Manganese Diphosphine and Phosphinoamine Complexes Are Effective Catalysts for the Production of Biofuel Alcohols via the Guerbet Reaction

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ABSTRACT: We report a variety of manganese-based catalysts containing both chelating diphosphine (bis(diphenylphosphino)methane (dppm: 1, 2, and 7) or 1,2-bis(diphenylphosphino)ethane (dppe: 3)), and mixed-donor phosphinoamine (2-(diphenylphosphino)ethylamine (dppea: 4−6)) ligands for the upgrading of ethanol and methanol to the advanced biofuel isobutanol. These catalysts show moderate selectivity up to 74% along with turnover numbers greater than 100 over 90 h, with catalyst 2 supported by dppm demonstrating superior performance. The positive effect of substituting the ligand backbone was also displayed with a catalyst supported by C-phenyl-substituted dppm (8) having markedly improved performance compared to the parent dppm catalysts. Catalysts supported by the phosphinoamine ligand dppea are also active for the upgrading of ethanol to n-butanol. These results show that so-called PNP-pincer ligands are not a prerequisite for the use of manganese catalysts in Guerbet chemistry and that simple chelates can be used effectively.

INTRODUCTION

The search for alternative energy sources which are sustainable and meet concerns about energy security is a crucial scientific and technological goal.1 Biofuels offer an attractive alternative to liquid fossil fuels for transportation and can be economically viable and environmentally sound if the appropriate crops and agriculture methods are used.2−8 Bioethanol is widely used as a sustainable alternative fuel to conventional gasoline, often as a gasoline/bioethanol blend, but there are technological issues with this fuel: Ethanol has only 70% of the energy density of gasoline, readily absorbs water, can cause problems with separation and transportation in existing fuel infrastructure, and can be corrosive to current engine technology.2,9 By contrast, butanol isomers have emerged as an attractive option, having fuel properties similar to those of conventional gasoline.6,7 Current methods for the synthesis of butanol include the ABE fermentation process, but this suffers from selectivity issues, separation problems, and low yields, making the bulk production of clean butanol a challenge.8−10 Butanol can also be accessed via hydroformylation/hydrogenation of propylene, but this relies on a nonrenewable feedstock.11

We and others have been exploring Guerbet chemistry (Scheme 1) to upgrade (bio)ethanol to n-butanol.12−20 This 100 year old reaction has enjoyed a renaissance in recent years as so-called borrowed hydrogen chemistry, in which a reaction sequence involving alcohol dehydrogenation to aldehyde, aldol coupling, and finally rehydrogenation to the longer chain alcohol has been established.21 Ethanol is a particularly challenging substrate for this reaction because of the high reactivity of the acetaldehyde leading to poor selectivity and multiple higher alcohol side-products; however, there are now a number of homogeneous catalysts, typically based on...
ruthenium complexes, that show good selectivity in this reaction.\textsuperscript{14,16,20} We have also extended this chemistry to the reaction of two methanol and one ethanol molecules to produce isobutanol, an even more advantaged fuel molecule, in a related sequence: Methanol and ethanol first form n-propanol which then reacts with a further methanol to yield isobutanol.\textsuperscript{22,23} Ruthenium complexes supported by bis-(diphenylphosphino)methane ligands (A, Figure 1) give exceptionally high selectivity at excellent conversion in this chemistry.

Manganese complexes, typically based on tridentate “pincer” type ligands (C), have emerged as promising alternatives to ruthenium catalysts in many hydrogen transfer reactions not in the least because of the advantages of using an earth-abundant metal, with pioneering work by Beller.\textsuperscript{24–27} It was inevitable that such complexes would be investigated for Guerbet chemistry, and in contemporaneous work, the groups of Jones and Liu reported that such complexes are indeed active in upgrading ethanol to n-butanol.\textsuperscript{28,29} Liu reports extremely high turnover numbers (>100 000) for these catalysts by running at very low (1 \texttimes 10^{-4} \text{ mol %}) catalyst loadings for extended reaction times (168 h) and being satis-

![Figure 1. Variety of ruthenium and manganese-based catalysts previously used for the formation of isobutanol from methanol and ethanol.](image1.png)

obtained in 37\% yield by irradiating a 2:1 benzene solution of the ligand and manganese precursor [MnBr(CO)]\textsubscript{4} with long wave UV light. Complexes 2, 5, 6, and 7 were prepared by refluxing either a 2:1 or 1:1 solution of the ligand and manganese precursor in toluene for several hours (yields 22–54\%). Complex 4 is novel and was obtained in 17\% yield via the same procedure used for the production of complex 1 (Scheme 2), giving a singlet \textsuperscript{31}P NMR resonance at 89 ppm and a single stretch in the CO region of the IR spectrum at 1869 cm\textsuperscript{-1}; these data are indicative of a trans-dicarbonyl complex.\textsuperscript{35} The diversity of structures obtained, depending on both the ligand and the preparation method, is surprising. For example, complex 1 with bis(diphenylphosphino)methane (dppm) ligands is isolated as a neutral bis chelate complex with trans CO and Br ligands, yet complex 4 with 2- (diphenylphosphino)ethylamine (dppea) ligands using an identical preparation method forms the trans-dicarbonyl manganese cation with a bromide counterion. Within the dppea family of complexes, both trans- (4) and cis-isomers (5) may be isolated depending on whether a thermal or irradiation preparation method is used (Scheme 2).

Single crystals of complexes 3 (Figure 3A) and 4 (Figure 3B) were obtained from a concentrated chloroform solution (3) or from layering ethanol onto a benzene solution (4). X-ray diffraction studies reveal the expected octahedral geometry in both cases, with the monodentate auxiliary ligands in the trans orientations; selected bond lengths and angles are given in the Supporting Information.

\section*{Catalyst Testing}

Using reaction conditions based on previous work with ruthenium catalysts but with longer run times (90 h),\textsuperscript{22} catalysts 1 and 2 both produced isobutanol (14 and 11\% respectively, Table 1, runs 2 and 4). For 2, catalyst loadings

![Figure 2. Manganese complexes used in this study.](image2.png)
could be decreased to 0.1% with no visible effect upon conversion or yield (Table 1, compare entries 4 and 5), giving turnover numbers exceeding 100. The structure−activity relationships for these manganese complexes mimic those for analogous ruthenium complexes within this limited set, so the dppm-supported complex (2) is the superior catalyst among those screened.14,16 However, while complex 2 is still active at low loadings (0.1 mol %), complex 1 requires higher loadings (0.3 mol %, entry 2) before an appreciable isobutanol yield is observed. Complex 2 produces only trace amounts of isobutanol at shorter run times (18 h, entry 3). At 0.1 mol % catalyst loading, 1,2-bis(diphenylphosphino)ethane (dppe)−supported complex 3 performed similarly to 1 and is essentially inactive (run 6). The dppea-supported complexes are active at 0.1 mol % catalyst loading but are still inferior to complex 2 (runs 7−9).

Table 1. Catalyst Screen for Isobutanol Yields

| entry | time (h) | catalyst | EtOH consumption (%) | iBuOH yield (%) | iBuOH selectivity (%) | turnover numbers |
|-------|---------|----------|----------------------|----------------|----------------------|-----------------|
| 1     | 90      | 1        | 10                   | 2              | 52                   | 22              |
| 2d    | 90      | 1        | 42                   | 14             | 74                   | 58              |
| 3     | 18      | 2        | <1                   |                |                      |                 |
| 4     | 90      | 2        | 27                   | 11             | 69                   | 113             |
| 5e    | 90      | 2        | 19                   | 11             | 68                   | 8               |
| 6     | 90      | 3        | 19                   | 3              | 58                   | 26              |
| 7     | 90      | 4        | 23                   | 6              | 59                   | 61              |
| 8     | 90      | 5        | 20                   | 9              | 62                   | 87              |
| 9     | 18      | 6        | 7                    | 1              | 66                   | 12              |
| 10    | 90      | 7        | 25                   | 7              | 62                   | 67              |
| 11    | 90      | 8        | 51                   | 21             | 71                   | 206             |
| 12    | 90      |          |                      |                |                      |                 |
| 13    | 4       | C        | 78                   | 10             | 64                   | 100             |
| 14f   | 24      | C        | 71                   | 27             | 82                   | 54              |

aConditions: 1 mL (17.13 mmol) of ethanol, 10 mL of methanol, 180 °C. bTotal selectivity to isobutanol in the liquid fraction was determined by gas chromatography; see the Supporting Information for yield/selectivity of other liquid products. cTurnover number (TON) is based on mmol of substrate converted to product per mmol of Mn. dUsing 0.3 mol % catalyst. eUsing 0.25 mol % catalyst, fUsing 0.5 mol % catalyst.
It is noteworthy that while both 4 and 5 are active the cis-isomer (5) marginally outperforms trans-isomer 4 (compare runs 7 and 8). A plausible explanation is that isomerization occurs slowly over the catalyst run time scale and that each isomer results in a distinct catalytic species or that there is a longer induction time for the trans-isomer to form a catalytically active species. To demonstrate this results to a literature catalyst, the pincer complex C was tested under a similar protocol. C was more active than other catalysts after shorter run times; for example, giving 10% isobutanol after 4 h (entry 13) even if overall turnover numbers for C are similar to other catalysts if these are allowed longer run times. The high (78%) ethanol conversion over this 4 h run time for C indicates a low overall selectivity for Guerbet products, with significantly more of the mass balance being solid products. In every case when catalytic activity is observed, these solids are also isolated in the postreaction mixtures, and 1H and 13C NMR analyses show this to be predominantly sodium formate (peak in the 1H NMR spectrum at 8.45 ppm), which accounts for most of the remainder of the mass balance in each case between ethanol consumption and butanol yield. This formate is presumably produced via a Cannizzaro-type reaction with methanol. A small amount of sodium acetate is also seen by conversion of ethanol with the same mechanism. Interestingly, NMR spectra show an absence of any carbonate salt, in contrast to isobutanol reactions using analogous ruthenium catalysts.22

Catalysts 2 and 5 were subsequently tested for the homocoupling of ethanol to form n-butanol (Scheme 3).

Scheme 3. Formation of n-Butanol via the Coupling of Two Ethanol Molecules

\[
\begin{align*}
2 \text{CH}_2\text{CH}_2\text{OH} & \xrightarrow{[\text{Mn}]_\text{NaOEt (10 mol%)}} \text{CH}_3\text{CH}(_2)\text{CH}_2\text{OH} + \text{H}_2\text{O} \\
& 150 ^\circ\text{C}, 90h
\end{align*}
\]

Owing to the rate of the catalyst appearing to be one of the limiting factors in the isobutanol chemistry, 90 h run times were used once again. Pleasingly, it appears catalyst 5 is also active for n-butanol formation with nearly 100 turnover numbers over 90 h (see Table S2 for further details). Unlike in isobutanol production where catalyst 2 shows little activity for this reaction, this is attributed to a lack of catalyst stability under these conditions; the postreaction mixture of 2 is dark brown, implying catalyst decomposition. This is in contrast to the postreaction mixture for catalyst 5 which is still a bright yellow homogeneous solution if kept under anaerobic conditions.

To gain insight into the active form of the best catalyst, the effect of adding base to catalyst 2 was investigated by 31P NMR spectroscopy. Complex 2 is insoluble in methanol but dissolved quickly upon addition of an excess of sodium methoxide. Immediately after base addition, resonances consistent with free ligand and monochelate 7 were observed, along with minor resonances exhibiting the distinctive broadening observed upon ligand manganese complexation. This suggests a more dynamic system in which ligand redistribution is occurring; similar observations are made with ruthenium catalysts. Complex 7 was tested for isobutanol formation to ascertain whether this was the most active species (Table 1, Entry 9). Although a competent catalyst, it remains inferior to the bis-chelate complexes of the same ligand suggesting its formation is detrimental. It is not clear why dpmp remains the most effective ligand for isobutanol production with both manganese and ruthenium. Given the importance of ligand-assisted mechanisms in hydrogen transfer catalysis, our working hypothesis is that involvement of the acidic hydrides in the methylene backbone of dpmp may be important; recent reports in related chemistry support this hypothesis.25,36,37

A recent paper by Kireev et al. supports our hypothesis of dpmp acting as a noninnocent ligand on manganese.50 In this paper, monochelate 7 is reacted with KHMDH to form complex 7b, containing two highly strained 3-membered rings. This can then be converted to hydride complex 7c under 50 atm of hydrogen (Scheme 4). Intriguingly, this paper shows that substitution of the C-backbone atom with a phenyl group makes conversion to the hydride significantly more favorable. With this in mind, monochelate 8 was synthesized and tested for isobutanol formation in our study (Table 1, entry 10).

Pleasingly, complex 8 outperforms both monochelate 7 and the previously most effective catalyst, 2, by a significant margin, with turnover numbers in excess of 200. This shows the potential positive effects that substitution of the dpmp backbone can have toward catalytic activity for manganese complexes. Again, a plausible explanation is a ligand-assisted mechanism, that is, substitution of the backbone facilitating a more favorable cycle of hydrogenation/dehydrogenation.

In conclusion, we show that simple dpmp or dppea ligand complexes of manganese are effective catalysts for the Guerbet reaction leading to butanol biofuel molecules; pincer-type complexes are not a prerequisite for competent performance. Substitution of the dpmp backbone also leads to a significant increase in catalytic performance, giving isobutanol yields of 21%.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.organomet.0c00588. Full experimental procedures along with detailed catalytic results (PDF)

Scheme 4. Activation of Manganese Complexes Containing Substituted dppm Ligands and Their Reactivity with Hydrogen

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Conditions: 7: R = H, (i) 50 atm H₂, 50 °C, 16 h. 8: R = Ph, (ii) 1 atm H₂, 25 °C, 5 min.

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CCDC 2012433 and 2012434 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes
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