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Combining Bio- and Chemo-Catalysis for the Conversion of Bio-Renewable Alcohols: Homogeneous Iridium Catalysed Hydrogen Transfer Initiated Dehydration of 1,3-Propanediol to Aldehydes

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Abstract.

Combining whole cell biocatalysis and chemocatalysis in a single reaction sequence avoids unnecessary separations, and the associated waste and energy consumption. Bacterial fermentation has been employed to convert waste glycerol from biodiesel production into 1,3-propanediol. This 1,3-propanediol can be extracted selectively from the aqueous fermentation broth using ionic liquids. 1,3-propanediol in ionic liquid solution was converted to propionaldehyde by hydrogen transfer initiated dehydration (HTID) catalysed by a Cp*IrCl₂(NHC) (Cp* = pentamethylcyclopentadienyl; NHC = carbene ligand) complex. The use of an ionic liquid solvent enabled the reaction to be performed under reduced pressure, facilitating the isolation of the product, and improving the reaction selectivity. The Ir(III) catalyst in ionic liquid was found to be highly recyclable.

Introduction.

The success of the oil and petrochemical industries can be attributed to the production of transportable fuels in parallel with the synthesis of chemicals, and in particular precursors to polymers and materials. Of the alternatives to fossil fuel energies, only biomass presents similar opportunities, and by analogy the production of biofuels is rendered more economical by coupling it to the production of chemicals from biomass, for example in a biorefinery. The conversion of food producing land to energy crops is understandably controversial, and should be avoided. More sustainable is the production of fuels from agricultural and food wastes. These wastes are ubiquitous, as all animals must eat, and therefore their utilisation provides real opportunities to develop low waste, highly sustainable industries. In Europe

used fats and oils are being upcycled into biodiesel in industrial plants on 100 thousand ton per annum scale. Biodiesel is a transportable bio-derived fuel, but production generates waste glycerol. This provides opportunities to introduce parallel chemicals production, but unfortunately the crude glycerol formed is a difficult substrate, as it is highly contaminated and very wet. The conversion of impure bio-renewable starting materials into valuable chemical products is a significant challenge.¹ Low cost starting materials available from biomass are, in general, very different from those derived from fossil fuels, and tend to be highly oxygenated, impure, aqueous, and dilute. These solutions of mixed aqueous oxygenates require purification from water and deoxygenation. This is in stark contrast to hydrocarbons, which require oxidation in their primary processing. As a result, the methods that have been developed for crude oil streams are not suitable for the treatment of biomass feeds, and a new generation of transformations and processes is required.

Whole cell biocatalysis provides a route by which crude biomass feeds can be mobilized. Bacteria, algae and fungi can be used to convert oxygenates at low concentration in impure aqueous solution into solutions rich in target chemicals.² A whole cell catalyst digests organic material and enriches the solution in the side-products of metabolism. Common products are alcohols and carboxylic acids. Coupling whole cell biocatalysis to downstream chemocatalytic transformations widens the variety of chemicals that can be prepared.³

1,3-propanediol (1,3-PDO) is a renewable platform chemical¹ that can be readily prepared by large scale whole cell biocatalysis.² Bio-derived 1,3-propanediol is currently produced by the bacterial fermentation of sugars.^{2,4} 1,3-PDO can be obtained at competitive cost and is commercially available from DuPont™ (marketed as Bio-PDO™).⁴

Although it is difficult to generate from biomass by chemical means, fermentative production of 1,3-PDO is relatively simple and environmentally friendly.⁵ 1,3-PDO is also a major product of glycerol fermentation employing many microbial species such as *Clostridium*,⁶ *Klebsiella*, *Citrobacter*,⁷ *Lactobacillus*,⁸ and of genetically modified microorganisms.⁹ The low crude glycerol price could lead to these feeds becoming the preferred substrates for microbial 1,3-PDO production. Since our report¹⁰ on the combination of *Clostridium butyricum* activity with hydrogen transfer chemocatalysis to convert crude glycerol from biodiesel production, further studies focused on direct crude glycerol fermentations have been reported.^{11,12,13} The conversion of glycerol to 1,3-PDO employs two enzymatic steps: glycerol dehydration by glycerol dehydratase to 3-hydroxypropionaldehyde, and its further reduction to 1,3-PDO by NADH dependent 1,3-propanediol oxidoreductase.⁹ This reductive metabolic pathway is used by microorganism to

maintain the steady state concentration of NADH and NAD⁺ cofactors.^{9,13} Concentrations as high as 93.7 g/l of 1,3-PDO from pure and 76.2 g/l of 1,3-PDO from crude glycerol with productivities of 3.3 and 2.3 g/l·h, respectively, have been reported¹¹ for fed-batch anaerobic production by *Clostridium butyricum* isolates. The main bottleneck of fermentative production of 1,3-PDO and its further applications for chemical catalysis is the formation of by-products such as butyrate, ethanol and acetate.⁵ These products contaminate the fermentation broth and complicate the downstream processing, and further developments are required on the isolation of the products of whole cell biocatalysis.

Following this biocatalytic step, the intermediate chemical must be extracted from the aqueous solution and converted into a marketable chemical. Extraction from water can be difficult and expensive, particularly as the chemicals generated often have high water solubility, and this has led to research into the application of newer solvent technologies. In the field of bio-renewable alcohol extraction from aqueous solution ionic liquids are showing considerable promise. Ionic liquids exhibit the dual advantages of tuneable physical properties, and high affinity for alcohols. The functional groups comprising the cation and anion can be tuned to alter solvent properties, and hydrophobic ionic liquids can be prepared.¹⁴ Hydrophobic ionic liquids still have excellent solubilising properties for polar organics; this enables the biphasic extraction of fermentation broth to be set up. The efficient extraction of bio-butanol has been demonstrated using imidazolium¹⁵ and phosphonium¹⁶ ionic liquids, and the optimisation of 1,3-propanediol extraction is ongoing in several research groups, including Marr and co-workers (X. Liu *et al* unpublished work). Varying the class of cation or anion, and even the functionality for a given ionic liquid type, changes the properties of extraction markedly. For ionic liquids that are not sufficiently hydrophobic, the addition of salts to the aqueous phase can yield biphasic mixtures to enable oxygenated targets to be selectively extracted.¹⁷⁻²⁰ Recently this approach has been applied to the removal of 1,3-propanediol from fermentation broths.^{21,22}

Once extracted into the ionic liquid, the desired organic product must be isolated. Extraction with a volatile organic solvent will render the initial extraction barely worthwhile! However, the primary product of fermentation is rarely the desired chemical target, and can be viewed as a chemical intermediate. Coupling biocatalysis with a downstream chemocatalytic reaction without intermediate isolation can avoid separation problems.^{3,10} Industrial scale fermentations to yield chemicals tend to be large. If a sufficient concentration of the product can be obtained, the aqueous solution could be drawn off and converted to chemical products or fuels as required. Ideally the extraction, downstream reaction, and

product removal will not contaminate the fermentation broth, and will render it recyclable, therefore conserving water. In a special case a functional ionic liquid could act as the extracting solvent and catalyst for chemical change,²² but instances in which the catalyst and extraction solvent optimise coincidentally will be exceptional. Alternatively the addition of a catalyst to the extracting solvent is acceptable, provided the catalyst does not leach into the aqueous solution.

New chemocatalytic transformations that can be coupled to biocatalytic 1,3-PDO production are being investigated by Marr and co-workers.^{3,10,23} Of specific interest is the potential of hydrogen transfer and dehydrogenation catalysts to transform bio-renewable alcohols into value added chemicals.^{24,25}

Reactions that involve the transfer of hydrogen from one organic donor to another (sometimes termed “hydrogen borrowing” reactions) have huge potential in organic synthesis, and have been the subject of several recent reviews.²⁴⁻³⁹ Typically these reactions employ a transition metal catalyst (most commonly an organometallic Ru or Ir complex) and a base to activate an alcohol by deprotonation and extraction of hydride from the α -position. The unsaturated group thus formed can then go on to participate in the formation of new C-N and C-C bonds. In this way a wide range of alcohols can act as the source of an alkyl group for alkylation, the most common substrates being amines or carbonyls. These methods avoid the use of activating leaving groups and halides, and do not lead to the formation of salt waste. In this way alkylated amines, carboxylic acids, amides and nitrogen containing heterocycles can be prepared.

The activation of 1,3-propanediol by hydrogen transfer and its use to prepare 1,3-diamino propanes by *N*-alkylation of secondary amines was demonstrated by Huh *et al.* employing $\text{RuCl}_3 \cdot n\text{H}_2\text{O}$ as the catalyst precursor in dioxane at 180 °C.⁴⁰ In boiling diglyme, quinolines result from the dehydrogenation initiated amination of 1,3-PDO in the presence of aniline catalysed by phosphine (P^nBu_3) promoted ruthenium (III) chloride.⁴¹

An alternative procedure has been published by Madsen and co-workers⁴² including the addition of $\text{MgBr}_2 \cdot \text{OEt}_2$ to the catalytic system as a promoter, and expanding the procedure to the synthesis of a range of functionalised quinoline derivatives. Treatment of naphthylamines with 1,3-PDO in the presence of $\text{IrCl}_3 \cdot n\text{H}_2\text{O}$ promoted by BINAP enables *N*-heterocyclization in an analogous manner.⁴³ Avoiding the dehydrogenation of the *N*-heterocyclized product, and therefore performing a dehydrative coupling, Achard and co-workers⁴⁴ have prepared (functionalised) julolidines from tetrahydroquinolines and 1,3-PDO. Pentamethylcyclopentadienyl iridium(III) chloride dimer $[\text{Cp}^*\text{IrCl}_2]_2$ was employed as the

catalyst precursor, promoted by diphenylphosphinobenzoic acid. The reaction was performed at 130 °C in toluene. Cp*Ir(III) complexes have wide applicability in reactions that involve the removal and transfer of hydrogen to activate alcohols; in addition to the well established transfer amination protocols,^{25,30,33} many other organic hydrogen transfer and dehydrogenation reactions are possible, for example Oppenauer-type oxidation,⁴⁵ dehydrogenation,^{29,36,46} the Guerbet reaction,⁴⁷⁻⁴⁹ and dynamic kinetic resolution.⁵⁰⁻⁵⁴

Previously Marr, Rebros and co-workers demonstrated that 1,3-PDO generated from the fermentation of crude glycerol from biodiesel can act as the substrate for the *N*-alkylation of aniline.¹⁰ A Cp*Ir(III) *N*-heterocyclic carbene hydrogen transfer catalyst was employed in ionic liquid or toluene assisted by simple carbonate salts. When amination is operated in ionic liquid solvents,^{10,55} we previously noted²³ that the substrate showed a tendency towards simultaneous dehydration. The resulting aldehydes can react together by aldol condensation and couple to yield C6 products. This cascade follows a similar mechanism to the Guerbet reaction.^{47,48} The potential importance of Guerbet chemistry in bio-renewable transformations has been underlined recently, as a method of transforming bio-ethanol to bio-butanol.⁵⁶ The application of ionic liquid solvents and alteration of the concentration of amine were later shown to enable control over the reaction selectivity.²³

Here is reported the use of a homogeneous hydrogen transfer catalyst to catalyse the dehydration of 1,3-propanediol in ionic liquid to propionaldehyde (propanal). This follows the report of amination by hydrogen transfer by coupled bio- and chemo-catalysis,^{10,23} and has the additional benefit of easier product separation. By assisting a dehydration reaction, the catalyst and ionic liquid remove oxygen from the bio-alcohol, and this reduces hydrogen bonding, rendering the organic products more volatile and easier to remove from the solvent. To the best of our knowledge, this is the first report on the selective transformation of 1,3-PDO into propionaldehyde. The production of aldehydes is targeted due to their importance in chemical synthesis,^{57,58} being precursors for carboxylic acids and esters, olefins, amines, amides and higher aldehydes and alcohols. Hundreds of thousands of tonnes of propionaldehyde are prepared worldwide per year. The leading production method is the hydroformylation of ethene derived from petroleum. Bulk uses of propionaldehyde include the synthesis of trimethylolethane (and its derivatives) for the production of resins, coatings, plasticisers and lubricants. Propionaldehyde is also used extensively in the organic synthesis of fine chemicals. The high purity aldehydes required for pharmaceuticals, foods and fragrances are particularly valuable, and have higher market values than the parent alcohols. Cp*IrCl₂(NHC) (Cp* = pentamethylcyclopentadienyl; NHC = carbene ligand) complex **1**

(See Figure 1) and base were applied to 1,3-PDO in ionic liquid; the major products observed were propionaldehyde (**2**), 2-methyl-pentenal (**3**), 2-methyl-pentanal (**4**), and 1-propanol (**5**) (See Scheme 1 (a)).

Experimental

1,3-Propanediol (98 % w, Aldrich), K₂CO₃ (99.5 % w, BDH), KOH (85 % w, Riedel-de Haen), Cs₂CO₃ (99.995 % w, Sigma-Aldrich), propionaldehyde (97 % w, Aldrich), 2-methyl-2-pentenal (97 % w, Aldrich), 2-methyl-pentanal (> 95.0 % w, TCI), propanol (97 % w, Sigma-Aldrich), CH₃OH (≥ 99.9 % w, CHROMASOLV, for HPLC, Sigma-Aldrich), CDCl₃ (99 % w, Aldrich), CD₃C(O)CD₃ (VWR Chemicals), were used as received. **1**,⁵⁹ 1-ethyl-2,3-dimethyl-imidazolium-*N,N*-bistriflimide (EmmimNTf₂),⁶⁰ and methyl-tri-*n*-octyl-ammonium-*N,N*-bistriflimide (N_{1,8,8,8}NTf₂)⁶¹ (Figure 1), were synthesized according to literature procedures. ¹H NMR spectra were run on 300 MHz and 400 MHz Bruker spectrophotometers. The chemical shifts are reported in ppm. Signal multiplicities are reported as singlet (s), doublet (d), triplet (t), quartet (q), and multiplet (m) (br = broad). GC/MS spectroscopic data were collected on a MassHunter Workstation Software – Qualitative Analysis – Version B.06.00 – Build 6.0.663.10 – Service Pack 1 – © Agilent Technologies, Inc. 2012. GC/MS column: Agilent Technologies, Inc.; 19091S-433UI; HP-5MS UI; 30 m X 0.250 mm; 0.25 Micron; –60 to 325/350C; SN: USE137316H. GC/MS spectroscopic data were processed on MassHunter Data Analysis – MassHunter GC/MS Acquisition B.07.01.1805 – 12-Mar-2014 – © 1989-2014 Agilent Technologies.

Hydrogen transfer initiated dehydration (HTID) of 1,3-propanediol (1,3-PDO) in the presence of **1 and a base, in ionic liquid: screening reaction conditions.**

1,3-PDO, **1**, a base, and an ionic liquid (see Table S8) were added to a 50 mL round bottom flask connected, through a distillation condenser, to a 50 mL glass tube. The mixture was reacted at the selected temperature, at a controlled pressure of *ca.* 0.35 bar, for six hours, stirring at 1000 rpm. The reaction product, a colourless liquid, was isolated by distillation, being collected, for the duration of the six hours reaction, in the collecting glass tube kept at *ca.* -196 °C (N₂ (l) bath). After separation from the minor water layer, the crude product (see % yield (based on propionaldehyde (**2**) in Table S8) was analysed by GC/MS (Table S18) and ¹H NMR (Table S27) spectroscopies. The reacted mixture, left in the 50 mL round bottom flask, was analysed by ¹H NMR spectroscopy. The crude product was distilled at

atmospheric pressure, at $T \cong 43$ °C, to yield **2**. ^1H NMR (CDCl_3 , 400 MHz): δ_{H} 1.09 (td, $J_{\text{HH}} = 7.42$, $J_{\text{HH}} = 1.10$ Hz, 3 H), 2.45 (m, 2 H), 9.78 (m, 1 H).

Detailed procedures for the recycling experiments are given in the supplementary data file.

Analysis of reaction product solutions of HTID of 1,3-PDO in the presence of **1 and a base, in ionic liquids: general methodology.**

The amount of **5** in the isolated crude product was calculated *via* GC/MS spectroscopy. Integration of the ^1H NMR spectrum allowed calculation of the molar amounts of **2**, **3** and **4**, relative to **5**. Combination of GC/MS and ^1H NMR spectroscopic information enabled calculation of the amount of **2**, **3** and **4**, in the isolated crude product.

The GC/MS and ^1H NMR analysis of reaction product solutions are described in the supplementary data file.

Results and discussion

Treatment of 1,3-PDO in ionic liquid solution with a base and a $\text{Cp}^*\text{IrCl}_2(\text{NHC})$ complex has been found to lead to dehydration to yield aldehydes.²³ The hydrogen transfer initiated dehydration (HTID) of 1,3-PDO was investigated in the presence of complex **1** and a base, in an ionic liquid as the solvent medium. The outcome of the reaction was explored in different ionic liquids, at different temperatures and pressures, and by varying the catalyst loading and the nature and loading of the base. Product solutions were analysed by a combination of ^1H NMR and GC/MS spectroscopies.

The ionic liquids reported (Figure 1) could be used to extract 1,3-propanediol from fermentation broth, as they are hydrophobic due to the presence of the NTf_2 anion, but they do not represent an optimized system for fermentation broth extraction. EmmimNTf_2 and $\text{N}_{1,8,8,8}\text{NTf}_2$ are examples of two very common classes of ionic liquid. An in depth study and optimization of the extraction is ongoing as part of the EU FP7 project GRAIL and many ionic liquids are being screened. At the same time the fermentation of glycerol to 1,3-PDO is being optimized and this is leading to an increase in the concentration of 1,3-propanediol that is achievable in solution, which has a direct effect on the ability to extract it efficiently.

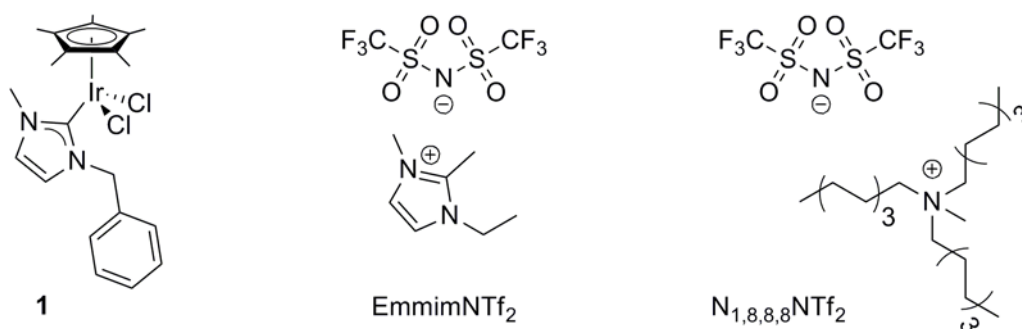
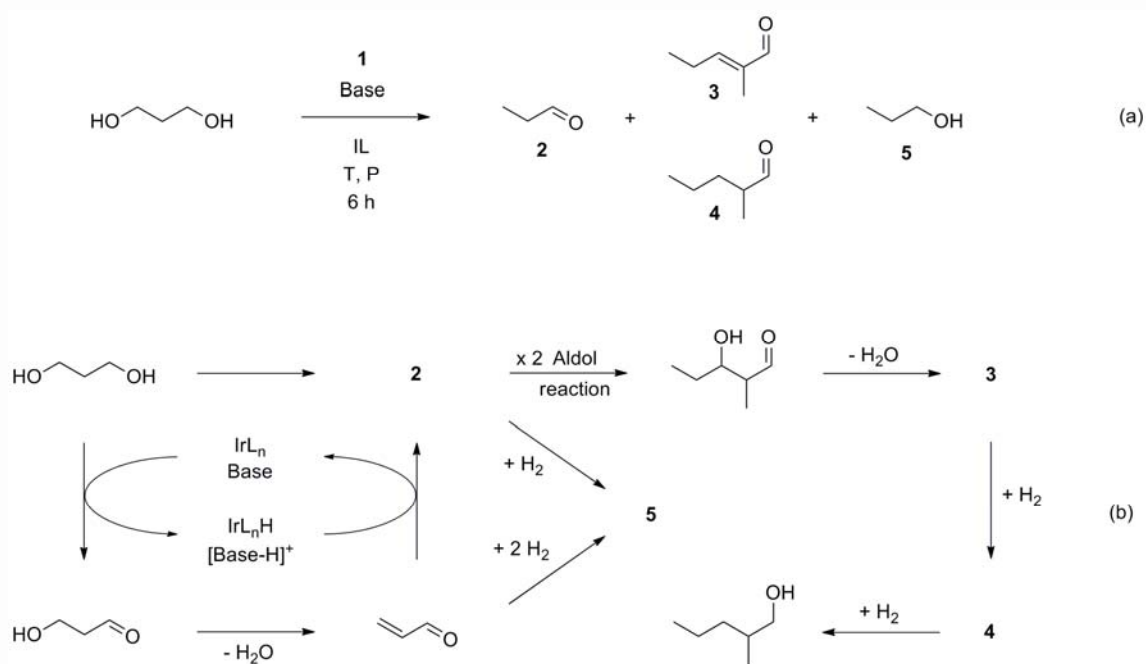


Figure 1. Structure of catalyst **1** and 1-ethyl-2,3-dimethyl-imidazolium-*N,N*-bistriflimide (EmmimNTf₂) and methyl-tri-*n*-octyl-ammonium-*N,N*-bistriflimide (N_{1,8,8,8}NTf₂), ionic liquids tested as the solvent media, in the Cp*IrX₂(NHC) catalysed HTID of 1,3-PDO.

The reaction was found to lead to a range of C3 and C6 alcohols and aldehydes: the major products observed were **2**, **3**, **4**, and **5** (Scheme 1 (a)). The reaction outcome was found to be affected by the experimental conditions: reaction yield and selectivity could be controlled by tuning (a) the ionic liquid used as the solvent, the reaction (b) temperature and (c) pressure, (d) the loading of **1**, and (e) the nature and loading of the base. The synthesis and isolation of **2** was first targeted.



Scheme 1. HTID of 1,3-PDO catalysed by Cp*IrX₂(NHC) complex **1** in the presence of a base, in ionic liquids, at different temperatures and pressures: (a) major reaction products; (b) postulated reaction mechanism.

A postulated reaction sequence for the HTID of 1,3-PDO catalysed by Cp*IrX₂(NHC) complexes in the presence of a base, that rationalises the formation of the major products, is shown in Scheme 1 (b). HTID of 1,3-PDO allows formation of **2** via the intermediates 3-

hydroxypropionaldehyde and acrolein. The formation of the dimer of acrolein was observed previously under similar conditions.²³ Both **2** and acrolein could then undergo hydrogenation to **5**. Furthermore, **2** can dimerise *via* the aldol reaction to yield, after dehydration, **3**. **3** can then undergo further hydrogenation to **4**. Hydrogenation of the latter leads to 2-methylpentanol. In addition to the main reaction sequence, the intermediate 3-hydroxypropionaldehyde could undergo a retro-aldol reaction to yield formaldehyde and acetaldehyde. Formaldehyde is a possible source of hydrogen, through dehydrogenation. Hydrogen can also be formed by dehydrogenation of alkyl chains to form olefins. The formation of traces of acetaldehyde and olefins are consistent with spectra obtained.

According to Scheme 1 (b) the formation of C6 products depends upon the aldol reaction of **2** in solution. The selectivity of the reaction should depend on the concentration of **2**. Therefore the reaction outcome should be driven towards specific target compounds by tuning the reaction conditions. Running the HTID of 1,3-PDO in ionic liquids under conditions that allow the removal of **2** from the reaction mixture as soon as it is formed should minimise, the occurrence of the side-reactions leading to **3**, **4** and **5**. Conversely, higher selectivity towards these products should be favoured when allowing **2** to further react after its formation.

The HTID of 1,3-PDO was therefore successfully driven towards the selective production of **2** by reacting 1,3-PDO in the presence of the Ir(III) complex **1** ([1,3-PDO]:[Ir] = 73.2 – 496.7; (see Table 1, Table 2, and tables S1 – S7) and a base (K₂CO₃, or KOH, or Cs₂CO₃; [Base]:[1,3-PDO] = 0.0302 – 0.2764), in ionic liquids EmmimNTf₂, or N_{1,8,8,8}NTf₂, at temperature varying in the range 100 – 180 °C, and at a dynamic vacuum of *ca.* 0.35 bar. The vacuum allowed removal of the highly volatile **2** out of the reaction mixture as soon as it was formed; then, a low temperature trap allowed isolation of the crude product (see Figure S16) in high yield (up to 99 %), and highly rich in **2**. 1,3-PDO was found to be completely consumed after six hours; the reaction outcome was then investigated after six hours. Selectivity towards **2** varied, depending on the reaction conditions, in the range 25.5 – 87.5 %. The rest 74.5 – 12.5 % of product was found to be composed by **3**, **4** and **5**, along with minor amounts of other side-products. Selectivity towards **3**, **4** and **5** varied in the range 2.8 - 61.2 %, 0.0 - 17.5 %, 3.3 - 56.7 %, respectively.

The ¹H NMR spectra of the isolated, crude product of HTID of 1,3-PDO at the above conditions (see Figure 2) display, in the aldehydic region, the triplet at δ_{H} 9.78 due to the aldehydic proton of the largely dominant species, **2**, along with the doublet at δ_{H} 9.60 and the singlet at δ_{H} 9.38 corresponding to the aldehydic protons of **4** and **3**, respectively; the triplet

detected at δ_{H} 3.59 is due to the CH_2OH protons of **5**. Consistently, the GC/MS spectrum of the corresponding solutions (see Figure S1) displays the peaks due to **2**, **3**, **4** and **5**.

EmmimNTf₂ and N_{1,8,8,8}NTf₂ are stable throughout the six hours reaction time: no decomposition of the ionic liquids was observed under any experimental conditions tested. The reacting mixtures were monitored by ¹H NMR spectroscopy: the resonances due to the protons of EmmimNTf₂ and N_{1,8,8,8}NTf₂ remain unchanged throughout the reaction time (see Figure S4 and Figure S8, respectively).

The catalytic system is not sensitive to air, and the reaction is not affected by the presence of significant amounts of water (Table S7).

Mercury poisoning experiments showed the Cp*Ir systems to be homogeneous: **1** displayed virtually unperturbed activity in the presence of mercury, strongly suggesting genuine solution-phase catalysis (Table 2).⁶²

The involvement of a monohydride iridium complex^{62,63} derivative of the catalytic precursor **1**, as intermediate in the catalytic cycle ruling the base-assisted HTID of 1,3-PDO, is suggested by the ¹H NMR investigation of the reacting mixture: after running the HTID of 1,3-PDO, in the presence of **1** and K₂CO₃, in N_{1,8,8,8}NTf₂, at 150 °C, for three hours, a sole singlet at δ_{H} -16.54 was observed in the hydride region (see Figure S14). In EmmimNTf₂, along with the largely major singlet at δ_{H} -16.57, a minor peak at δ_{H} -16.09 is also observed (see Figure S15). The ¹H NMR resonance of the hydride (in CDCl₃) lies in the expected range for terminal hydride complexes, by comparison with similar complexes reported previously.⁶⁴⁻⁶⁷ Further mechanistic work is required to comment on the role of such monohydride iridium complex in the catalytic cycle.

Complex **1** was monitored by ¹H NMR whilst running the HTID of 1,3-PDO in the presence of **1** and K₂CO₃, in N_{1,8,8,8}NTf₂, (analysis in EmmimNTf₂ was hampered by solvent-signal overlap), at T 150 °C, and at [1,3-PDO]:[Ir] \cong 220.0. The doublet at δ_{H} 6.02 (J_{HH} = 15.3 Hz), due the methylenic protons of **1**, was monitored during the course of the reaction. The catalyst precursor **1** was observed in the reaction mixture for *ca.* two hours since the reaction started. Several overlapping resonances were detected in the region δ_{H} 5.00 – 7.00 since the beginning of the reaction, preventing any further speculation regarding the nature of the active Ir complex formed in solution. The doublet at δ_{H} 6.02 was observed collapsing *ca.* three hours after starting the reaction. Further investigation will be carried out in order to understand the nature of the active catalytic Ir species.

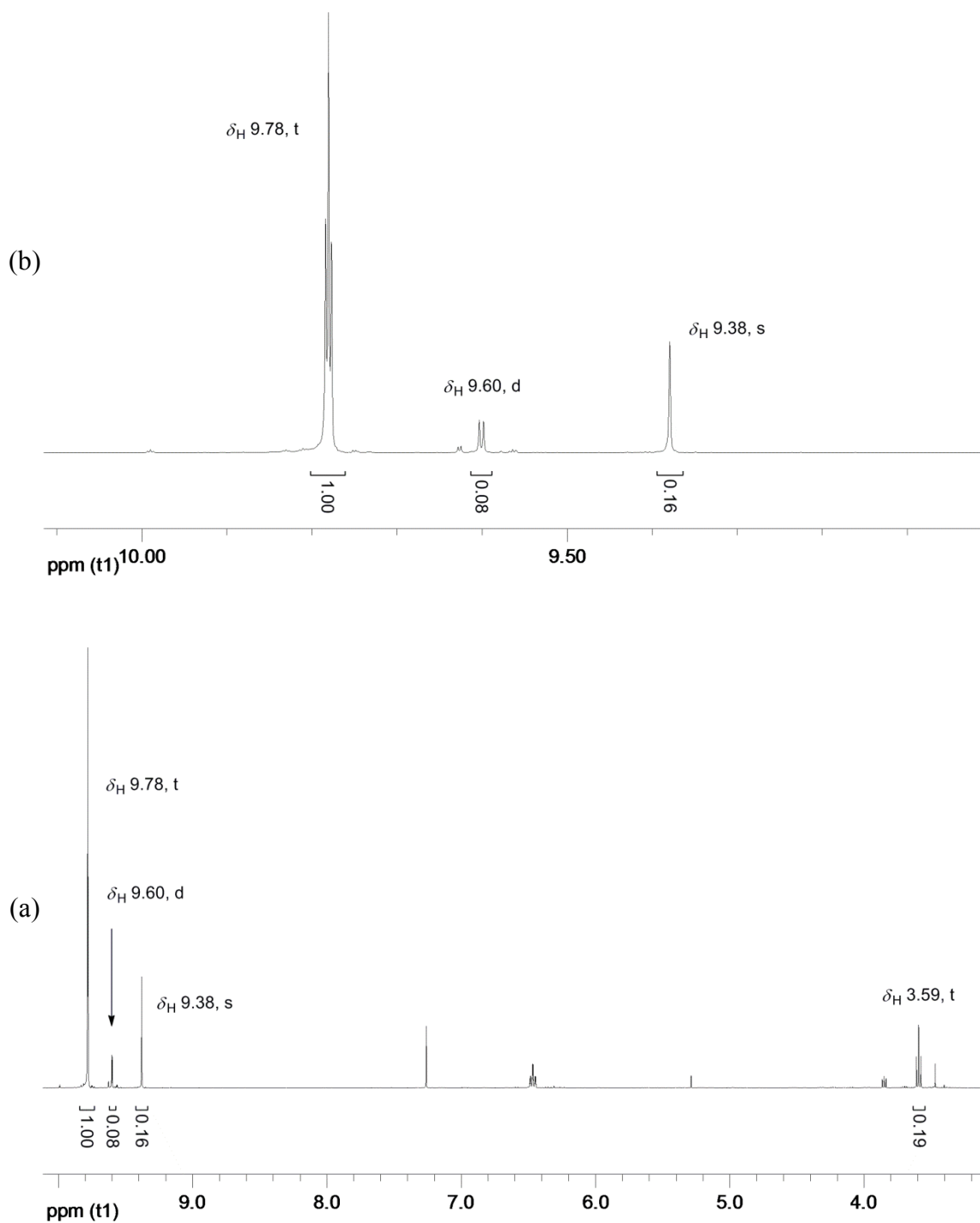


Figure 2. Example of a ¹H NMR spectrum of the isolated, crude product of HTID of 1,3-PDO in the presence of **1** and a base, in EmmimNTf₂ or N_{1,8,8}NTf₂, at temperature varying in the range 100 – 180 °C, and at a dynamic vacuum of *ca.* 0.35 bar: enlargement of the aldehydic and 1-propanol CH₂OH region (δ_H 3.10 - δ_H 10.10) (a); enlargement of the aldehydic region (δ_H 9.00 - δ_H 10.12) (b).

The non-volatility of the ionic liquid, along with the much lower boiling point of **2** (46.0 °C) compared to that of the by-products (**3**: 137.5 °C; **4**: 119.5 °C; **5**: 97.0 °C) allowed then the facile separation of **2**. The isolation of highly pure **2** was achieved *via* a mild distillation

at P_{atm} and $T = 43\text{ }^{\circ}\text{C}$. The ^1H NMR spectrum of the distilled, isolated product (Figure S2) only displays resonances due to **2**: a triplet at δ_{H} 9.78, a quartet of doublets at δ_{H} 2.45, and a triplet at δ_{H} 1.10. Consistently, only the peaks due to **2** are displayed in the GCMS spectrum of the distilled, isolated product (Figure S3). In conclusion, highly pure **2** was produced *via* HTID of 1,3-PDO, catalysed by **1** in the presence of a base, in ionic liquids, followed by a mild distillation. To the best of our knowledge, this is the first report on the selective transformation of 1,3-PDO into **2**. **2** was only reported as a very minor component in the product mixture of dehydrogenation of 1,3-PDO, performed in several, extreme conditions.⁶⁸⁻

70

The influence of (a) the ionic liquid used as the solvent, (b) the catalyst loading, the reaction (c) temperature and (d) pressure, and (e) the nature and loading of the base on the selectivity towards the C3 and C6 aldehydes and alcohols and the yields of **2** was then investigated (see Table 1).

The catalyst **1** and the base are indispensable: in the absence of the iridium catalyst, 1,3-PDO remains unreacted; also, no reaction of 1,3-PDO is observed when the HTID is carried out in the presence of **1** but in the absence of base (In Table 1: see entries 17 and 18, respectively).

The ionic liquids tested as the solvent media were EmmimNTf₂ and N_{1,8,8,8}NTf₂. The imidazolium cation is C2 protected with a methyl group to prevent side reactions involving deprotonation and the formation of carbenes. The ammonium ionic liquid was chosen as a cheaper alternative to the more common imidazolium ionic liquids. The bis(trifluoromethylsulfonyl)imide (NTf₂) anion confers hydrophobicity, ensuring the solvent forms two phases with water, and enabling a biphasic extraction of fermentation broth.

Yields and selectivities towards **2** are generally higher in EmmimNTf₂ than N_{1,8,8,8}NTf₂ (Table 1: entries 3 and 23; 7 and 26; 9 and 25; 16 and 30). Although ionic liquids have been selected as solvents for the reaction primarily in order to enable a facile separation of the final, volatile products from the non-volatile solvent media (and also, prior to chemocatalysis, in the prospect of allowing extraction of 1,3-PDO from the aqueous glycerol fermentation broths), it was found that their use also affects the reaction outcome: while little effect on yields was observed, selectivity towards **2** was found to significantly improve in ionic liquids when compared to HTID of 1,3-PDO carried out in the absence of ionic liquid (Table 1: entries 7, 19, and 26). We have previously shown that ionic liquids support greater dehydration activity than toluene under related conditions.^{10,23}

It is also worthy of note that when the HTID of 1,3-PDO was carried out in neat 1,3-PDO, in molar concentrations corresponding to those of $N_{1,8,8,8}NTf_2$ (Table 1: entry 31) and $EmmimNTf_2$ solvents (Table 1: entry 32), the catalyst was found to turnover at a greater frequency. In these reactions the selectivity towards **2** was lower than for the optimised ionic liquid system.

The effect of catalyst loading on the yield of and selectivity towards **2** was investigated varying the ratio [1,3-PDO]:[Ir] in the range *ca.* 70.0 - *ca.* 500.0. While no significant effect on selectivity was observed, catalyst loading affects the yields of **2**: the lower the ratio [1,3-PDO]:[Ir], the higher the yield (Table 1: entries 5, 6, 7, and 8; 20 and 25; 21 and 26; 22, and 27). In both $EmmimNTf_2$ and $N_{1,8,8,8}NTf_2$, only traces amount of **2** were observed to be formed when [1,3-PDO]:[Ir] > *ca.* 220.0.

Only a minor effect on the reaction outcome was observed when changing the base: yields and product distributions were similar when using either K_2CO_3 , KOH or Cs_2CO_3 (Table 1: entries 7, 12, and 16; 26, 28, and 30). K_2CO_3 was then selected as the base for the HTID of 1,3-PDO catalysed by **1**. Yields of and selectivity towards **2** were affected by the base molar concentration: the higher the base concentration the lower the yield of, and selectivity towards **2** (Table 1: entries 7, 14, and 15). This may suggest that the higher base concentration stimulates side-reactions, which could include dehydrogenation, retro-aldol, and orthometallation⁵⁹ of **1**. The HTID of 1,3-PDO was found to perform best when $[K_2CO_3]:[1,3-PDO] \cong 0.0310$.

The effect of the reaction temperature has been explored in the range 80 – 180 °C. Satisfying yields of and selectivity towards **2** were achieved at temperatures $120 \leq T \leq 150$ °C, in both $EmmimNTf_2$ and $N_{1,8,8,8}NTf_2$, and at a ratio [1,3-PDO]:[Ir] varying in the range *ca.* 70.0 - *ca.* 220.0. Minor conversions are observed at $T < 100$ °C (Table 1: entries 4 and 24). In the range 100 – 150 °C, the higher the temperature, the higher the yields of and selectivity towards **2**, at any ratio [1,3-PDO]:[Ir] and in both $EmmimNTf_2$ and $N_{1,8,8,8}NTf_2$ (Table 1: entries 1, 2, 3, and 4; 21, 22, 23, and 24). Raising the temperature to 180 °C resulted in little improvement, and similar amounts of isolated **2** were formed (entries 7 and 9; 20 and 21): the ¹H NMR spectra of the isolated crude products show formation of further by-products containing alkenic protons, suggesting an increase in dehydrogenation activity. It is worth noting that selectivity towards **2** fails under 100 °C: selectivity towards **3** was found to increase up to 61.2 % when running the HTID of 1,3-PDO in $N_{1,8,8,8}NTf_2$ at 80 °C, while selectivity towards **2** was 25.5 % (Table 1: entry 4).

Table 1. HTID of 1,3-PDO in the presence of **1** and a base, in ionic liquids: yields^a of **2**, selectivity towards **2**, **3**, **4**, and **5**, and TOF.

Entry	Solvent	Catalyst	[1,3-PDO]:[Ir]	Base	[Base]:[1,3-PDO]	T	% Yield ^a (2)	2	3	4	5	TOF ^b [s ⁻¹] ($\times 10^3$)
1	N _{1,8,8} NTf ₂	1	74.8	K ₂ CO ₃	0.0310	150	84	85.9	5.9	1.5	6.7	2.90
2	N _{1,8,8} NTf ₂	1	73.2	K ₂ CO ₃	0.0311	120	60	52.9	28.3	9.8	9.0	2.02
3	N _{1,8,8} NTf ₂	1	76.1	K ₂ CO ₃	0.0302	100	27	70.4	12.1	13.1	4.4	0.96
4	N _{1,8,8} NTf ₂	1	75.6	K ₂ CO ₃	0.0313	80	1	25.5	61.2	0.0	13.2	0.04
5	N _{1,8,8} NTf ₂	1	73.3	K ₂ CO ₃	0.0308	150	84	75.2	10.4	5.1	9.3	2.83
6	N _{1,8,8} NTf ₂	1	98.9	K ₂ CO ₃	0.0309	150	69	72.2	14.9	7.3	5.6	3.16
7	N _{1,8,8} NTf ₂	1	219.9	K ₂ CO ₃	0.0303	150	51	76.2	11.8	6.4	5.5	5.23
8	N _{1,8,8} NTf ₂	1	496.7	K ₂ CO ₃	0.0310	150	6	78.2	10.8	6.6	4.4	1.44
9	N _{1,8,8} NTf ₂	1	217.0	K ₂ CO ₃	0.0316	180	49	82.0	7.1	4.2	6.8	4.96
10	N _{1,8,8} NTf ₂	1	73.6	KOH	0.0545	150	78	78.4	9.5	4.0	8.1	2.65
11	N _{1,8,8} NTf ₂	1	74.8	KOH	0.0536	100	11	73.0	8.8	9.9	8.3	0.39
12	N _{1,8,8} NTf ₂	1	218.7	KOH	0.0541	150	62	84.2	2.8	2.8	5.7	6.26
13	N _{1,8,8} NTf ₂	1	218.3	KOH	0.0496	100	2	39.3	4.1	0.0	56.7	0.18
14	N _{1,8,8} NTf ₂	1	219.8	K ₂ CO ₃	0.1365	150	29	52.1	24.3	11.5	12.1	2.99
15	N _{1,8,8} NTf ₂	1	218.1	K ₂ CO ₃	0.2764	150	20	54.1	22.4	12.8	10.6	2.07
16	N _{1,8,8} NTf ₂	1	207.3	CsCO ₃	0.0321	150	17	78.1	10.8	2.6	8.5	1.58
17	N _{1,8,8} NTf ₂	No catalyst	/	K ₂ CO ₃	0.0312	150	/	/	/	/	/	/
18	N _{1,8,8} NTf ₂	1	220.9	No base	/	150	/	/	/	/	/	/
19	No IL	1	226.6	K ₂ CO ₃	0.0311	150	69	55.6	27.8	12.2	4.3	7.20
20	EmmimNTf ₂	1	75.2	K ₂ CO ₃	0.0309	180	85	72.5	12.5	3.7	11.3	2.97
21	EmmimNTf ₂	1	75.1	K ₂ CO ₃	0.0315	150	78	73.0	10.1	8.6	8.3	2.72
22	EmmimNTf ₂	1	75.6	K ₂ CO ₃	0.0307	120	74	73.3	13.9	7.4	5.3	2.60
23	EmmimNTf ₂	1	74.7	K ₂ CO ₃	0.0311	100	60	69.2	7.2	17.5	6.1	2.09
24	EmmimNTf ₂	1	74.8	K ₂ CO ₃	0.0312	80	1	67.3	3.5	25.0	4.2	0.04
25	EmmimNTf ₂	1	221.9	K ₂ CO ₃	0.0314	180	62	77.1	10.6	3.9	8.4	6.35
26	EmmimNTf ₂	1	219.7	K ₂ CO ₃	0.0315	150	70	72.7	12.5	6.1	8.6	7.07
27	EmmimNTf ₂	1	225.8	K ₂ CO ₃	0.0304	120	51	80.3 ^c	8.0 ^c	9.6 ^c	2.0 ^c	5.33
28	EmmimNTf ₂	1	226.1	KOH	0.0555	150	54	85.2	5.9	1.4	7.5	5.68
29	EmmimNTf ₂	1	74.5	KOH	0.0540	80	1	37.3	5.8	41.5	15.4	0.04
30	EmmimNTf ₂	1	220.2	CsCO ₃	0.0313	150	67	82.9	5.7	2.8	8.6	6.85
31	1,3-PDO	1	350.9	K ₂ CO ₃	0.0068	150	- ^d	61.2	24.3	10.3	4.1	10.28 ^d
32	1,3-PDO	1	203.2	K ₂ CO ₃	0.0118	150	- ^d	66.3	18.3	9.0	6.5	7.03 ^d

All operations were carried out (a) at P = 0.35 bar; (b) with reaction time: 6 h; (c) at RPM: 1000. ^a Crude, isolated product. ^b TOF = n(product formed) / [n(catalyst) × time]. ^c Calculations based on ¹H NMR (See Table S18, entry 27). ^d In entries 31 and 32, 1,3-PDO was used as both the substrate and the solvent.

The recyclability of the catalytic system generated by precursor **1** towards the HTID of 1,3-PDO was investigated in both EmmimNTf₂ and N_{1,8,8,8}NTf₂. In the presence of K₂CO₃, at 120 and 150 °C and 0.35 bar, at catalyst loading [1,3-PDO]:[Ir] \cong 75.0 and 220.0, **1** was found to be a highly recyclable catalyst precursor. The base was found to be unstable and further aliquots of base were required to attain good recycling. Reloading only with **1**, in the absence of additional base, the catalyst activity collapsed almost entirely after the first cycle when testing the recyclability in N_{1,8,8,8}NTf₂, at 150 °C and 0.35 bar, at catalyst loading [1,3-PDO]:[Ir] \cong 75.0. In EmmimNTf₂, under the same conditions, still reloading only with **1**, the crude product yield fell from 78 % to 54 % and then 29 % from the first to the second and then third cycle, respectively, showing significant, quick decrease in catalyst activity.

In EmmimNTf₂, the catalyst was found to be recyclable for at least 10 catalytic runs at 150 °C and at catalyst loading [1,3-PDO]:[Ir] \cong 75.0. No significant loss of activity or selectivity towards **2** was observed (Figure 3, and Table S1): the percentage yield of crude **2** varied in the range 75 – 99 % (1st catalytic run: 82 %; 10th catalytic run: 75 %) (Figure 3 (a)); the selectivity towards **2** varied in the range 65.3 – 71.7 % (Figure 3 (b)).

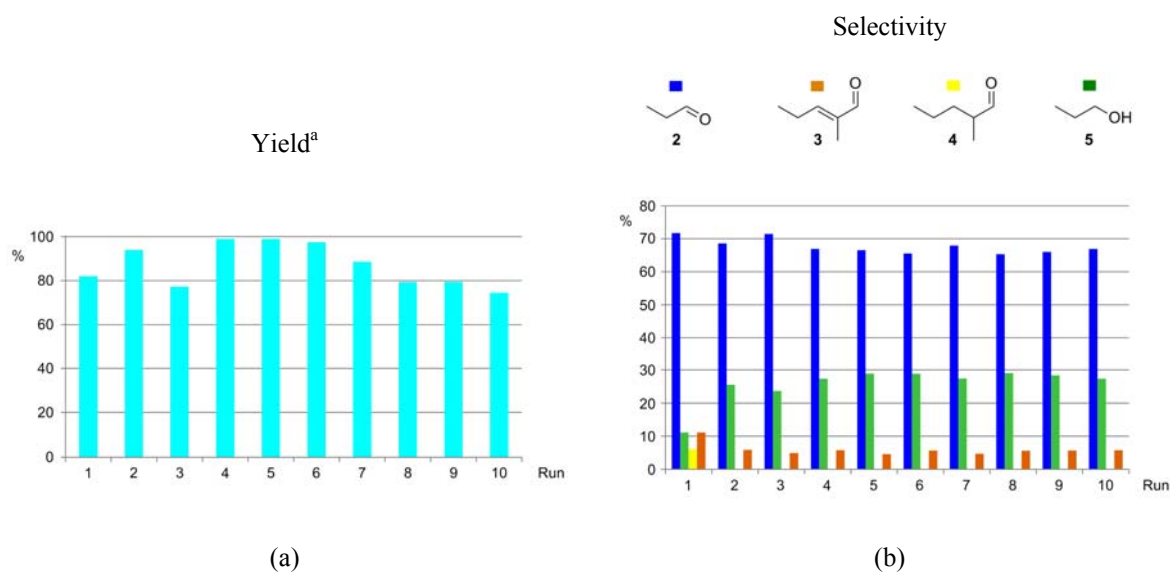


Figure 3. Recycling **1** as catalyst precursor towards HTID of 1,3-PDO ([1,3-PDO]:[Ir] \cong 75.0) in EmmimNTf₂, in the presence of K₂CO₃, at 150 °C and 0.35 bar: (a) yield of crude **2**; (b) selectivity towards **2**, **3**, **4**, and **5**.^a Crude, isolated product.

The recyclability of **1**, proven to be effective over the 10 catalytic runs at 150 °C and [1,3-PDO]:[Ir] \cong 75.0, was then tested, and successfully confirmed, at different temperatures and catalyst loadings, over 5 catalytic runs. At 150 °C and [1,3-PDO]:[Ir] \cong 220.0 (Table S2), very little changes in the percentage yields of crude **2** were observed over the 5 catalytic runs

(1st catalytic run: 73 %; 5th catalytic run: 74 %) (Figure 4 (a)). Also, the reaction remained highly selective towards **2** (% of **2**: 1st catalytic run, 77.6 %; 5th catalytic run, 76.2 %) (Figure 4 (b)). When testing the recyclability of **1** at 120 °C and [1,3-PDO]:[Ir] \cong 75.0 over 5 catalytic runs (Table S3), the percentage yields of crude **2** varied in the range 72 - 79 % (1st catalytic run: 72 %; 5th catalytic run: 78 %) (Figure 5 (a)), while the selectivity towards **2** varied in the range 71.2 – 76.2 % (Figure 5 (b)).

The ionic liquid EmmimNTf₂ is stable throughout the 10 and 5 recycling runs, at any of the above experimental conditions: the ¹H NMR spectrum of the CDCl₃ solutions of the reacting mixture after the six hours reaction shows that the triplet at δ_{H} 1.51 and the singlets at 2.64, and 3.83, due to the methylic protons, the quartet at δ_{H} 4.14, due to the methylenic protons, and the singlet at δ_{H} 7.19, due to the alkenic protons of EmmimNTf₂, remain unchanged throughout the reaction time of each of the 10 and 5 recycling runs (see Figure S4).

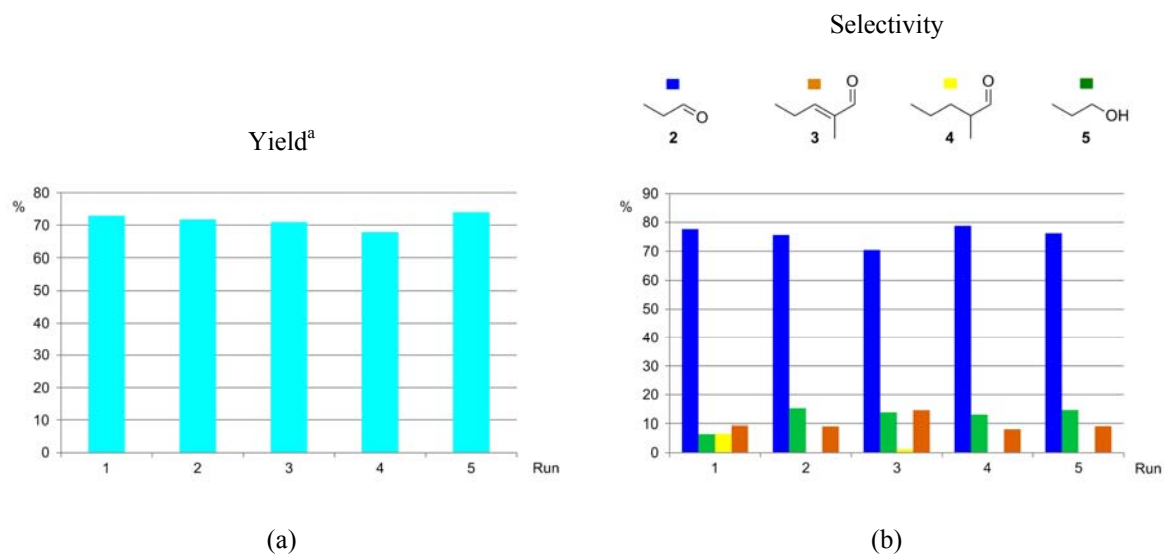


Figure 4. Recycling **1** as catalyst precursor towards HTID of 1,3-PDO ([1,3-PDO]:[Ir] \approx 220.0) in EmmimNTf₂, in the presence of K₂CO₃, at 150 °C and 0.35 bar: (a) yield of crude **2**; (b) selectivity towards **2**, **3**, **4**, and **5**.^a Crude, isolated product.

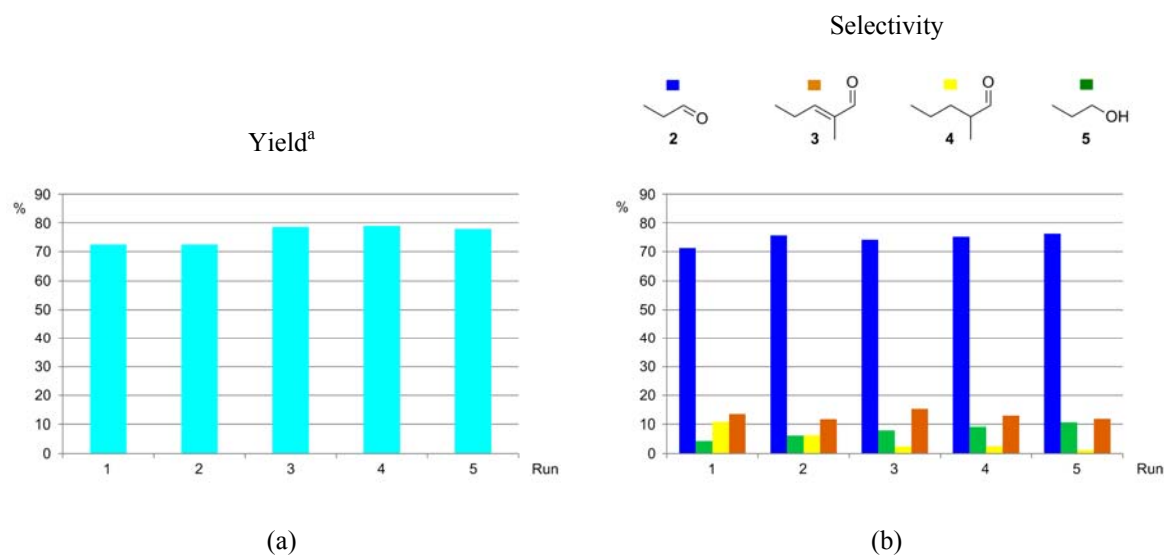


Figure 5. Recycling **1** as catalyst precursor towards HTID of 1,3-PDO ([1,3-PDO]:[Ir] \approx 75.0) in EmmimNTf₂, in the presence of K₂CO₃, at 120 °C and 0.35 bar: (a) yield of crude **2**; (b) selectivity towards **2**, **3**, **4**, and **5**.^a Crude, isolated product.

1 is recyclable also in $N_{1,8,8,8}\text{NTf}_2$. High selectivity towards **2** was observed over the 10 catalytic runs when testing the catalyst recycling at 150 °C and $[1,3\text{-PDO}]:[\text{Ir}] \cong 75.0$ (% of **2**: 1st catalytic run, 83.9 %; 10th catalytic run, 73.4 %) (Table S6 and Figure S7 (b)), and over the 5 catalytic runs at 150 °C and $[1,3\text{-PDO}]:[\text{Ir}] \cong 220.0$ (% of **2**: 1st catalytic run, 87.5 %; 5th catalytic run, 82.2 %) (Table S4 and Figure S5 (b)) and at 120 °C and $[1,3\text{-PDO}]:[\text{Ir}] \cong 75.0$ (% of **2**: 1st catalytic run, 81.3 %; 5th catalytic run, 76.0 %) (Table S5 and Figure S6 (b)).

At 150 °C and $[1,3\text{-PDO}]:[\text{Ir}] \cong 220.0$, the percentage yield of crude **2** was found to be 60 % in the 1st run and 57 % in the 5th run, with maximum and minimum values of 62 % (3rd run) and 48 % (2nd run), respectively (Figure S5 (a)). At 120 °C and $[1,3\text{-PDO}]:[\text{Ir}] \cong 75.0$, the percentage yield of crude **2** varied in the range 44 - 67 %, and was found almost identical in the 1st (59 %) and 5th run (60 %) (Figure S6 (a)). More fluctuation in the percentage yields of crude **2** was observed over the 10 catalytic runs when testing the recyclability of **1** at 150 °C and at $[1,3\text{-PDO}]:[\text{Ir}] \cong 75.0$ in $N_{1,8,8,8}\text{NTf}_2$ (Figure S7 (a)), when compared to EmmimNTf_2 . The percentage yield of crude **2**, after dropping from 86 % (1st run) to 22 % (2nd run), was found to vary in the range 54 - 77 % from the 3rd to the 10th catalytic run (3rd catalytic run: 54 %; 10th catalytic run: 58 %).

The ionic liquid $N_{1,8,8,8}\text{NTf}_2$ is also stable throughout the 10 and 5 recycling runs, at any of the above experimental conditions: the ¹H NMR spectra of the CDCl_3 solutions of the reacting mixture after the six hours reaction show that the triplet at δ_{H} 0.88 due to the $-\text{CH}_2\text{CH}_3$ methylic protons, the broad multiplets at δ_{H} 1.31 and 1.64 due to the $-\text{CCH}_2\text{C}-$ methylenic protons, the singlet at 3.01 due to the $-\text{NCH}_3$ methylic protons, and the multiplet at δ_{H} 3.18 due to the $-\text{NCH}_2-$ methylenic protons of $N_{1,8,8,8}\text{NTf}_2$, remain unchanged during the course of the reaction for each of the 10 and 5 recycling runs (Figure S8).

Table 2. Mercury poisoning test of the iridium precatalyst in HTID of 1,3-PDO in the presence of **1** and K₂CO₃, in EmmimNTf₂, at T 150 °C: yields^a of **2**, selectivity towards **2**, **3**, **4**, and **5**, and TOF.

[1,3-PDO]:[Ir]	[Base]:[1,3-PDO]	% Yield ^a (2)	2	3	4	5	TOF ^b [s ⁻¹] (×10 ³)
206.3	0.0312	77	78.0	9.4	6.6	6.0	7.32

The reaction was carried out (a) at P = 0.35 bar; (b) with reaction time: 6 h; (c) at RPM: 1000. ^aCrude, isolated product. ^b TOF = n(product formed) / [n(catalyst) × time].

Further investigation of the HTID of 1,3-PDO will be aimed at targeting other value-added chemicals. The reaction parameters will be tuned in order to drive the reaction outcome selectively towards the other products. Allowing propionaldehyde to further react after its formation should increase the percentage of C6 aldehydes, compared to propionaldehyde, in the reaction mixture. Amongst them, 2-methyl-pentenal is a valuable chemical.⁵⁸

Conclusions.

We have shown that complex **1** forms a highly recyclable catalyst for the selective production of a range of C3 and C6 aldehydes *via* homogeneous HTID of 1,3-PDO in ionic liquids. The successful isolation of highly pure propionaldehyde can be easily achieved under reduced pressure, and distillation, with minimal waste. In addition HTID of 1,3-PDO in ionic liquids is successful also when significant volumes of water are involved in the reaction, and in the presence of air. The successful synthesis and isolation of value-added chemicals out of the ionic liquid solutions of 1,3-PDO (mimicking the product of extraction of aqueous glycerol fermentation broth) proves that the combination of Cp*IrX₂(NHC) catalysed HTID of 1,3-PDO in ionic liquids with bio-catalysis has, ultimately, the potential to allow the transformation of waste glycerol into valuable chemicals that can be simply isolated. This valorisation of waste to chemicals would add significant value and improve the economics of biomass waste utilization.

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