrin complexes in supercritical carbon dioxide. Although activities of the iron porphyrins were higher in organic solvents the reaction was accompanied by solvent oxidation. Other applications of $scCO_2$ as solvent for heterogeneous catalysis, including oxidations, can be found in a recent review [74].

3.5. Heterogeneous molybdenum based systems

Molybdenophosphate/silica based catalysts provide the most promising results to date in the liquid phase aerobic oxidation of α-IP to KIP (Table 3). Aerobic oxidation of α-IP in the presence of phosphomolybdic acid/silicomolybdic acid and copper sulfate systems, and an aromatic amine gave KIP in good yield [75–78]. On the basis of the available patent literature Freer and Yates [79] described the oxidation of 5,5-dimethyl-2-cyclohexen-1-one and α-IP to 5,5-dimethyl-2-cyclohexen-1,4-dione (60% yield) and KIP, respectively, using a catalyst system comprising phosphomolybdic acid, potassium dichromate and cupric sulfate.

Table 3
Comparison of molybdenum based systems for α-IP oxidation using molecular oxygen as oxidant

Catalyst	Catalyst/α-IP (wt.%)	Time (h)	Temperature (°C)	α-IP conversion (%)	KIP yield (%)	Reference
MoPO/$CuSO_4$	3.3	90	110	–	47	[75]
MoPO/MoSiO/$CuSO_4$	0.1–10	–	50–150	83–100	45–61	[76]
MoPO/MoSiO/V or Mo/MoO_3 or $CuSO_4$	0.5–4.0	95	100	98.5	45	[77]
MoPO/SiMoO/Ar amine	–		–	37	35.7	[78]

Table 4
Allylic oxidation of 1-alkenes over an iron-antimony oxide catalyst in a tubular flow reactor [88]

1-Alkene	Temperature (°C)	Conversion (%)	Percentage selectivity to alkenal
C_2	450–470	4–6	0
C_3	350–400	3–22	80–88
C_4	350–400	7–35	30–35
C_5	350–400	1–22	0–1
C_6–C_9	350–400	4–37	0

Interestingly, selective aerobic oxidation of α-IP catalyzed by molybdovanadophosphate supported on activated carbon afforded formylisophorone (FIP) in good yield (55%). It has been suggested that pore size and acidity of the activated carbon support play a crucial role in the selectivity/activity relationships in these systems. This is substantiated by the fact that the unsupported molybdovanadophosphate gave KIP as major product (7% yield), with a complex mixture of over-oxidation products [80,81]. Recently it has been demonstrated that addition of a platinum-group metal to the carbon-supported system leads to improved yields of KIP (53%) while obviating formation of FIP [82].

3.6. Palladium based catalysts

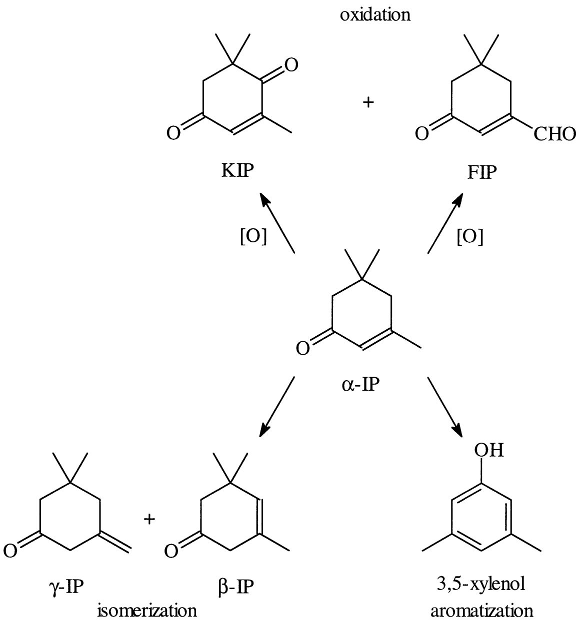
Palladium plays a central role in allylic oxidation catalysis [83]. Oxidation of α-IP with TBHP in the presence of palladium(II), triethylamine and copper(I) catalysts gave KIP in good yields (49–55%). 5,5-dimethylcyclohexen-1-one is oxygenated similarly to 5,5-dimethylcyclohexen-1,4-dione (32% yield), while aromatization of the less sterically hindered cyclohexenone and methylcyclohexenone prevented oxidation [84].

4. Gas phase allylic oxidation of cyclic olefins to α,β-unsaturated ketones

Gas phase oxidation of propylene to acrolein and isobutylene to methacroline with molecular oxygen over multicomponent bismuth molybdate and iron antimonate containing metal oxide systems are now two well established large scale processes in the commodity chemical industry [85–87]. As a result of the substantial R&D effort in the past decades, the activity of the early composites has since been increased by orders of magnitude, and nowadays catalysts provide over 90% yield to the corresponding unsaturated aldehydes operating under industrial conditions. However, successful examples of the allylic oxofunctionalization of higher alkenes in the gas phase are rare. Apparently the sophisticated catalysts developed for the transformation of small alkenes to alkenones do not function in the oxidation of higher alkenes. Oxidation of C_2–C_9 alkenes over a Fe–Sb catalyst is shown in Table 4. Reasonable selectivities to the corresponding alkenals were obtained in the case of 1-propene and 1-butene [88]. Similarly, only propene and isobutene yielded unsaturated aldehydes as major products over a Bi–Mo-oxide catalyst [89].

Recently the oxidation of α-IP to KIP over a vanadia based catalyst with dioxygen at atmospheric pressure has been reported [90]. Excellent combined selectivities to KIP and FIP (>75%, at 17% conversion of α-IP) were obtained over vanadia and lithium phosphate supported on pumice. Other catalyst systems such as vanadia, 20 wt.% vanadia/magnesia, bismuth molybdate ($Bi_2O_3 \cdot 2MoO_3$), vanadium phosphate (V:P = 1.0) which afforded the V(IV) β-phase selectively after calcination in air, 10 wt.% chromia/γ-alumina, and 5 wt.% silver/γ-alumina were less selective [90].

One reason for the lack of work in this area [91] may be that larger cyclic molecules, such as cyclohexene, isophorone and terpenes, are markedly more thermally sensitive. Unlike propylene and isobutylene, they may decompose under oxidizing conditions at elevated temperatures (ca. 400–500°C) which are necessary for maintaining activity of bismuth molybdate or iron antimonate catalysts. In the case of IP oxidation, thermal sensitivity of the reactants and products demanded experimental temperatures in the range 200–250°C [90]. Operating



Scheme 9.

under these conditions catalyst deactivation proved to be a characteristic of all systems investigated. The study was further complicated by a background oxidation effect in the absence of any catalyst [90].

Overall selectivity to the desired oxidation product is also a function of isomerization and aromatization reactions which occur competitively in the presence of metal oxide catalysts as shown in Scheme 9. In the case of IP, heterogeneous gas phase catalysis of the latter two reactions is typically conducted under anaerobic conditions [92,93]. Heterogeneous gas phase isomerization of α- to β-IP occurs readily over metal oxide catalysts including nickel, magnesium, aluminum and silicon oxides [92]. In the oxidation of α-IP to KIP, simultaneous conversion to 3,5-dimethylphenol is a prominent gas phase reaction in the temperature range 250–400°C. The reaction is accompanied by elimination of methane and proceeds via a dienone–phenol rearrangement (keto–enol tautomerization) [93].

In gas phase oxidations of α-IP, the large number of possible products (including combustion products), complicates the process further. For instance, allylic oxidation of α-IP may occur at the 4-position affording KIP or at the α-methyl substituent to give FIP [91,94]. Vapor phase decomposition of α-IP in the presence of various heterogeneous catalysts has been investigated in the temperature range 300–800°C. Contact with low surface area catalysts at 550°C gave β-IP and trimethylcyclohexadienes. In the presence of magnesium oxide and alumina with a broad distribution of various acid–base centers the reaction temperatures are significantly reduced to 150 and 300°C, respectively [95].

5. Summary

Allylic oxofunctionalization of cyclic olefins is an attractive process transforming cheap and readily available substrates to valuable intermediates for the fine chemicals industry. A broad range of homogeneous catalysts has been tested, some of them affording over 90% yield to the desired α,β-unsaturated ketone. The search for truly heterogeneous systems has been less successful. Conventional gas phase allylic oxidation catalysts are non-selective at the typical high operating temperatures. At lower operational temperatures (ca. 200°C), which are necessary in the selective oxidation of thermally sensitive substrates, the conventional catalysts do not function properly. Liquid phase oxidation with solid catalysts, such as Cr-pillared clays and molecular sieves, suffer from metal leaching. Unfortunately, there are no solid catalysts available yet which function at near ambient temperature, such as Pt metals for alcohol oxidation, or Ti-substituted molecular sieves and titania–silica mixed oxides for epoxidation. Apparently, the search for truly heterogeneous catalysts for allylic oxofunctionalization is not a trouble-free route to replace homogeneous catalysts. At present, the most attractive solution appears to be the heterogenization of proven homogeneous catalysts.

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References

[1] Pei-Shing, E. Dai, Catal. Today 26 (1995) 3.
[2] R.A. Sheldon, J. Mol. Catal. A 107 (1996) 75.
[3] J.H. Clark, D.J. Macquarrie, Chem. Soc. Rev. 25 (1996) 303.
[4] E.R. Hartley, Catalysis by Metal Complexes, Supported Metal Reagents, Reidel, Dordrecht, 1984.
[5] P.A. Chaloner, Handbook of Coordination Catalysis in Organic Chemistry, Butterworths, London, 1986 (Chapter 6).
[6] R.A. Sheldon, J.K. Kochi, Metal Complex Catalyzed Oxidations of Organic Compounds, Academic Press, New York, 1981.
[7] K. Kaneda, S. Haruna, T. Imanaka, K. Kawamoto, J. Chem. Soc., Chem. Commun. (1990) 1467.
[8] R.A. Sheldon, J. Mol. Catal. 20 (1983) 1.
[9] H. Mayer, Pure Appl. Chem. 51 (1979) 535.
[10] O. Isler, Carotenoids, Birkhauser, Basel, 1971.
[11] K.K. Light, B.M. Spencer, J.F. Vinals, J. Kiwala, M.H. Vock, E.J. Shuster, US Patent 4 076 854, Chem. Abstract 89 (1978) 23843d.
[12] P. Weyerstahl, T. Meisel, K. Mewes, S. Negahdari, Liebigs Ann. Chem. (1991) 19.
[13] M. Shibagaki, S. Shibata, H. Kaneko, Agric. Biol. Chem. 45 (1981) 2911.
[14] J.N. Marx, Tetrahedron 31 (1975) 1251.
[15] E. Demole, P. Enggist, Helv. Chim. Acta 57 (1974) 2087.
[16] E. Widmer, Hoffmann-La Roche, US Patent 4 005 145, Chem. Abstract 86 (1975) 155268.
[17] Margueron, Ann. Chim. 21 (1797) 174.
[18] P.A. Wender, T.P. Mucciaro, J. Am. Chem. Soc. 114 (1992) 5878.
[19] M.R. Sivik, K.J. Stanton, L.A. Paquette, Org. Synth. 72 (1994) 57.
[20] G. Rothenberg, Y. Yatziv, Y. Sasson, Tetrahedron 54 (1998) 593.
[21] J. Muzart, Chem. Rev. 92 (1992) 113.
[22] C.S. Foote, J.S. Valentine, A. Greenberg, J.F. Liebman, Active Oxygen in Chemistry, Blackie, London, 1995.
[23] L.I. Simandi, Catalytic Activation of Dioxygen by Metal Complexes, Kluwer, Dordrecht, 1992.
[24] A. Bielanski, J. Haber, Oxygen in Catalysis, Marcel Dekker, New York, 1991.
[25] R.A. Sheldon, Stud. Surf. Sci. Catal. 110 (1997) 151.
[26] M. Hartmann, L. Kewvan, Chem. Rev. 99 (1999) 635.
[27] D.E. De Vos, F. Thibault-Strazyk, P.P. Knops-Gerrits, R.F. Parton, P.A. Jacobs, Macromol. Symp. 80 (1994) 157.
[28] P.P. Paul, Prog. Inorg. Chem. 48 (1999) 457.
[29] R.J.P. Corrin, D. Leclercq, Angew. Chem., Int. Ed. Engl. 35 (1996) 1420.
[30] H.E.B. Lempers, R.A. Sheldon, J. Catal. 175 (1998) 62.
[31] W. Partenheimer, Catal. Today 23 (1995) 69.
[32] J.J. Becker, U.P. Hochstrasser, W. Skorianetz, Firmenich, US Patent 3 944 620, 1976.
[33] J.J. Becker, W. Skorianetz, P. Ulrich, Firmenich, DE Patent 2 459 148, 1974.
[34] B. Dawson, J. Pugach, Aristech, US Patent 96/15094, 1996.
[35] W. Brenner, Hoffmann-La Roche, CH Patent 605 536, Chem. Abstract 90 (1977) 5988.
[36] W. Brenner, Hoffmann-La Roche, DE Patent 2 515 304, Chem. Abstract 84 (1975) 58767.
[37] J.J. Becker, K.H. Schulte-Elte, H. Strickler, G. Ohloff, Firmenich, DE Patent 2 457 157, Chem. Abstract 83 (1975) 96564z.
[38] J.J. Becker, K.-H. Schulte-Elte, H. Strickler, G. Ohloff, Firmenich, FR Patent 2 253 730, 1974.
[39] P. Regimbeau, J. Corre, Y. Paillet, Shell Int., FR Patent 1 446 246, 1965.
[40] Huels, DE Patent 3 842 547, 1990.
[41] M. Constanini, A. Dromard, M. Jouffret, Rhone-Poulenc, DE Patent 2 657 386, Chem. Abstract 87 (1987) 184078.
[42] J. Kizlink, M. Hronec, Z. Cvengrosova, M. Harustiak, A. Oblozinsky, J. Hutnik, J. Ilavsky, CS Patent 268 571, Chem. Abstract 116 (1987) 214747m.
[43] Z. Cvengrosova, M. Hronec, CS Patent 270 181, Chem. Abstract 116 (1988) 6775s.
[44] Z. Cvengrosova, M. Hronec, CS Patent 270 180, Chem. Abstract 116 (1988) 41802v.
[45] M. de F.T. Gomes, O.A.C. Antunes, J. Mol. Catal. A 121 (1997) 145.
[46] H. Alper, M. Harustiak, J. Mol. Catal. 84 (1993) 87.
[47] R.S. Drago, R. Riley, J. Am. Chem. Soc. 112 (1990) 215.
[48] S. Sakaguchi, S. Kato, T. Iwahama, Y. Ishii, Bull. Chem. Soc. Jpn. 71 (1998) 1237.
[49] J. Kizlink, M. Hronec, Z. Cvengrosova, M. Harustiak, J. Bavsky, Chem. Prum. 39 (1989) 576.
[50] M. Lajunen, A.M.P. Koskinen, Tetrahedron Lett. 35 (1994) 4461.
[51] J. Muzart, Tetrahedron Lett. 28 (1987) 4665.
[52] B.M. Choudary, A.D. Prasad, V. Swapna, V.L.K. Valli, V. Bhuma, Tetrahedron 48 (1992) 953.
[53] H.E.B. Lempers, R.A. Sheldon, App. Catal. A 143 (1996) 137.
[54] R.A. Sheldon, in: B.K. Hodnett, A.P. Kybett, J.H. Clark, K. Smith (Eds.), Proceedings of Conference Supported Reagents and Catalysts in Chemistry, Ireland, 1997, p. 37.
[55] O.B. Ryan, D.E. Akporiaye, K.H. Holm, M. Stocker, Stud. Surf. Sci. Catal. 106 (1997) 369.
[56] M. Constanini, A. Dromard, M. Jouffret, Rhone-Poulenc, DE Patent 2 610 254, Chem. Abstract 86 (1976) 5022.
[57] M. Constanini, A. Dromard, M. Jouffret, Rhone-Poulenc, FR Patent 2 303 785, 1975.
[58] N. Ito, K. Kinoshita, K. Suzuki, T. Eto, Soda Aromatic, JP Patent 1 090 150, Chem. Abstract 111 (1987) 153260.
[59] R. Hahn, U. Gora, K. Huthmacher, F. Hübner, S. Krill, Degussa, DE Patent 19 619 570, 1996.
[60] N. Ito, K. Kinoshita, K. Suzuki, T. Eto, Soda Aromatic, JP Patent 1 175 955, Chem. Abstract 112 (1987) 76460.
[61] M. Constantini, A. Dromard, M. Jouffret, B. Brossard, J. Varagnat, J. Mol. Catal. 7 (1980) 89.
[62] M. Reddy, T. Punniyamurthy, J. Iqbal, Tetrahedron Lett. 36 (1995) 159.
[63] T. Punniyamurthy, J. Iqbal, Tetrahedron Lett. 35 (1994) 4003.
[64] H.C. Volger, W. Brackmann, J.W.F.M. Lemmers, Recl. Trav. Chim. 84 (1965) 1203.
[65] T.J.J. Wallace, Org. Chem. 30 (1965) 3768.

[66] D. Ostovic, G.-S. He, T.C. Bruice, in: R.A. Sheldon (Ed.), Metalloporphyrins in Catalytic Oxidations, Marcel Dekker, New York, 1994 (Chapter 2).
[67] B. Meunier, in: F. Montanari, L. Casella (Eds.), Metalloporphyrins Catalyzed Oxidations, Kluwer, Dordrecht, 1999.
[68] N. Ito, T. Etoh, H. Hagiwara, M. Kato, Synthesis (1997) 153.
[69] E.R. Birnbaum, M.W. Grinstaff, J.A. Labinger, J.E. Bercaw, H.B. Gray, J. Mol. Catal. A 104 (1995) 119.
[70] N. Ito, K. Kinoshits, K. Suzuki, T. Eto, Soda Aromatic, EP Patent 311 408, 1989.
[71] H.S. Hilal, W. Jondi, S. Khalaf, A. Keilani, M. Suleiman, A.F. Schreiner, J. Mol. Catal. A 113 (1996) 35.
[72] Z.Q. Lei, Y.P. Wang, J. Macromol. Sci. Pure Appl. Chem. A 29 (1992) 321.
[73] E.R. Birnbaum, R.M. Le Lacheur, A.C. Horton, W. Tumas, J. Mol. Catal. A 139 (1999) 11.
[74] A. Baiker, Chem. Rev. 99 (1999) 453.
[75] H.-D. Martin, B. Albert, K. Kessel, BASF, EP Patent 425 976, Chem. Abstract 115 (1990) 234695.
[76] E. Widmer, M. Seuret, Hoffmann-La Roche, US Patent 3 960 966, 1976.
[77] E. Widmer, M. Seuret, Hoffmann-La Roche, DE Patent 2 526 851, 1975.
[78] Sagami Chem. Res., JP Patent 61 191 645, Chem. Abstract 106 (1986) 49661.
[79] V.J. Freer, P. Yates, Chem. Lett. (1984) 2031.
[80] A. Hanyu, Y. Sakurai, S. Fujibayashi, S. Sakaguchi, Y. Ishii, Tetrahedron Lett. 38 (1997) 5659.
[81] K. Matsuoka, Y. Ishii, Kokai Tokkyo Koho, JP Patent 10 158 209, Chem. Abstract 129 (1996) 81538.
[82] K. Chikamori, I. Takahashi, Kokai Tokkyo Koho, JP Patent 10 182 543, Chem. Abstract 129 (1996) 108849.
[83] J.-E. Bäckvall, R.B. Hopkins, H. Grennberg, M.M. Mader, A.K. Awasthi, J. Am. Chem. Soc. 112 (1990) 5160.
[84] T. Hokosawa, S. Inui, S.-L. Murahashi, Chem. Lett. (1983) 1081.
[85] K. Othmer, Encyclopedia of Chemical Technology, 3rd Edition, Wiley, New York, 1978, p. 277.
[86] Y. Moro-Oka, W. Ueda, Adv. Catal. 40 (1994) 233.
[87] M.M. Bettahar, G. Constentin, L. Savary, J.C. Lavalley, Appl. Catal. A 145 (1996) 1.
[88] E. van Steen, M. Schnobel, C.T. O'Connor, Heterogeneous Hydrocarbon Oxidation, Vol. 638, ACS Symp. Series, 1996, p. 278.
[89] C.R. Adams, in: W.H.M. Sachtler, G.C.A. Schuit, P. Zwietering (Eds.), Proceedings of the Third International Congress on Catalysis, Amsterdam, 1964, North Holland, Amsterdam, 1965, pp. 240–251.
[90] E.F. Murphy, T. Mallat, A. Baiker, M. Schneider, Appl. Catal. A, in press.
[91] H. Strickler, J.J. Becker, G. Ohloff, Firmenich, DE Patent 2 457 158, Chem. Abstract 83 (1973) 96565a.
[92] P. Nösberger, A.J. Vieth, Hoffmann-La Roche, EP Patent 488 045, Chem. Abstract 117 (1991) 151177.
[93] G.S. Selvapati, K.V. Ramanamurty, V. Khandavel, M.J. Rao, R. Vaidyeswaran, IN Patent 167 840, Chem. Abstract 118 (1987) 61910.
[94] H. Strickler, J.J. Becker, G. Ohloff, Firmenich, US Patent 3 931 327, 1973.
[95] L.F. Korzhova, Y.V. Churkin, K.M. Vaisberg, Neftekhim. 31 (1991) 677.