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Efficient isomerization of α -pinene oxide to campholenic aldehyde promoted by a mixed-ring analogue of molybdenocene

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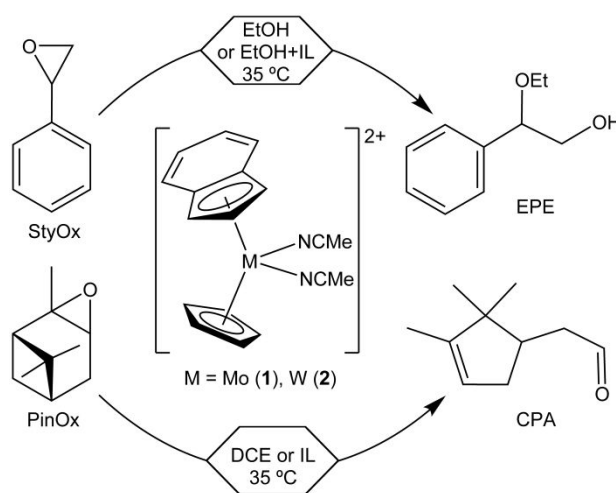
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ABSTRACT: The Mo^{IV} complex [(η^5 -indenyl)(η^5 -cyclopentadienyl)Mo(MeCN)₂](BF₄)₂ (**1**) has been used to promote two acid-catalyzed epoxide ring-opening reactions under ambient conditions. The alcoholysis of styrene oxide in neat ethanol gave 2-ethoxy-2-phenylethanol in quantitative yield within 10 min. The use of an ionic liquid (IL) as cosolvent benefitted catalyst solubility and recycling while not impairing catalytic performance. Complex **1** in 1,2-dichloroethane was effective for the isomerization of α -pinene oxide to campholenic aldehyde (CPA), leading to 87% yield at 1 h reaction. The same yield could be achieved within 1 min by using the IL [Choline][NTf₂] as solvent. CPA yields at 1 min reached near-quantitative values (98%) upon recycling of the catalyst/IL mixture, demonstrating an unparalleled combination of activity, selectivity and recyclability for this commercially important reaction. Considering the catalytic features of the **1**/IL system, a CPA process flow diagram is proposed and compared to patented technology.

INTRODUCTION

Epoxides are important building blocks in organic synthesis owing to their ability to undergo

various types of ring-opening reactions.¹⁻⁴ For these processes to be of practical use, mild reaction conditions are desirable and the selectivity towards the target product must be high. These requirements usually demand the use of an acid or base catalyst. Two synthetically valuable acid-catalyzed reactions are ring-opening with nucleophiles to give 1,2-disubstituted products, and Meinwald rearrangement to give aldehydes and ketones.⁴ The first reaction generates β -substituted alcohols such as β -aminoalcohols and β -alkoxyalcohols,⁵⁻⁶ which have important pharmacological properties, biological activities, and are useful synthetic reagents, particularly as chiral auxiliaries. An important example of the second reaction is the acid-promoted isomerization of α -pinene oxide (PinOx) to campholenic aldehyde (CPA) (Scheme 1).⁷⁻¹⁰ PinOx originates from the epoxidation of α -pinene, which is the most abundant terpene in nature and is obtained industrially from turpentine, a byproduct of the wood pulping process to produce paper. The classical process for the preparation of PinOx is the so-called Prilezhaev reaction, i.e. epoxidation of α -pinene by means of peroxycarboxylic acids in stoichiometric amounts. A lot of progress has been made towards the development of more sustainable methods to produce PinOx, e.g. methyltrioxorhenium-catalyzed epoxidation with hydrogen peroxide,¹¹ and ultrasonic and catalyst-free epoxidation using dimethyl dioxirane.¹²



Scheme 1. Ethanolysis of styrene oxide to give 2-ethoxy-2-phenylethanol, and isomerization of α -pinene oxide to campholenic aldehyde, in the presence of **1** and **2** (DCE = 1,2-dichloroethane; IL = ionic liquid).

The main value of CPA is as an intermediate in the synthesis of fragrances such as

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3 naturanol¹³ and sandalwood-type odorants.¹⁴ CPA has also been explored as a chiral starting
4 material in the synthesis of cyclopentanoid chiral synthons, which have utility in the synthesis of
5 natural products.¹⁵
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8 PinOx isomerization is a complex reaction that can give more than 200 different products
9 if run at temperatures higher than 100 °C,^{16,17} with examples of the more common ones being
10 CPA, *trans*-carveol, *trans*-sobrerol, *iso*-pinocamphone and pinocarveol. The formation of CPA is
11 favored in the presence of Lewis acids. Traditionally, zinc halides have been considered to be the
12 state-of-the-art homogeneous catalysts, giving CPA selectivities up to about 85%.¹⁸ Patented
13 technologies of CPA production comprise feeding continuously PinOx to a mixture of a Lewis
14 acid catalyst (e.g. zinc bromide or zinc chloride) and a solvent that has a higher boiling point
15 than CPA (e.g. diphenyl ether), operating under conditions to favor very high conversion, which
16 is followed by the separation of CPA via vacuum distillation.¹⁹ Several shortcomings of this
17 process, such as catalyst deactivation, difficulty in catalyst recycling and toxic zinc-containing
18 waste disposal issues, have motivated studies on the development of alternative homogeneous or
19 heterogeneous catalytic systems for the selective synthesis of CPA from PinOx. A major
20 challenge is to unite high activity and high CPA selectivity. In this direction, promising
21 developments of catalytic routes to PinOx have appeared in the literature. Pitínová-Štekrová *et*
22 *al.* reported that the reaction of PinOx over a Ti-MCM-22 catalyst in toluene at 70 °C led to total
23 conversion within 1 h and a CPA selectivity of 96%.²⁰ This result was deemed to substantially
24 exceed all other previously published results, although recovery/reuse of the catalyst was not
25 reported.
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39 We have determined that molybdenum dicarbonyl, tricarbonyl and tetracarbonyl
40 complexes can effectively promote the isomerization of PinOx to CPA,²¹⁻²³ and the alcoholysis
41 of epoxides.²³⁻²⁵ All the complexes studied led to 100% selectivity towards 2-ethoxy-2-
42 phenylethanol (EPE) in the ethanolysis of styrene oxide (StyOx), with the η^5 -indenyl complex
43 [IndMo(CO)₂(MeCN)₃]BF₄ being particularly active (full conversion after 1 min at 35 °C).²⁵ The
44 best result for the isomerization reaction was a CPA selectivity of 68% at full conversion (30 min
45 at 35 °C or 1 min at 55 °C) in the presence of the dinuclear complex [{(Ind)Mo(CO)₂(μ -Cl)}₂] in
46 1,2-dichloroethane.²²
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53 Herein we report a major advance on the PinOx-to-CPA conversion by the use of the
54 organometallic Lewis acid [IndCpMo(MeCN)₂](BF₄)₂ (**1**) as catalyst in conjunction with an ionic
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liquid (IL) solvent. Complex **1** was identified as a potentially interesting catalyst for this reaction for a number of reasons: (i) The Mo^{IV} center in molybdenocene-derived molecules containing the Cp'₂Mo²⁺ unit is known to act as a Lewis acid, and the molecules have proven to be efficient catalysts for a number of organic reactions²⁶; (ii) the MeCN ligands in **1** are labile,²⁷ facilitating partial ligand dissociation and opening up of coordination sites; (iii) indenylmetal complexes have been shown in many instances to be superior catalysts to their cyclopentadienyl counterparts in terms of reactivity, selectivity, and stability, with a common explanation for this being the increased ability of the Ind ligand to undergo ring slippage and thereby open up a coordination site for substrate binding/activation.²⁸

With complex **1** and the right choice of IL, a CPA selectivity of up to 98% has been achieved at complete conversion, under mild reaction conditions (35 °C). Furthermore, the best-performing IL+catalyst systems can be reused in consecutive cycles without loss of performance. A possible CPA production process using the IL+catalyst combination has been designed and discussed.

RESULTS AND DISCUSSION

The ability of **1** to promote acid-catalyzed reactions was first assessed by using the formation of EPE from StyOx as a model reaction (Scheme 1). The reaction was initially performed in neat ethanol. Fast reaction kinetics at 35 °C led to complete StyOx conversion at 10 min and an initial turnover frequency (TOF) of 20.3 mol mol_{Mo}⁻¹ min⁻¹, which is very similar to that found previously for the complex [IndMo(CO)₂(MeCN)₃]₂BF₄ (Table 1).²⁵ EPE was always the only product observed. To the best of our knowledge, tungsten carbonyl complexes have not yet been tested for this reaction and therefore the tungsten analogue [IndCpW(MeCN)₂](BF₄)₂ (**2**) was prepared. Complex **2** was only slightly less active than **1**, leading to a TOF of 17.2 mol mol_{Mo}⁻¹ min⁻¹ and 100% EPE yield after 30 min.

Under the reaction conditions used for the ethanolysis of StyOx, complexes **1** and **2** were only partially soluble.²⁹ To completely dissolve the metal complexes, the IL [bmim][BF₄] (bmim = 1-butyl-3-methylimidazolium) was used as a cosolvent (EtOH:IL volume ratio = 1:3.3). Both complexes led to 99% conversion after 1 min at 35 °C (TOF = 20.3 mol mol_M⁻¹ min⁻¹), with an EPE selectivity of 100% (Table 1). With complex **1** EPE was obtained in 100% yield after 10 min. The reaction without a catalyst gave 23% conversion at 30 min. A catalytic test for **1** and **2**

under identical conditions, but without IL ($[\text{StyOx}] = 0.9 \text{ M}$), gave comparable StyOx conversions to those obtained for the corresponding IL-containing system. Hence, the use of an IL enabled solubilization of the complexes but did not affect considerably the catalytic performances.

Table 1. Ethanolysis of StyOx in the presence of complexes 1 and 2^a

Complex	Solvent	Run	$[\text{StyOx}] \text{ (M)}^b$	Time (min)	Conversion (%) ^c
1	EtOH	1	0.4	1	99
				10	100
	EtOH-[bmim][BF ₄]	1	0.9	1	99
				10	100
		2	0.9	1	98
				10	99
2	EtOH	1	0.4	1	84
				10	99
				30	100
	EtOH-[bmim][BF ₄]	1	0.9	1	84
				10	100
		2	0.9	1	98
			10	99	

^a Reaction conditions: 40 μmol Mo complex, 0.82 mmol StyOx, solvent [2 mL EtOH for $[\text{StyOx}] = 0.4 \text{ M}$; 780 μL EtOH or EtOH:IL (180 μL :600 μL) for $[\text{StyOx}] = 0.9 \text{ M}$], 35 °C.

^b Initial StyOx concentration. ^c 100% selectivity to 2-ethoxy-2-phenylethanol.

One of the advantages of using ILs for homogeneously catalyzed reactions is that the organic products can be readily isolated by extraction/distillation, allowing recycling of the IL/catalyst system.³⁰ The IL phases containing **1** or **2** were reused after separating the reaction

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3 product by solvent extraction, and subsequently adding (to the IL) StyOx and EtOH in amounts
4 equivalent to those used in the first batch run. No significant drop in StyOx conversion occurred,
5 suggesting that the promoter/IL systems may be effectively reused, which is important for
6 enhancing the productivity.
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10 The catalytic performance of **1** was further explored for the isomerization of PinOx to
11 CPA in 1,2-dichloroethane (Table S1 in the Supporting Information). Complete conversion was
12 reached within 1 h at 35 °C with an excellent CPA selectivity of 87%. As shown in Table S1 for
13 the specific case of organometallic promoters, this result has only previously been matched by
14 methyltrioxorhenium(VII) (MTO), which gave the same CPA yield after 1.5 h reaction at 15 °C
15 in α,α,α -trifluorotoluene.³¹ Even if we widen the scope of the comparison to include various
16 kinds of homogeneous and heterogeneous catalysts reported in the literature (Table S3 in the
17 Supporting Information), there are very few examples of CPA yields higher than 85%. A yield of
18 93% was reported for ZnBr₂ (toluene, 1 h, 25 °C), albeit with a large catalyst amount of 68
19 mol%.⁹ The metal-organic framework (MOF) [Cu₃(BTC)₂] (BTC = benzene-1,3,5-
20 tricarboxylate) displayed high selectivity to CPA (84-86% in 1,2-dichloroethane or MeCN, 25
21 °C), but very long reaction times of several days were required to reach complete conversion.⁹
22 The best results reported so far for the isomerization of PinOx to CPA were obtained in toluene
23 at 70 °C with the titanosilicates Ti-MCM-36 (90% yield, 6 h) and Ti-MCM-22 (96% yield, 1
24 h).²⁰
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36 The reaction mechanism of PinOx to CPA may follow similar pathways to those
37 described in the literature for Lewis acid catalysts.^{8,20,32} A mechanistic proposal is presented in
38 Figure 1, where [Mo] represents complex **1**. The catalytic cycle may be triggered via a primary
39 activation step involving the coordination of PinOx to the metal center and concomitant epoxide
40 ring opening to give the carbenium ion (I). Subsequently, (I) may rearrange (involving alkyl
41 shifts) to give carbenium ion (II) which, in turn, may undergo C1-C2 bond scission to (III) which
42 ultimately gives CPA. The electronic and steric properties of the catalyst may influence the
43 PinOx activation. The molybdenum catalyst **1** possesses a coordination sphere composed of four
44 simple and relatively small, common organic ligands (robust Cp, and labile MeCN and Ind) that
45 simultaneously allow the stabilization of a +4 oxidation state for the Mo atom and the structural
46 flexibility needed to sterically facilitate the coordination of the reactant molecules.
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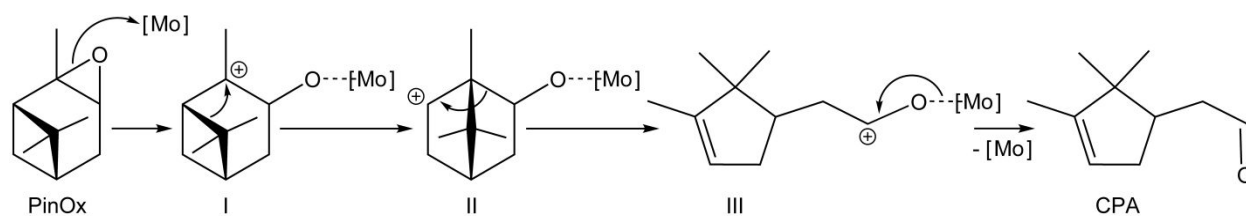


Figure 1. Mechanistic proposal of the conversion of PinOx to CPA in the presence of **1** ([Mo] represents complex **1**).

Considering the results obtained using [bmim][BF₄] as a cosolvent in the ethanolysis of StyOx, we further explored the performance of **1** for the isomerization of PinOx to CPA using this IL and others as solvents (Table 2). The two tetrafluoroborate ILs [bmim][BF₄] and [bmpy][BF₄] (bmpy = N-butyl-3-methylpyridinium) led to complete conversion within 1 h at 35 °C with CPA selectivities of 78-81%. *trans*-Carveol, pinocarveol and less relevant side products such as *iso*-pinocamphone, *trans*-sobrerol and fencholenic aldehyde were formed. Much better catalytic performance was obtained with ILs containing the anion bis(trifluoromethylsulfonyl)imide ([NTf₂]⁻), [bmim][NTf₂], [bmpy][NTf₂] and [Ch][NTf₂] (Ch = choline), which gave complete PinOx conversion within 1 min and CPA selectivities of 86-94%, with the excellent CPA yield of 94% being obtained with [bmpy][NTf₂]. The blank reaction of PinOx in [bmpy][NTf₂] (i.e., without **1**) showed no CPA formation after 30 min.

The catalytic results obtained with the systems **1**/IL are consistent with many other examples of catalysis in ILs in that the choice of the anion can strongly influence the reaction rate and selectivity.^{30,33} In accordance with the results obtained with **1**, MTO displayed better performance for the isomerization of PinOx in [bmim][NTf₂] (100% conversion at 10 min, 60% CPA selectivity) than in [bmim][BF₄] (78% conversion at 10 min, 35% CPA selectivity).³¹ When these two ILs have been compared as solvents in other acid-catalyzed reactions, such as in the benzoylation of aromatic substrates using metal salt catalysts,^{34,35} [bmim][NTf₂] has frequently yielded better results. The anions [BF₄]⁻ and [NTf₂]⁻ impart very different physical properties to the respective ILs that may be responsible for the different catalytic performances observed. In particular, [NTf₂]⁻ is hydrophobic, while [BF₄]⁻ is hydrophilic, and the former has lower basicity/nucleophilicity.^{36,37} Costa *et al.*³² reported that enhanced basicity of the solvent may favor proton shifts of intermediates leading to side products such as *trans*-carveol and pinocarveol. Rocha *et al.*³⁸ reported that (i) the isomerization of the carbenium ion (I) (Figure 1)

Table 2. Isomerization of α -pinene oxide to campholenic aldehyde in the presence of catalyst/ionic liquid combinations^a

Catalytic system	Run	Time (min)	Conversion (%)	CPA yield (%)
1/[bmim][BF ₄]	1	1	87	41
		60	100	81
1/[bmpy][BF ₄]	1	1	92	47
		60	99	78
1/[bmim][NTf ₂]	1	1	100	90
		2	100	92
		3	100	94
1/[bmpy][NTf ₂]	1	1	100	94
		2	100	85
		3	100	52
1/[Ch][NTf ₂]	1	1	100	86
		2	100	91
		3	100	95
		4	100	98
		5	100	98
2/[Ch][NTf ₂]	1	1	100	80
		2	100	59
		3	100	38
ZnCl ₂ /[Ch][NTf ₂]	1	1	100	98
		2	100	75
		3	100	55

^a Reaction conditions: 40 μ mol Mo or W complex or ZnCl₂, 0.82 mmol PinOx, [PinOx] = 0.9 M, 35 °C. CPA yields at 30 min for blank reactions using the IL without catalyst were 14% for [bmim][BF₄], 36% for [bmim][NTf₂], 0% for [bmpy][BF₄], 0% for [bmpy][NTf₂] and 34% for [Ch][NTf₂].

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3 may be sensitive to bonding with nucleophilic species such as anions present in the reaction
4 medium, and (ii) stronger basic solvents (stronger proton-acceptor properties) may favor
5 deprotonation pathways leading to (six-membered carbon ring) *p*-menthenic side products such
6 as *trans*-carveol. Figure S3 in the Supporting Information shows possible side reactions
7 involving intermediate (I) to byproducts such as pinocarveol, *iso*-pinocamphone, fencholenic
8 aldehyde, and (*p*-menthenic type) *trans*-carveol and *trans*-sobrerol.³² According to the
9 mechanistic considerations discussed above, the relatively low nucleophilicity of the anion
10 $[\text{NTf}_2]^-$ may avoid competitive interactions of the solvent with the substrate molecules in the
11 coordination to the Lewis acid metal center, favoring PinOx conversion.^{8,20,32} On the other hand,
12 the hydrophilic contribution from the cation of the IL may enhance the solubilization of the
13 PinOx molecules. Other contributing factors may include viscosity and water content: the ILs
14 with $[\text{NTf}_2]^-$ have lower viscosities and, in their as-received states, lower water contents when
15 compared with the corresponding ILs with $[\text{BF}_4]^-$ (Table S2 in the Supporting Information).
16 Although the ILs were vacuum-dried prior to use in the catalytic reactions, traces of water may
17 still be present which could contribute to the formation of side products.³⁸ Besides the solvent
18 properties and reaction conditions, the acid properties of the catalyst may also influence the
19 product distributions in different ways, depending on the catalytic system.^{32,38,39} The Lewis
20 acidity of complex **1** coupled with an ideal IL solvent favors the (100% atom economy) PinOx
21 conversion to CPA which is formed in very high yields under approximately ambient conditions,
22 which accounts for high reaction and energy efficiency and reduced waste production, in line
23 with green chemistry principles.
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40 For the ILs with $[\text{NTf}_2]^-$, recycling of the catalyst/IL systems was performed in a manner
41 similar to that carried out for the ethanolysis of StyOx in $[\text{bmim}][\text{BF}_4]$. Gas chromatography was
42 used to confirm the complete solvent extraction of the products from the **1**/ $[\text{Ch}][\text{NTf}_2]$ system.
43 The FT-IR spectrum of the IL phase after the extraction step matched the spectrum of the unused
44 IL (Figure S2 in the Supporting Information). Between 3 and 5 catalytic runs were performed for
45 each system (Table 2, Figure 2). The PinOx reaction was complete at 1 min for all cycles
46 performed for each system. While CPA selectivity progressively decreased upon recycling of
47 **1**/ $[\text{bmpy}][\text{NTf}_2]$, the opposite trend was observed with **1**/ $[\text{bmim}][\text{NTf}_2]$ and **1**/ $[\text{Ch}][\text{NTf}_2]$. The
48 yield for the latter system stabilized at the near-quantitative value of 98% for the fourth and fifth
49 cycles.⁴⁰ ICP-OES analysis indicated that the initial amount of molybdenum remained similar;
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9.4 and 9.8 mg Mo per liter of IL for the fresh and recovered catalyst+IL system, respectively, which is within the experimental range of error (5-10%). These results are consistent with the steady PinOx conversion in recycling runs, and validate the efficiency of the solvent extraction protocol used for the CPA product separation and recycling of the catalyst+IL system. To the best of our knowledge, this is the highest yield yet reported for the rearrangement of PinOx to CPA. In a separate experiment, the stability of CPA in this catalytic system was checked by using CPA as a substrate in the presence of **1**/[Ch][NTf₂] (under similar reaction conditions to those used with PinOx as substrate), which led to negligible CPA conversion after 6 h. Hence, the catalytic system **1**/[Ch][NTf₂] did not decompose CPA.

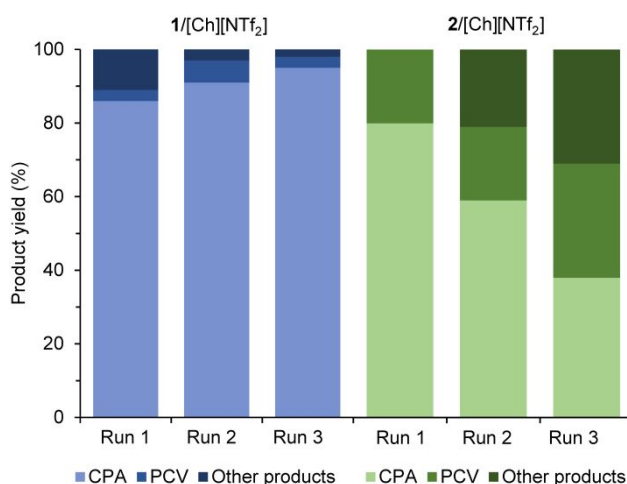


Figure 2. Reaction of α -pinene oxide in the presence of (**1** or **2**)/[Ch][NTf₂]: yields of campholenic aldehyde (CPA), pinocarveol (PCV) and other products at 100% PinOx conversion, 35 °C, 1 min reaction, for three consecutive batch runs.

The performance of the system **1**/[Ch][NTf₂] was compared with that for **2**/[Ch][NTf₂] and ZnCl₂/[Ch][NTf₂] (Table 2, Figure 2). Both of these systems led to complete conversion at 1 min for three reaction cycles. For the tungsten analogue **2**, the CPA selectivity in the first run was slightly lower than that observed for **1** (80% vs. 86%), with pinocarveol being the other product formed with 20% selectivity. In contrast to **1**, a drastic lowering of CPA selectivity was observed upon recycling, with increasing amounts of pinocarveol and other products being formed. Similarly, the system ZnCl₂/[Ch][NTf₂] displayed poor recyclability, with CPA selectivity decreasing from 98% in the first run to 55% in the third run. One cannot rule out the

possibility of ZnCl_2 decomposing into different species in the ionic liquid medium, altering the acidic features.

Overall, this work shows that the molybdenum catalyst **1**, when used with an effective ionic liquid solvent, may offer very high activity and selectivity in the conversion of PinOx to CPA, which is an industrially important reaction. A possible CPA production process using the recyclable ionic liquid-standing mixed-ring molybdenocene-type catalyst is proposed, which may be of interest for future engineering studies. A simplified Process Flow Diagram (PFD) for this catalytic process is given in Figure 3, where the catalytic reaction using a continuous stirred tank reactor (R1) is followed by the recovery of the desired CPA product using a vacuum distillation tower (T1), in a comparable fashion to that suggested in patented technology for PinOx conversion using a zinc halide (salt) catalyst and a solvent with a higher boiling point than CPA.¹⁹

The tower T1 is physically located above the reactor such that the IL+catalyst mixture may be recycled to the reactor under gravity (as mentioned above, the ILs with $[\text{NTf}_2]^-$ have lower viscosities). The CPA product is taken as a condensed overhead liquid stream. The tower T1 overhead pressure may be controlled by throttling a slip stream through the vacuum steam educator ED1. The bottoms temperature (of T1) may be the same or higher than the reactor temperature. The bottoms sump area height may provide the necessary height of liquid to, in turn, provide enough pressure drop across a control valve to allow recycling of the IL+catalyst mixture (stripped of product) back into the reactor R1, under bottoms level control. Further details of the overall process are given in the Supporting Information.

The proposed process advantageously avoids solvent extraction (used in our lab-scale studies) for separating the product from the catalyst, which would also require subsequent distillation of the extract to separate the volatile organic solvent from the desired CPA product. According to the process disclosed in the patent by Kane *et al.*,¹⁹ our catalyst/solvent system may offer an advantage in that the high activity and stability it exhibits may prevent carryover of unreacted PinOx feed into the product during vacuum distillation, which was a limitation to cycle length in the patent. On the other hand, the byproduct drag stream (taken to control build-up of byproducts, Figure 3) is minimized by the exceptionally high selectivity exhibited by our catalyst/solvent system. The very high conversions reached with our catalyst/solvent system

avoid additional distillation units to recycle PinOx and waste production. These features may permit enhanced economic and environmental sustainability.

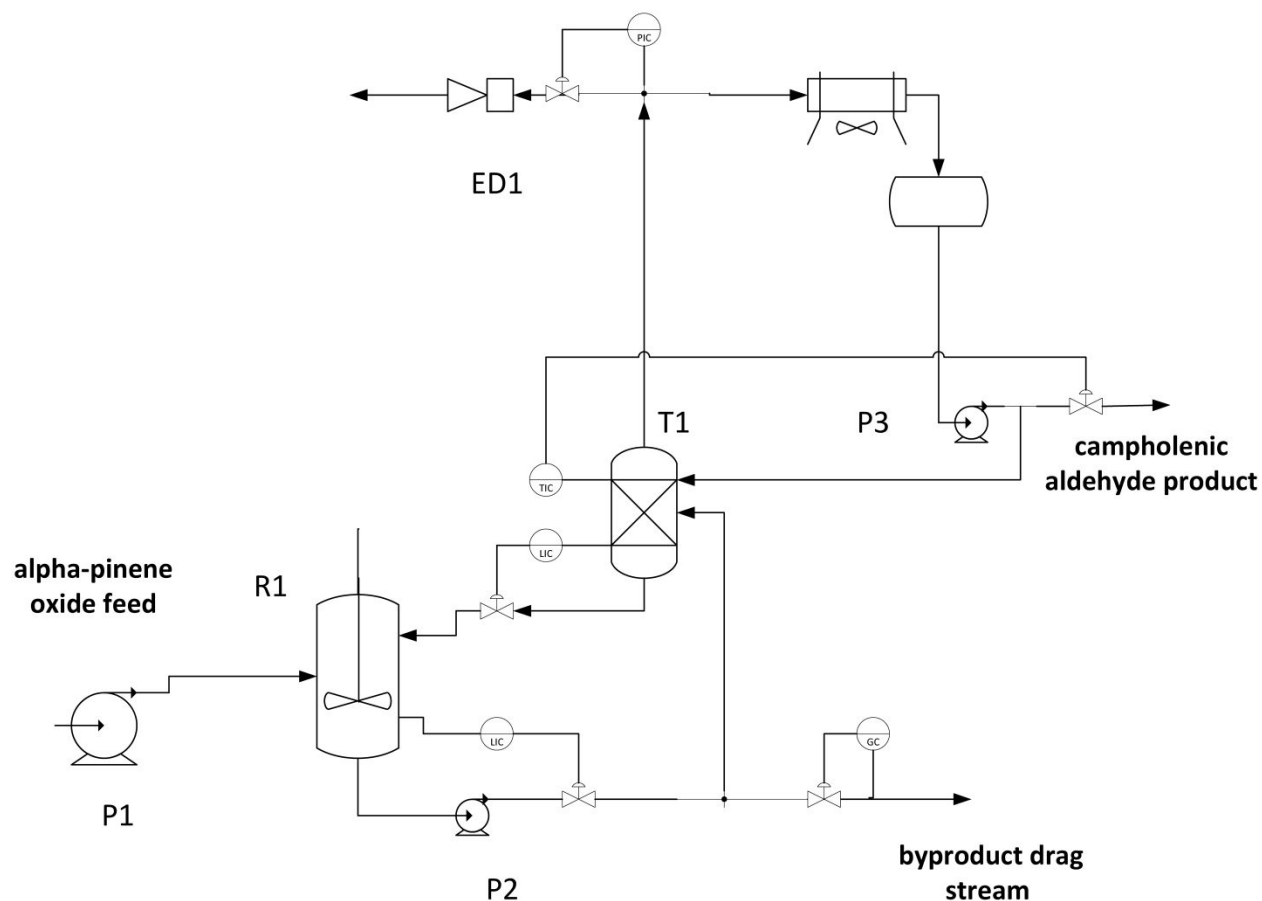


Figure 3. PFD for a possible process to convert α -pinene oxide to campholenic aldehyde product over an ionic liquid-standing mixed-ring molybdenocene-type catalyst: stirred tank reactor R1, distillation tower T1, pumps P1-P3, vacuum steam educator ED1. Only some of the process controls are shown for the sake of clarity.

CONCLUSION

In summary, the cationic Mo^{IV} complex $[\text{IndCpMo}(\text{MeCN})_2](\text{BF}_4)_2$ (**1**) can efficiently promote acid-catalyzed epoxide ring-opening reactions. The desired products, 2-ethoxy-2-phenylethanol from styrene oxide and campholenic aldehyde from α -pinene oxide, can be obtained in excellent yield (100% or close) on a time-scale of minutes at approximately ambient temperature. For the ethanolysis of StyOx, the use of an IL as cosolvent allows recycling while not affecting catalytic performance. For the isomerization of PinOx, the nature of the anion in the IL strongly

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3 influenced catalytic activity, with those containing [NTf₂]⁻ giving better results than those
4 containing [BF₄]⁻ (for the same cation). On the other hand, for the ILs with [NTf₂]⁻, the nature of
5 the cation influenced the recycling performance. Selectivity to CPA increased in recycling runs
6 for [bmim]⁺ and [Ch]⁺, settling at 98% for the latter. As far as we know, this combination of
7 activity, selectivity and recyclability is unprecedented for the liquid-phase catalytic isomerization
8 of PinOx to CPA. A possible process Flow Diagram was designed for producing CPA
9 continuously using the IL+catalyst system, where a stirred tank reactor is in line with a vacuum
10 distillation tower for separating the target CPA product from the IL+catalyst mixture which is
11 recycled back to the reaction. The proposed strategy is comparable to patented technologies,
12 although it may benefit from the high activity, selectivity and relatively good stability of our
13 catalytic system. Organomolybdenum complexes such as molybdenocene derivatives deserve
14 further investigation as promoters of commercially relevant epoxide ring-opening reactions, such
15 as the atom economic and sustainable transformation of α -pinene oxide to campholenic
16 aldehyde.
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28 ASSOCIATED CONTENT

29 **Supporting Information**

30 The Supporting Information is available free of charge on the ACS Publications website at DOI:
31 10.1021/acssuschemeng.xxxxxxx.
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34

35 Experimental procedures, FT-IR spectra, selected physical properties of the ILs used,
36 mechanistic proposal for the conversion of PinOx to side products, table comparing
37 literature data for the catalytic isomerization of α -pinene oxide, full explanation of the
38 PFD for a CPA production process.
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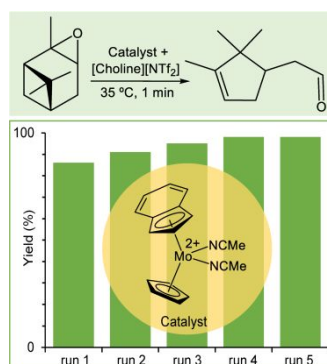
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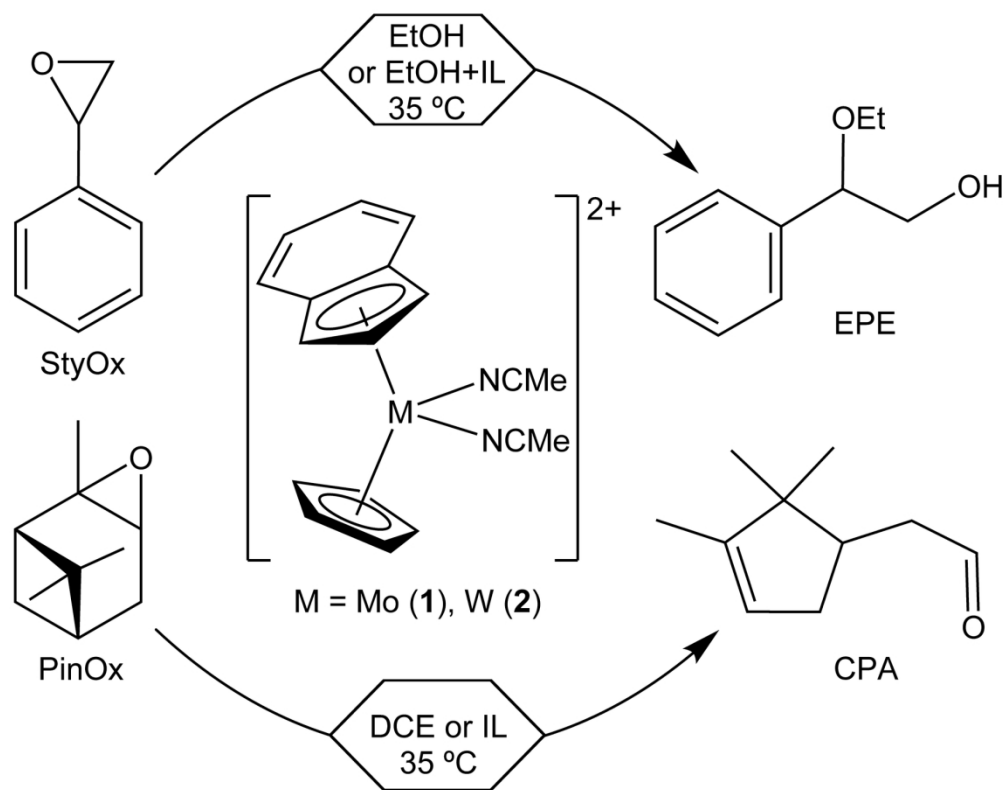
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42 Information.
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41 between consecutive reuses. It is a known fact that ILs contain impurities that may impact on
42 catalytic performances.
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An efficient catalytic process for the atom economic conversion of a biorenewable terpene derivative to a valuable fine chemical is reported.



32 **Scheme 1.** Ethanolsis of styrene oxide to give 2-ethoxy-2-phenylethanol, and isomerization of α -pinene
33 oxide to campholenic aldehyde, in the presence of **1** and **2** (DCE = 1,2-dichloroethane; IL = ionic liquid).

34 81x63mm (600 x 600 DPI)

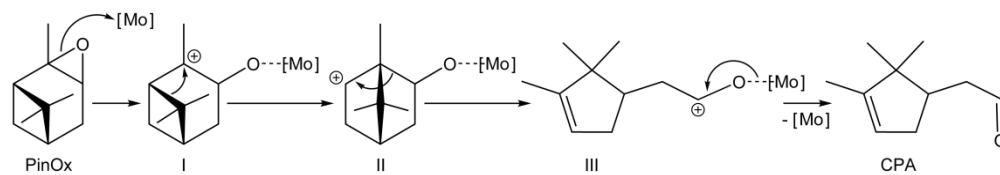


Figure 1. Mechanistic proposal of the conversion of PinOx to CPA in the presence of **1** ($[Mo]$ represents complex **1**).

164x28mm (600 x 600 DPI)

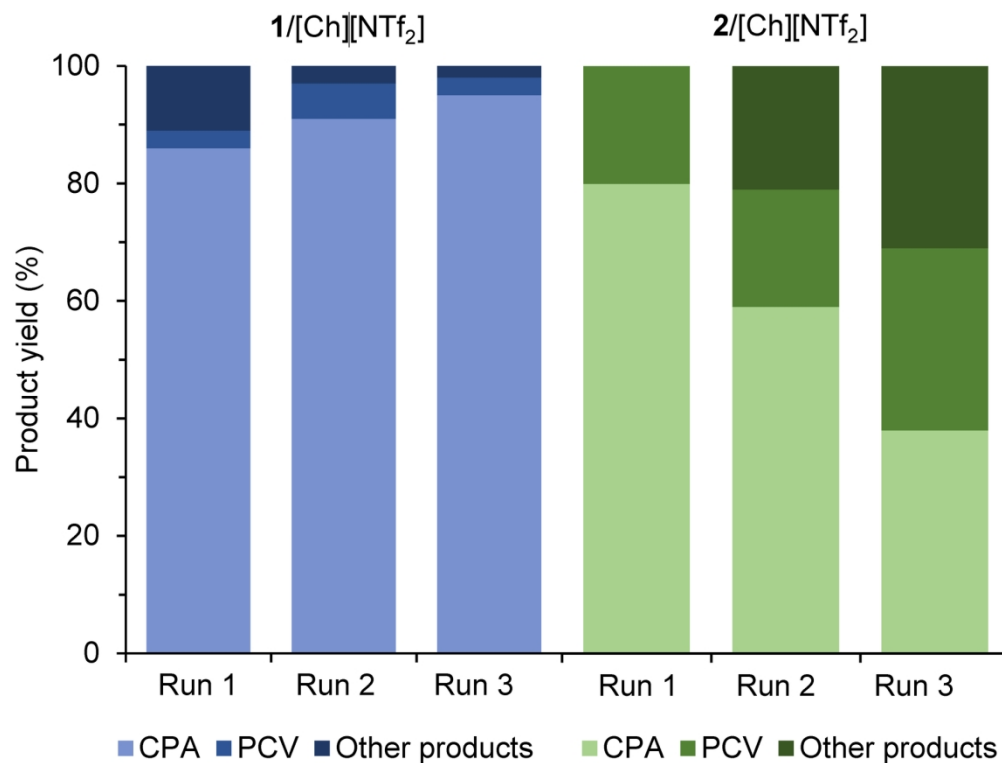


Figure 2. Reaction of α -pinene oxide in the presence of (**1** or **2**)/[Ch][NTf₂]: yields of campholenic aldehyde (CPA), pinocarveol (PCV) and other products at 100% PinOx conversion, 35 °C, 1 min reaction, for three consecutive batch runs.

82x62mm (600 x 600 DPI)

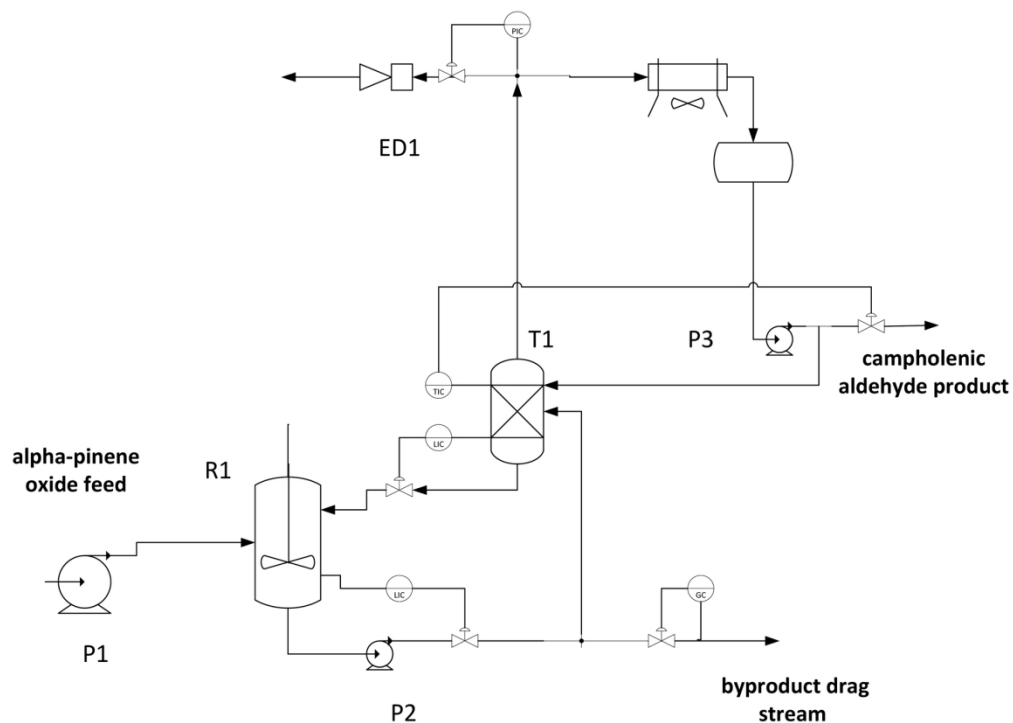
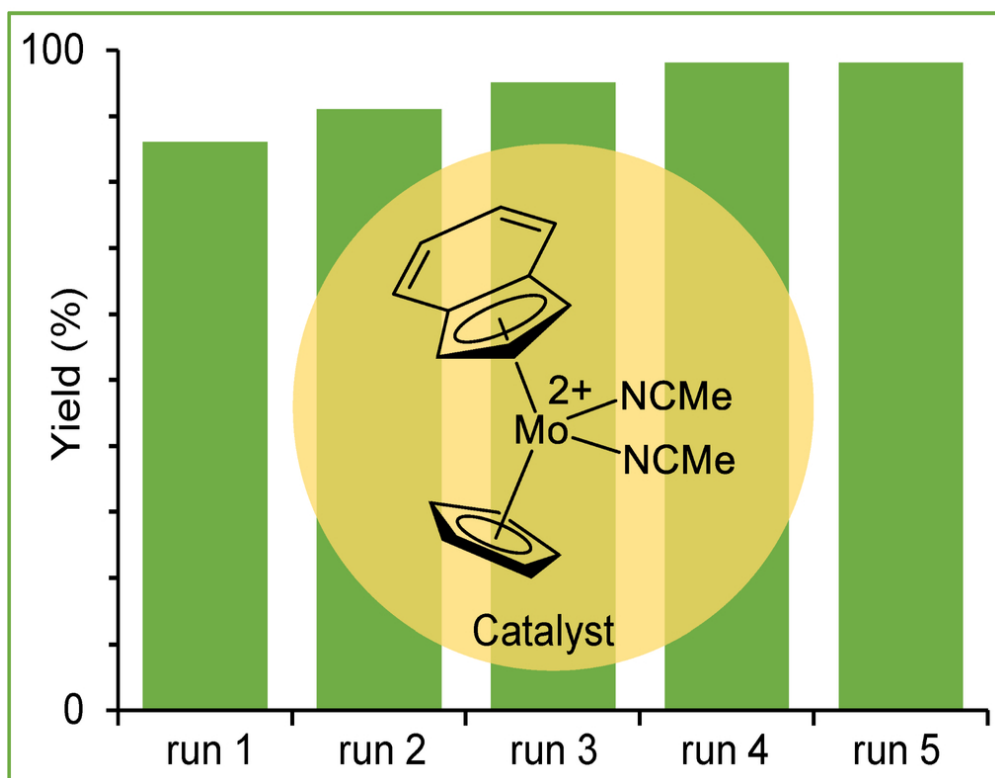
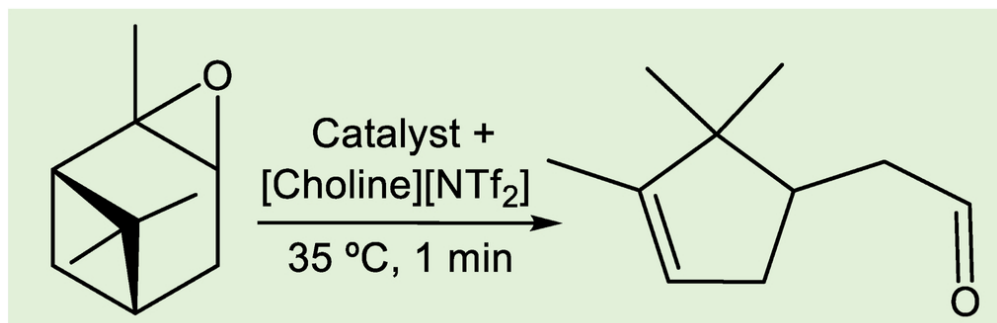


Figure 3. PFD for a possible process to convert α -pinene oxide to campholenic aldehyde product over an ionic liquid-standing mixed-ring molybdenocene-type catalyst: stirred tank reactor R1, distillation tower T1, pumps P1-P3, vacuum steam educator ED1. Only some of the process controls are shown for the sake of clarity.

165x118mm (300 x 300 DPI)



Graphical Abstract

42x47mm (600 x 600 DPI)