Selective isomerization of α-pinene oxide to campholenic aldehyde by ionic liquid-supported indenyl-molybdenum(II)-bipyridine complexes

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ABSTRACT

Campholenic aldehyde (CPA), an important flavor and fragrance intermediate, can be obtained by the Lewis acid-catalyzed isomerization of α-pinene oxide (PinOx), although achieving high yields (>90%) is a difficult challenge due to the high reactivity of the epoxide. In the present work, indenyl-molybdenum(II)-bipyridine complexes [IndMo(bipy^R)(CO)$_2$](BF$_4$) (bipy^R = 2,2′-bipyridine (R = H) or 4,4′-disubstituted-2,2′-bipyridine) have been combined with various ionic liquid solvents to develop an efficient process for the selective conversion of PinOx to CPA under mild (35 °C) conditions. Excellent CPA yields (95%) were repeatedly obtained within 1 min reaction time for the easily recyclable catalytic system comprising [IndMo(4,4′-dinonyl-2,2′-bipyridine)(CO)$_2$](BF$_4$) and choline bis(trifluoromethylsulfonyl)imide.

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1. Introduction

Terpenes and their oxygenated derivatives are valuable chemicals within the food, fragrance, flavor and pharmaceutical industries [1–3]. α-Pinene is the most abundant terpene in nature and a constituent (ca. 45–97%) of turpentine, obtained from pines and other coniferous trees [4]. Epoxidation of α-pinene gives α-pinene oxide (PinOx), which can undergo acid-catalyzed rearrangement to give value-added products such as campholenic aldehyde (CPA), *trans*-carveol (TCV), isopinocamphone, pinocarveol, *p*-cymene and *trans*-sobrerol [5–12].

CPA is one of the most important products of PinOx isomerization. It is used, for example, as an intermediate in the synthesis of fragrances such as naturanol and sandalore® [13,14]. Sandalore®, an effective substitute for natural sandalwood oil, may be a cosmetic treatment option for hair loss disorders [15]. CPA formation is favored in the presence of Lewis acid catalysts. The conventional process, carried out in a batch reactor and catalyzed by zinc halides (ZnCl$_2$ and ZnBr$_2$), has several drawbacks such as relatively poor selectivity, catalyst deactivation, difficult catalyst recycling and toxic zinc-containing waste disposal issues [16], which have led to the search for alternative catalysts for the conversion of PinOx to CPA. Table S1 in the Supplementary Materials lists PinOx conversions, CPA and TCV yields for various homogeneous and supported or bulk heterogeneous catalysts that have been tested in this rearrangement reaction.

In the fine chemicals industry, the use of organometallic Lewis acid catalysts for the manufacture of intermediates and products has great appeal due to the high selectivity often reachable with such catalysts together with their easy modification by ligand exchange [17]. We have explored the ability of organometallic complexes to promote ring-opening reactions of epoxides under mild conditions. For the reaction of PinOx in 1,2-dichloroethane (DCE) at 35–55 °C, catalytic activities and CPA yields (at >97% PinOx conversion) varied considerably from catalyst to catalyst, e.g. 51% at 24 h for the cyclopentadienyl (Cp) complex [CpMo(CO)$_3$CH$_2$COOH] [18], 56% at 3 h for the indenyl (Ind) complex [(η^5-Ind)Mo(η^3-C$_3$H$_5$)(CO)$_2$] [19], 62% at 1 h for methyltrioxorhenium(VII) [20], 67% at 30 min for the bimetallic complex [{(η^5-Ind)Mo(CO)$_2$(μ-Cl)}$_2$] [21], and 87% at 1 h for the mixed-ring complex [IndCpMo(MeCN)$_2$](BF$_4$)$_2$ [22]. For the mixed-ring complex, the same CPA yield could be achieved within 1 min at 35 °C by using the ionic liquid (IL) choline bis(trifluoromethylsulfonyl)imide, [Ch][NTf$_2$], as a solvent instead of DCE. CPA yields at 1 min reached near-quantitative values (98%) upon recycling of the catalyst/IL mixture. To date, very few catalytic systems have achieved CPA yields comparable to those for [IndCpMo(MeCN)$_2$](BF$_4$)$_2$/[Ch][NTf$_2$] (i.e. > 85%, Table S1 in the Supplementary Materials), and efficient catalyst recycling is rarely demonstrated.

Molecular catalysts "immobilized" in ILs constitute systems that combine advantages of homogeneous catalysis (e.g. reduced mass transfer resistances, enhanced accessibility of the reactant to the

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active species) and heterogeneous catalysis (facilitated recovery and reuse of the IL+catalyst mixture, leading to enhanced catalyst productivity). Apart from the study with [IndCpMo(MeCN)$_2$](BF$_4$)$_2$ and its tungsten analog [22], methyltrioxorhenium(VII) is the only other organometallic catalyst that has been used in association with ILs for the isomerization of PinOx [20].

A recent study found that the indenyl molybdenum carbonyl complex [IndMo(CO)$_2$(bipy^H)](BF$_4$) (bipy^H = 2,2′-bipyridine) led to superior catalytic performance (compared to previously studied complexes) in the ring-opening reaction of epoxides with alcohols to give β-alkoxy alcohols [23]. We have been exploring the catalytic potential of these types of complexes for other acid-catalyzed reactions and now wish to describe the excellent results obtained for PinOx isomerization with catalyst systems based on the bipyridine complexes [IndMo(bipy^R)(CO)$_2$](BF$_4$) and ILs containing the NTf$_2^-$ anion. Catalytic performance is strongly influenced by the reaction conditions (catalyst amount, PinOx concentration, reaction temperature) and type of cation in the IL. It is shown that the dicarbonyl complexes have the advantage of a co-ordinated 2,2′-bipyridine that allows further catalyst improvement through functionalization with appropriate substituents.

2. Experimental

2.1. Materials and methods

All preparations and manipulations were carried out using standard Schlenk techniques under nitrogen. The catalyst synthesis precursor [IndMo(η^3-C$_3$H$_5$)(CO)$_2$] was prepared from [Mo(η^3-C$_3$H$_5$)(CO)$_2$(NCMe)$_2$Cl] [24] and LiInd according to previously reported procedures [25].

Hexacarbonyl molybdenum (technical grade), allyl chloride (99%), indene (technical, ≥90%), sec–butyllithium solution (1.6 M in hexanes), HBF$_4$ (solution in diethyl ether), anhydrous THF (≥99.9%), anhydrous dichloromethane (≥99.8%), *n*-hexane (≥98.5%, Carlo Erba), acetonitrile (≥99.9%, Riedel-de Haën), diethyl ether (≥99.8%, Riedel-de Haën), 2,2′-bipyridine (Fluka, 97%), 4,4′-di–*tert*–butyl-2,2′-bipyridine (98%), 4,4′-dinonyl-2,2′-bipyridine (97%), α-pinene oxide (97%), and anhydrous *n*-pentane (≥99%) were purchased from Sigma-Aldrich (unless otherwise indicated) and used as received. The ionic liquids choline bis(trifluoromethylsulfonyl)imide (99%), butyltrimethylammonium bis(trifluoromethylsulfonyl)imide (99%), 1–butyl–3–methylimidazolium bis(trifluoromethylsulfonyl)imide (99%), and 1–butyl–4–methylpyridinium bis(trifluoromethylsulfonyl)imide (99%) were acquired from Io-li-tec and vacuum-dried for 2 h at 100 °C prior to use.

Microanalyses for C, H and N were carried out at the Department of Chemistry, University of Aveiro, with a TruSpec Micro CHNS 630–200–200 elemental analyzer (Leco, Saint Joseph, MI, USA). FT-IR spectra (KBr pellets) were recorded using a Unicam-Mattson 7000 spectrophotometer. Solution ^{1}H and ^{13}C NMR spectra were measured with a Bruker CXP 300 instrument at ambient temperature (295 K).

2.2. Preparation of [IndMo(bipy^R)(CO)$_2$](BF$_4$) (bipy^R = 2,2′-bipyridine (R = H) (**1**), 4,4′-di–tert–butyl–2,2′-bipyridine (R = tBu) (**2**) or 4,4′-dinonyl-2,2′-bipyridine (R = nonyl) (**3**))

The complexes [IndMo(bipy^R)(CO)$_2$](BF$_4$) were synthesized by adapting previously reported procedures (Scheme 1) [26]. One molar equivalent of HBF$_4$·Et$_2$O was added to a stirred solution of [IndMo(η^3-C$_3$H$_5$)(CO)$_2$] in CH$_2$Cl$_2$ (ca. 0.08 M) at ambient temperature, giving the adduct [IndMo(η^3-C$_3$H$_5$)(CO)$_2$(FBF$_3$)]. After stirring for 30 min (for bipy^H) or 1 min (for bipy^{tBu} and bipy^{nonyl}), the ligand bipy^R was added (1 equiv.) and the mixture was stirred for

1 h at ambient temperature. After concentration of the mixture via solvent evaporation (under vacuum), the addition of *n*-hexane and diethyl ether led to the precipitation of the pink-red solids **1** and **2**, and the dark-red solid **3**. ^{1}H NMR and FT-IR (ν(CO)) data for **1** (vide infra) matched those reported previously for the same complex [26].

Data for **1**. Yield: 0.54 g, 76%. Anal. Calcd for C$_{21}$H$_{15}$BF$_4$MoN$_2$O$_2$ (510.10): C, 49.45; H, 2.96; N, 5.49. Found: C, 49.37; H, 3.11; N, 5.68%. Selected FT-IR (KBr): ν(CO) 1975, 1958, 1902, 1872 vs cm^{-1}. ^{1}H NMR (NCMe-d$_3$): δ 9.38 (ddd, 2H, bipy-H), 8.31 (ddd, 2H, bipy-H), 8.08 (ddd, 2H, bipy-H), 7.58 (ddd, 2H, bipy-H), 6.95 (m, 2H, H$^{5-8}$), 6.67 (m, 2H, H$^{5-8}$), 6.47 (dd, 2H, H$^{1/3}$), 5.47 (t, 1H, H^2) ppm. ^{13}C NMR (NCMe-d$_3$): δ 251.88 (CO), [157.34, 153.41, 140.79, 125.82, 119.50] (CH, bipy), [130.23, 126.57, 126.49, 92.50, 79.87] (CH, Ind) ppm.

Data for **2**. Yield: 0.63 g, 95%. Anal. Calcd for C$_{29}$H$_{31}$BF$_4$MoN$_2$O$_2$ (622.31): C, 55.97; H, 5.02; N, 4.50. Found: C, 55.71; H, 4.77; N, 4.70%. Selected FT-IR (KBr): ν(CO) 1968, 1887 vs cm^{-1}. ^{1}H NMR (NCMe-d$_3$): δ 9.23 (dd, 2H, bipy-H), 8.26 (dd, 2H, bipy-H), 7.58 (dd, 2H, bipy-H), 6.92 (m, 2H, H$^{5-8}$), 6.65 (m, 2H, H$^{5-8}$), 6.48 (dd, 2H, H$^{1/3}$), 5.46 (t, 1H, H^2), 1.42 (s, 18H, CH$_3$) ppm. ^{13}C NMR (NCMe-d$_3$): δ 252.71 (CO), [166.01, 156.85, 153.54, 123.06, 119.74] (CH, bipy), [130.18, 126.33, 124.08, 92.55, 79.78] (CH, Ind), 36.40 (*C*(CH$_3$)$_3$), 30.23 (C(*C*H$_3$)$_3$) ppm.

Data for **3**. Yield: 0.27 g, 50%. Anal. Calcd for C$_{39}$H$_{51}$BF$_4$MoN$_2$O$_2$ (762.58): C, 61.43; H, 6.74; N, 3.67. Found: C, 61.08; H, 6.48; N, 3.72%. Selected FT-IR (KBr): ν(CO) 1972, 1891 vs cm^{-1}. ^{1}H NMR (CH$_2$Cl$_2$-d$_2$): δ 9.20 (d, 2H, bipy-H), 8.01 (d, 2H, bipy-H), 7.40 (dd, 2H, bipy-H), 6.98 (m, 2H, H$^{5-8}$), 6.70 (m, 2H, H$^{5-8}$), 6.41 (d, 2H, H$^{1/3}$), 5.35 (t, 1H, H^2), 2.82 (t, 4H, CH$_2$), 1.70 (m, 4H, CH$_2$), 1.22–1.35 (m, 24H, CH$_2$), 0.87 (m, 6H, CH$_3$) ppm. ^{13}C NMR (CH$_2$Cl$_2$-d$_2$): δ 250.40 (CO), [157.28, 155.74, 152.27, 124.40, 118.68] (CH, bipy), [129.31, 126.20, 125.60, 91.16, 78.57] (CH, Ind), [35.38, 31.89, 30.21, 29.51, 29.38, 29.31, 29.19, 22.71] (CH$_2$, nonyl), 13.91 (CH$_3$, nonyl) ppm.

2.3. Catalytic tests

The catalytic reactions were carried out with magnetic stirring (1000 rpm) under air atmosphere in 5 mL borosilicate reaction vessels which were closed and immersed in an oil bath set to 35 °C. The reaction mixtures consisted of PinOx (820–8200 μmol), catalyst (25.6–40 μmol) and IL (780 μL) as solvent. Reaction time was counted from the instant that the pre-heated (10 min at 35 °C) substrate was added to the pre-heated reactor containing catalyst and IL.

Samples were withdrawn and analyzed using a Varian 3800 GC equipped with a Bruker BR-5 capillary column (30 m × 0.25 mm; 0.25 μm) and a flame ionization detector, with H$_2$ as the carrier gas. The concentrations of PinOx and corresponding reaction products were calculated based on calibrations using cyclododecane epoxide as internal standard. The calculated concentrations are reliable (experimental range of error of ca. 5–7%), i.e., the conversion values account for substrate consumption irrespective of the types of products formed being detected or not by GC. The products were identified (based on mass spectra similarities and commercial databases Wiley229 and NIST14) using a Shimadzu QP2010 ultra GC–MS coupled to a Shimadzu AOC-20i autosampler, with a quadrupole mass spectrometric detection system equipped with a Phenomenex Zebron ZB5-MS capillary column (30 m × 0.25 mm; 0.25 μm), using He as the carrier gas.

Catalyst reuse was performed for selected systems. The reaction products were extracted from the IL phase using *n*-pentane, followed by centrifugation to accelerate L-L phase separation. The recovered IL solution was dried under vacuum (40 °C, 1 h, <0.1 bar) and analyzed by GC to confirm the absence of reaction products
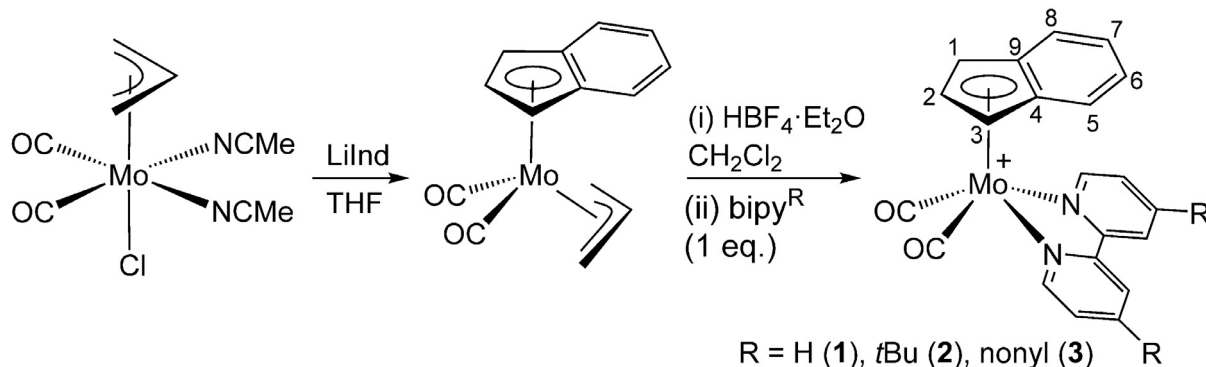
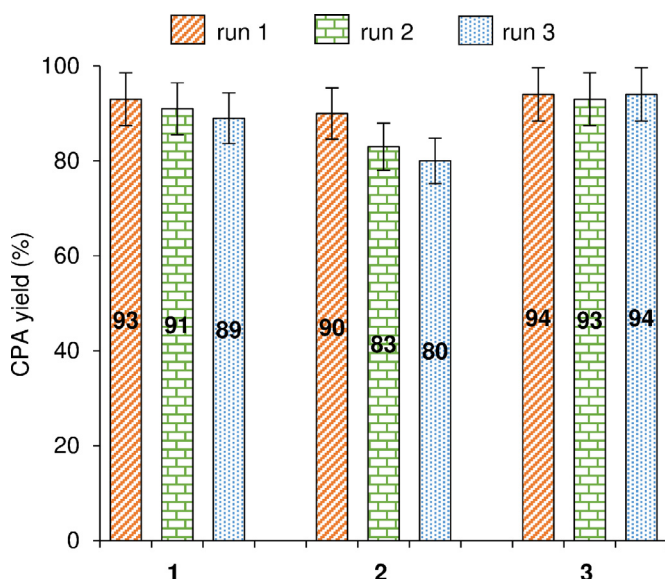**Scheme 1.** Preparation of complexes **1**–**3**.

Fig. 1. Catalyst reuse in consecutive one minute batch runs of PinOx isomerization in the presence of complexes **1**–**3** (error bars are included). Reaction conditions: solvent [Ch][NTf$_2$], 35 °C, Mo:PinOx molar ratio = 1:20.

after solvent extraction. In the reuse of the IL phase containing the catalyst, PinOx was added in an amount equivalent to that used for the first batch run.

3. Results and discussion

The catalytic performances of complexes **1**–**3** (Scheme 1) were investigated for PinOx isomerization under mild conditions (35 °C, atmospheric pressure) using [Ch][NTf$_2$] as solvent. The three com-

plexes possessed very high activity, leading to 100% conversion within 1 min reaction, and CPA was the main product, formed in 90–94% yield (Fig. 1, Scheme 2). Without catalyst, CPA yield was 34% at 30 min. Other products included *trans*-carveol (TCV) and (less frequently) *trans*-pinocarveol (PCV). All three complexes perform better than the best previously found organomolybdenum catalyst for this reaction, namely [IndCpMo(MeCN)$_2$](BF$_4$)$_2$, which led to 86% CPA yield after 1 min in [Ch][NTf$_2$] (Mo:PinOx = 1:20, 35 °C) [22].

The molybdenum-catalyzed isomerization of PinOx may proceed via the coordination of the substrate to the molybdenum center, upon which oxirane ring opening occurs (forming a {C-O–Mo} bridge) with concomitant formation of a carbenium ion that may subsequently undergo rearrangements (alkyl shifts, opening of the aliphatic ring) to give CPA (Scheme 3) [27–29]. The coordination of PinOx to the metal center may be accompanied by changes in the coordination sphere of the organometallic complex, e.g., associated with the flexible hapticity (η^5/η^3 haptotropic shifts) of the coordinated Ind ligand [30]. The reaction rate and CPA yields for **1**–**3** exceeded those for the synthesis precursor complex [IndMo(η^3-C$_3$H$_5$)(CO)$_2$] (79%/80% CPA yield at 1 min/10 min, Table 1). These results may be partly due to electronic effects. Complexes **1**–**3** are cationic whereas the allyl complex is neutral, and thus the Lewis acidity of the metal species may be considerably different, influencing the catalytic activity. On the other hand, the kinetics of the dissolution of the cationic complexes in the IL medium may be faster than that of the neutral complex, favoring the overall reaction.

Following the above comments, ligand modification in organometallic catalysts for PinOx isomerization can be pursued to alter the Lewis acidity of the metal center (and hence catalytic activity and selectivity) and/or catalyst solubility. In the case of 2,2′-bipyridine, the introduction of electron-donating or electron-withdrawing groups at the 4,4′-position can increase or
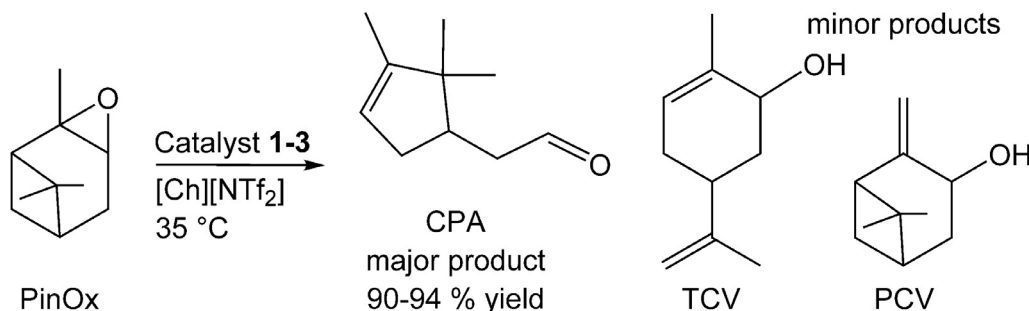
Scheme 2. Products obtained in the isomerization of PinOx in the presence of **1**–**3** as catalyst and the IL [Ch][NTf$_2$] as solvent.

Table 1

Catalytic isomerization of PinOx in the presence of complexes **1–3** and the synthesis precursor.[a]

Complex	Run	t (min)	Conv. (%)[b]	Selectivity (%)		
				CPA	TCV	Other[c]
[IndMo(η^3-C$_3$H$_5$)(CO)$_2$]	1	1	100	79	6	15
		10	100	80	5	15
[IndMo(η^3-C$_3$H$_5$)(CO)$_2$][d]		10	100	60	14	26 (11)
1	1	1	100	93	0	7
1[d]	1	1	100	72	0	28 (5)
2	1	1	100	90	1	9
2[d]	1	1	100	68	5	27 (6)
3	1	1	100	94	0	6
3[d]	1	1	100	75	0	25 (5)

[a] Reaction conditions: Mo:PinOx molar ratio of 1:20, pre-dried [Ch][NTf$_2$] as solvent, [PinOx] = 0.9 M, [Mo] = 0.044 M. [b] PinOx conversion. [c] Other reaction products formed. Values in parentheses are for *trans*-sobrerol. [d] The IL was used as received (ca. 85 ppm water content).

Table 2

Influence of the PinOx reaction conditions on CPA formation using **3**/[Ch][NTf$_2$].

| Entry	Mo:PinOx molar ratio	[Mo] (M)[a]	[PinOx] (M)[a]	T (°C)[b]	t (min)	Conv. (%)[c]	CPA yield (%)	TOF[d]
1	1:20	0.044	0.9	35	1	100	94	1200
2					10	100	94	
3	1:31	0.028	0.9	35	1	97	82	1800
4					10	98	83	
5	1:100	0.028	2.8	35	1	46	43	2760
6					10	94	86	
7	1:200	0.019	3.9	35	1	15	13	1800
8					10	91	86	
9	1:200	0.019	3.9	55	1	48	46	5760
10					10	95	86	
11					30	99	87	
12					60	100	90	

[a] [Mo] and [PinOx] are the initial molar concentrations. [b] T is the reaction temperature. [c] PinOx conversion. [d] Initial turnover frequency (mol mol$_{Mo}^{-1}$ h^{-1}).

decrease electron density at the metal center (while excluding steric effects since the substituents are far away from the metal). For complexes **1–3**, however, changing the substituent at the 4,4′-position did not result in considerable differences in activity, although differences in recycling stability were observed (vide infra).

Complexes **1–3** were reused under typical conditions (Mo:PinOx = 1:20; 0.9 M PinOx, 0.044 M complex). For the three complexes, the reaction was complete within 1 min in three batch runs (accumulated TON = 60), although CPA yield varied in some cases. For **1**, the CPA yield decreased slightly from 93% in run 1 to 89% in run 3. For **2**, the CPA yield decreased from run 1 to run 2 (90 and 83%, respectively) and then remained similar (80% in run 3); increasing the reaction time from 1 to 10 min led to CPA yields of 90% in run 2 and 93% in run 3. Complex **3** displayed very stable recycling performance, leading to 93–94% CPA yield for all three runs.

The influence of the reaction conditions on the isomerization of PinOx was studied for the catalytic system **3**/[Ch][NTf$_2$] (Table 2). The CPA yield of 94% did not change between 1 and 10 min reaction under the standard reaction conditions, i.e., 35 °C, Mo:PinOx = 1:20, 0.9 M PinOx, 0.044 M complex, indicating a rel-

atively fast and selective formation of CPA (Table 2, entries 1 and 2). Keeping the initial PinOx molar concentration constant, a 36% decrease in the catalyst concentration (to give Mo:PinOx = 1:31) led to a decrease in CPA yield from 94% to 82–83% (1–10 min, entries 3 and 4). Under these conditions, the catalyst/IL mixture still exhibited stable recycling performance, leading to 88% CPA yield at 1 min in the second run. Increasing the substrate to catalyst ratio to 100 (by increasing the PinOx concentration to 2.80 M) led to a slower reaction (conversion at 1 min decreased from 97% to 46%, entries 3 and 5 in Table 2). Nevertheless, 86%/95% CPA yield was reached at 10 min/30 min reaction, and the reused catalyst/IL performed steadily under these conditions (86%/88% CPA yield at 10 min, for run 1/run 2). These results, i.e., converting a concentrated PinOx solution to CPA in high yields, are interesting from the viewpoint of process intensification. A further decrease in the catalyst concentration to 0.019 M coupled with an increase in [PinOx] to 3.9 M, to give Mo:PinOx = 1:200, led to a considerably slower reaction (15% conversion at 1 min, Table 2, entry 7), although 86%/92% CPA yield was reached at 10 min/60 min. The initial reaction rate under these conditions (3.9 M PinOx, Mo:PinOx = 1:200) was enhanced by increasing the temperature from 35 to 55 °C: the turnover frequency increased from 1800 to 5760 mol mol$_{Mo}^{-1}$ h^{-1},
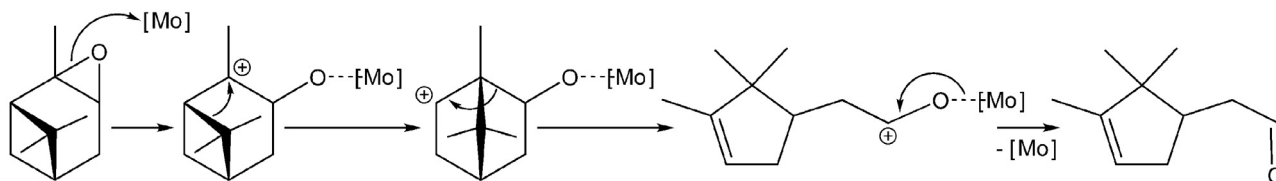
Scheme 3. Plausible reaction mechanism of PinOx isomerization to CPA in the presence of the molybdenum catalyst.
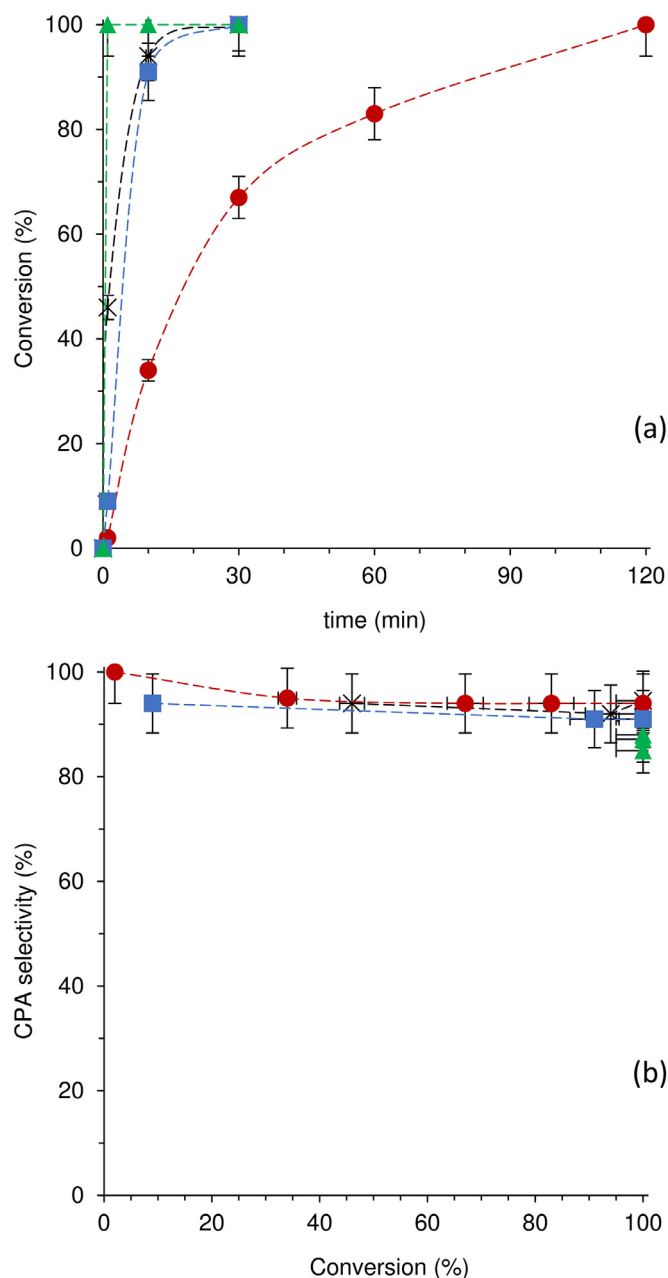
(a)

(b)

Fig. 2. PinOx isomerization in the presence of **3** using the ILs [Ch][NTf₂] (×), [btma][NTf₂] (●), [bmim][NTf₂] (■) or [bmpy][NTf₂] (▲) as solvents. The dashed lines are visual guides and error bars are included. Reaction conditions: Mo:PinOx molar ratio = 1:100, [Mo] = 0.028 M, [PinOx] = 2.8 M, 35 °C.

Chart 1. Structures of the ILs possessing the anion NTf₂⁻ and the cation [choline]⁺, butyltrimethylammonium ([btma]⁺), 1–butyl–3–methylimidazolium ([bmim]⁺) or 1–butyl–4–methylpyridinium ([bmpy]⁺).

and 90% CPA yield was reached at 60 min (Table 2, entries 9–12). Overall, the initial CPA yields were enhanced by using more dilute PinOx solutions and higher Mo:PinOx ratios.

In this work the IL [Ch][NTf₂] was chosen as the solvent due to the promising results obtained previously with [IndCpMo(MeCN)₂](BF₄)₂ [22] together with the fact that choline-based ILs are generally considered as being environmentally benign owing to the low toxicity and biodegradability of the cholinium cation, [NMe₃(CH₂CH₂OH)]⁺ [31]. ILs possessing NTf₂⁻ are attractive since this anion is weakly coordinating, hydrophobic, and establishes weak coulombic interactions with relatively large asymmetric cations in ILs [32], which may influence important properties such as solubility and viscosity. Hence, to study the influence of the IL on the catalytic performance of **3** for PinOx isomerization,
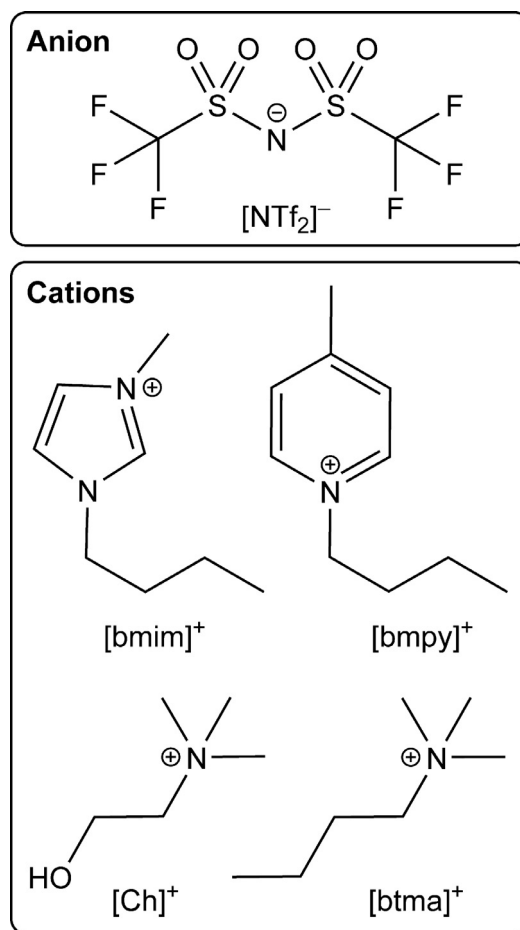
we compared four ILs based on the NTf₂⁻ anion and having different organic cations, namely [choline]⁺, butyltrimethylammonium ([btma]⁺), 1–butyl–3–methylimidazolium ([bmim]⁺), and 1–butyl–4-methylpyridinium ([bmpy]⁺) (Chart 1). For a clearer evaluation of the initial reaction rate, the conditions used were Mo:PinOx molar ratio = 1:100, [Mo] = 0.028 M and [PinOx] = 2.8 M (Fig. 2). The reaction was faster for [cation]⁺ = [bmpy]⁺ (TOF = 6000 mol mol$_{Mo}^{-1}$ h^{-1}), intermediate for [Ch]⁺ and [bmim]⁺, and slower for [btma]⁺. The CPA selectivity vs PinOx conversion profiles were similar for the latter three systems, with maximum yields of 91–95% being reached at 100% conversion (Fig. 2b). CPA selectivity was slightly lower for [bmpy][NTf₂] (85–88%). The differences in reaction kinetics may be due to an interplay of several factors. Complex **3** was not completely soluble in the pure ILs, although it dissolved completely after the addition of PinOx. The pyridinium IL [bmpy][NTf₂] may allow a faster initial dissolution of the metal species, thereby leading to a higher overall reaction rate.

Besides the kinetics of the dissolution process, the viscosity and water contents of the ILs may influence the catalytic reaction. The IL with [cation]⁺ = [btma]⁺ is far more viscous (100 cP) than the remaining ILs (49–54 cP; Table 3), which may contribute to the slower reaction observed (100% conversion reached after 2 h, compared to less than 30 min for the other ILs, Fig. 2a). Although the ILs were treated under primary vacuum prior to the catalytic reaction (100 °C, 2 h, < 0.1 bar), it is likely that water was not completely removed. Based on the above mechanistic considerations, water may compete with PinOx in the coordination

Table 3
Thermal and physicochemical properties of ionic liquids used in this work.

Ionic liquid	Melting point (°C)[a]	Viscosity (cP)[a]	Density (g/cm^3)	Water content (ppm)
[btma][NTf$_2$]	< rt	100 (25 °C)	1.395 (24 °C)	56
[bmim][NTf$_2$]	−4	49 (25 °C)	1.44 (19 °C)	80
[bmpy][NTf$_2$]	10	54 (25 °C)	1.41 (22 °C)	50
[Ch][NTf$_2$]	35–37	50 (45 °C)	–	85

[a] Data obtained from https://iolitec.de (consulted 20 April 2021).

to the metal center, retarding the catalytic reaction. The ILs with [cation]$^+$ = [bmim]$^+$ and [Ch]$^+$ possessed similar water contents (80–85 ppm) and led to roughly coincident kinetic profiles (100% conversion at 30 min). On the other hand, the IL [bmpy][NTf$_2$], possessing a low water content (50 ppm) and low viscosity (54 cP), led to the fastest PinOx reaction (100% conversion at 1 min, 85% CPA yield). Although the systems with [Ch][NTf$_2$] and [btma][NTf$_2$] required longer reaction times (30 and 120 min, respectively) to reach complete conversion, an excellent CPA yield of 95% was obtained.

To support the hypothesis of the negative effect of water on the PinOx to CPA reaction system, catalytic tests were carried out using [Ch][NTf$_2$] without pre-treatment (Table 1). For all complexes prepared, the CPA selectivity dropped significantly (e.g., from 94% to 75%, at 100% conversion, for **3**), and the other products formed included *trans*-sobrerol. According to the literature, *trans*-sobrerol may be formed in the presence of water via a parallel pathway to that leading to CPA [12,27,33]. An additional catalytic test was carried out for the very active system **3**/[bmpy][NTf$_2$], using the IL without pre-treatment, which led to slower reaction of PinOx and lower CPA selectivity; 48% CPA selectivity at 75% conversion, compared to 85% selectivity at 100% conversion for the pre-treated IL (at 1 min, Fig. 2). For the latter system, TCV and *trans*-sobrerol were formed with 8% and 4% selectivity, respectively. Besides the above physical factors associated with the IL which may influence the catalytic performance, one cannot rule out possible chemical factors (e.g., types of active species in the IL medium). However, attempts to isolate metal species from the ILs were unsuccessful.

4. Conclusions

The organometallic cations used in this work, [IndMo(bipy^R)(CO)$_2$]$^+$, are readily prepared in good isolated yields by protonation of the starting complex [IndMo(η^3-C$_3$H$_5$)(CO)$_2$] with HBF$_4$·OEt$_2$, followed by addition of the desired bipy^R ligand. For the reaction of PinOx in the ionic liquid [Ch][NTf$_2$] under mild conditions (35 °C), the starting complex and organometallic cations display very high catalytic activities, leading to complete substrate conversion within one minute. Whereas yields of campholenic aldehyde do not exceed 80% in the presence of the starting η^3-allyl complex, the cationic complexes can afford up to near-quantitative (95%) yields. The nature of the substituent on the bipyridine ligand seems to exert an important influence on catalyst recycling, with the long nonyl group giving a complex that can be recycled together with the IL without loss of performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2022.122372.

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