# Deoxygenation of Biomass-Derived Feedstocks: Oxorhenium-Catalyzed Deoxydehydration of Sugars and Sugar Alcohols**

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The conversion of renewable cellulosic biomass into fuels and chemicals has attracted increased attention with the growing demand for sustainability.[1] However, one fundamental challenge is that saccharides, the major component of cellulosic biomass, are highly oxygen-rich when compared with the majority of current commodity chemicals and fuels. The polyol structure also generally presents poor solubility in organic solvents, thermal instability, and limited scope for functionalization, making its chemical manipulation difficult. Therefore, efficient deoxygenation reactions of sugars and sugar derivatives need to be developed. Current methods are dominated by the high-temperature pyrolysis,[2] acid-catalyzed dehydration,[3] and hydrogenolysis reactions.[4] A much less developed deoxygenation pathway is the deoxydehydration (DODH) reaction, which removes two adjacent hydroxy groups from vicinal diols to afford alkenes (Scheme 1).
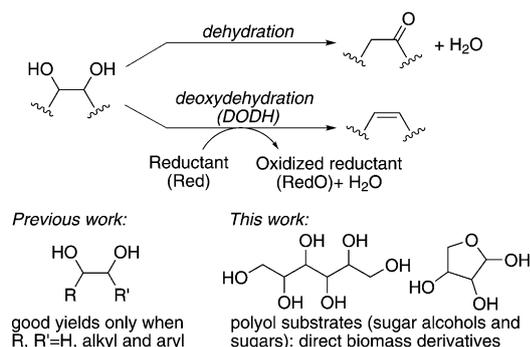
Scheme 1. A general scheme for DODH reaction.

Existing examples of catalytic DODH reactions use high-valent oxorhenium complexes, and employ PPh_3,[5] H_2,[6] or Na_2SO_3[7] as reductants. The Bergman and Ellman groups demonstrated a hydrogen-transfer-type DODH reaction using $[Re_2(CO)_{10}]$ and $[BrRe(CO)_5]$ as catalyst in conjunction with a secondary alcohol as solvent/reductant,[8] and Fernandes and Sousa reported the oxorhenium-catalyzed deoxygenation of styrene oxides in the absence of a reductant.[9] More recently, Srivastava and co-workers utilized

$[(Cp*Ru(CO)_2)_2]$ for deoxygenation of diols and epoxides using H_2 as reductant to produce alkanes and hydrocracking products.[10] While these methods are effective for simple vicinal diols and appear to lay solid foundations in the context of biomass deoxygenation, no system has been reported to have a general efficiency on polyols. The only sugar alcohol employed in this reaction to date is erythritol (C_4 sugar alcohol) and product yields were moderate (21–62%) after long reaction times (12–100 h).[7b,8] To the best of our knowledge, there is no report of DODH reaction of larger (C_5 and C_6) sugar alcohols, which can be readily obtained by hydrogenation of naturally abundant sugars such as xylose (the major hemicellulose component) and glucose (cellulose component). Moreover, the direct DODH reaction of saccharides is unprecedented, although it could constitute a major advance towards sustainable chemical production.

Based on this background, we sought to develop a more-efficient DODH protocol capable of deoxygenating the challenging polyol substrates. We focused our attention on the alcohol transfer hydrogenation system because of the significant advantage, that the oxidized alcohol (ketone or aldehyde) can be readily hydrogenated if reductant recycling is necessary. In addition, whereas only large secondary alcohols (such as 5-nonanol, 3-octanol, and 2-octanol) have been used as DODH reductants thus far, we were interested in examining the use of other inexpensive/bio-derived alcohols. We noted that $[Re_2(CO)_{10}]$ and $[BrRe(CO)_5]$ catalysts employed in the original report of Bergman and Ellman[8] required air and high temperature for activation. We postulated that the actual active catalyst may be an oxidized rhenium species,[11] and that consequently the oxorhenium compounds could constitute superior catalysts for this reaction.

In the initial experiments to evaluate the viability of oxorhenium compounds, 1,4-anhydroerythritol (**1**) was used as a model substrate (Table 1). When 2.5 mol% of $[Re_2(CO)_{10}]$ was used, 2,5-dihydrofuran (**2**) was obtained in >90% yield[12] in 3-octanol (entry 1). When $[CH_3ReO_3]$ (methyltrioxorhenium; MTO) was used in place of $[Re_2(CO)_{10}]$, a similarly excellent yield was obtained (entry 2). The difference in reactivity between these catalysts was revealed when the alcohol was changed to 1-butanol, a typical biomass-derived alcohol.[13] While no reaction was observed with $[Re_2(CO)_{10}]$ (entry 3), three other oxorhenium compounds catalyzed the formation of **2** in approximately 70% yield (entries 6–8).[14] We selected MTO as our catalyst of choice based on its simple ligand-free structure and the ease of handling as a crystalline solid, as opposed to an aqueous solution, which is the commercial form of $HReO_4$.[15] Other alcohols (for full details see the Supporting Informa-

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Table 1: Comparison of rhenium catalysts and alcohols.
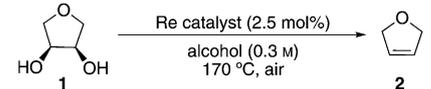
| Entry	Re Catalyst	t [h]	Alcohol	Yield [%][a]	Conv. [%][a]
1	[Re$_2$(CO)$_{10}$]	1.5	3-octanol	91	100
2	[CH$_3$ReO$_3$]	1.5	3-octanol	92	100
3	[Re$_2$(CO)$_{10}$]	1.5	1-butanol	0	0
4	[ReO(PPh$_3$)$_2$Cl$_3$]	1.5	1-butanol	20	54
5	[NH$_4$ReO$_4$]	1.5	1-butanol	25	62
6	[ReIO$_2$(PPh$_3$)$_2$]	1	1-butanol	68	100
7	[HReO$_4$][b]	1	1-butanol	66	100
8	[CH$_3$ReO$_3$]	1	1-butanol	70	100
9[c]	[CH$_3$ReO$_3$]	1	ethanol	0	0
10	[CH$_3$ReO$_3$]	1	3-pentanol	95	100

[a] Yields and conversions were determined by ^{1}H NMR spectroscopy using mesitylene as an internal standard. [b] 77% solution in water. [c] Same result was obtained when anhydrous alcohol was used under N$_2$ atmosphere.

tion) were tested in the reaction using MTO; unfortunately small alcohols (≤ 3 carbon atoms), such as ethanol, were ineffective (entry 9). For larger (≥ 5 carbon atoms) alcohols, various alcohols could be used including amyl alcohols, which can be produced by fermentation,[16] but secondary alcohols were found to be generally more favorable than primary alcohols (entry 10).[17]

We began our investigation by applying this DODH system to glycerol (**3**), a by-product of biodiesel (fatty acid esters) production from oil-based feedstocks and considered an important platform chemical for bio-based materials.[18] To our delight, allyl alcohol (**4**) was obtained in excellent yield (Scheme 2). Encouraged by this result, we then tested
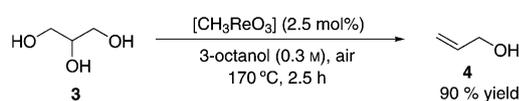
Scheme 2. DODH reaction of glycerol.

erythritol (**5**), a C$_4$ sugar alcohol that can be obtained by the fermentation of glucose[19] or by the decarbonylation of pentoses[20] (Scheme 3). 1,3-Butadiene (**6**), an industrially important rubber precursor, was obtained in 89% yield, with 2,5-dihydrofuran (**2**) as a minor product (11%). The experiments were generally conducted under N$_2$ as a precaution; however, the reaction could be conducted in air, albeit
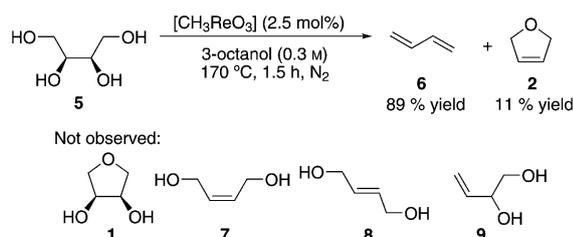

Scheme 3. DODH reaction of erythritol.

producing **6** in slightly lower yield (**6**, 72%; **2**, 15%). The reaction temperature could be decreased to approximately 150°C (**6**, 79%; **2**, 6% at 155°C, 2.5 h). We also tested HReO$_4$ to examine if Brønsted acidity increases the yield of **2**,[8] but both product distribution and total yield were similar to MTO (**6**, 73%; **2**, 7% at 155°C, 5.5 h). When DL-threitol (**10**) was subjected to the optimized reaction conditions, **6** was obtained in a similar yield (81%) and the minor product (13%) was 1,4-anhydroethreitol (**11**) instead of **2** (Scheme 4). In both
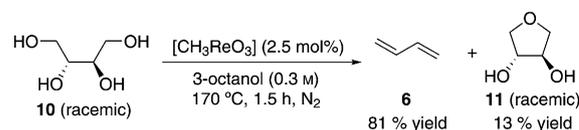

Scheme 4. DODH reaction of DL-threitol.

cases, compounds **7**, **8**, and **9** were not observed, thus suggesting that a) the diol substrate needs to adopt the *cis* conformation (assuming **2** is produced via **1**), and b) terminal diols and cyclic, internal *cis* diols (e.g. moiety **1**) are more reactive toward DODH than acyclic internal diols.

To understand the mechanism of this process, we combined the reductant alcohol (3-pentanol), MTO, and alkyne ligand[21] and obtained a stable organorhenium(V) compound **12**[22] along with 3-pentanone, at 155°C (Scheme 5).[23]
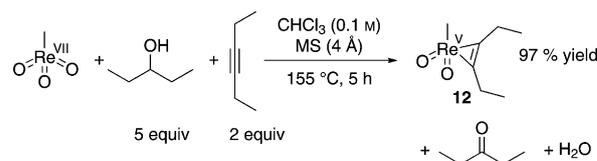
**Scheme 5.** The reduction of MTO by 3-pentanol.

Whereas binding of diol **1** to **12** occurred immediately at room temperature to afford Re^V complex **13**, extrusion of olefin **2** required heating of **13** to 155°C (Scheme 6 a).[24] The extent of binding to **12** was dependent on the diol structure. Although *trans*-hexanediol showed no evidence of binding (Scheme 6 b), combining *meso*-2,3-butanediol **14** (1.2 equiv) and **12** in C$_6$D$_6$ produced **15** but only in 56% conversion (observed molar ratio **12/14/15** = 0.8:1.1:1; Scheme 6 c, top). When **1** (1.2 equiv) was subsequently added to this mixture, all rhenium compounds (**12** and **15**) were exclusively converted into **13**, thus resulting in a solution of **13**, **14**, and the excess **1** (observed molar ratio **13/14/1** = 1:1.2:0.2; Scheme 6 c, bottom). The diol exchange from **15** to **13** indicates that this binding is reversible. Moreover, rhenium complex **12** exhibited DODH catalytic activity that is virtually identical to MTO (Scheme 7). Although the effect of the 3-hexyne ligand should be considered, these results provide support for methyldioxorhenium(V) as the catalytically relevant species. Based on these observations, a plausible catalytic cycle is depicted in Scheme 8. We postulate that the product selectivity originates from the relative rate of diol coordination to the Re^V species and/or the alkene extrusion.
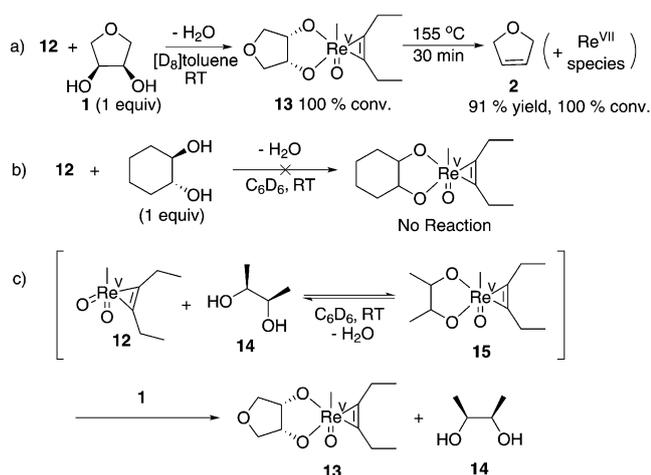
Scheme 6. The diol binding to **12**.
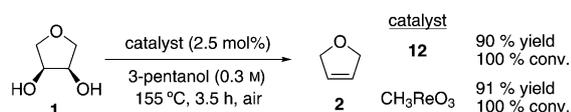

**Scheme 7.** Rhenium complex **12** as a DODH catalyst.
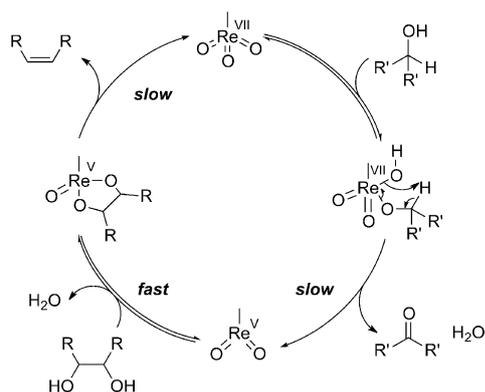
Scheme 8. A proposed catalytic cycle for MTO-catalyzed alcohol-driven DODH reaction.

To extend our method to C$_5$ sugar alcohols, we first investigated xylitol (**17**). In the initial experiments under previously employed reaction conditions, (*E*)-5-penta-1,3-diene ethers (e.g. **16**) were obtained in low yields (10–20%). Considering that three equivalents of alcohol are required for this transformation, lowering the concentration of xylitol improved the yield to 61% (Scheme 9). D-Arabinitol (**18**) and ribitol (**19**) also gave the *E* isomer **16**. The presumed *cis*-diol stereochemical requirement of the DODH reaction suggests that an *E–Z* isomerization process is involved. We propose the Lewis acid catalyzed formation of a pentadienyl cation and its trapping by the alcohol solvent, thus favoring the more-stable *E* conformation.[25] Gratifyingly, D-sorbitol (**21**) and D-mannitol (**22**), C$_6$ sugar alcohols derived from glucose and fructose, also underwent clean DODH reaction (Scheme 10). (*E*)-hexatriene (**20**), an interesting polymer
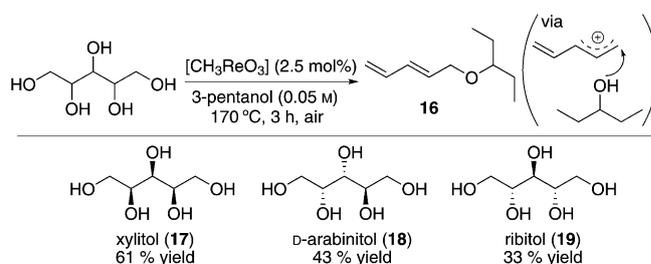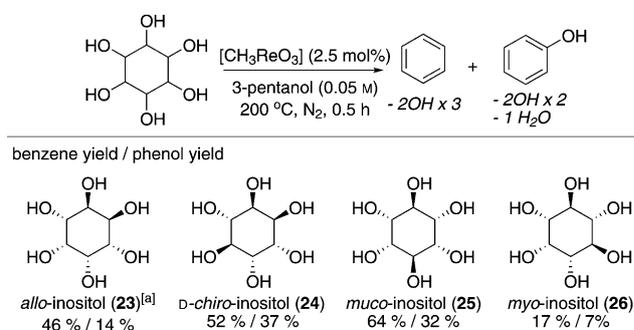

Scheme 9. DODH reaction of C$_5$ sugar alcohols.
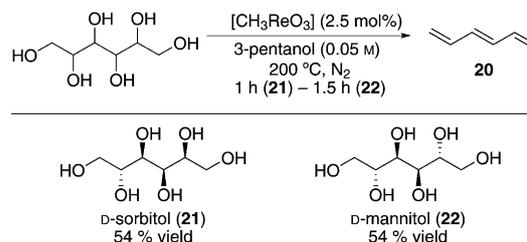
Scheme 10. DODH reaction of C$_6$ sugar alcohols.

precursor,[26] was obtained in 54% yield in both cases when high temperature and short reaction time were employed.

To further diversify the scope of biomass-derived chemicals accessible through DODH, we applied our reaction to inositols, a class of natural carbohydrate.[27] On one hand, one can imagine the formation of benzene by three consecutive DODH reactions, given the appropriate stereochemistry or fast isomerization. On the other hand, based on the knowledge garnered from xylitol DODH reactions, a cationic species may readily form after two DODH events. Driven by aromatization, the net loss of water would yield a phenol moiety. As both benzene and phenol are stable, high-volume chemicals conventionally produced only from petroleum source, their bio-derived alternatives would be highly attractive. When different inositol isomers were examined, benzene and phenol were indeed obtained as a mixture, in the total yields of 24-96% (Scheme 11).[28] High yields of benzene were obtained not only from *allo*-inositol (**23**) but also from D-*chiro*-inositol (**24**) and *muco*-inositol (**25**). In contrast, *myo*-inositol (**26**), bearing only one *cis*-diol group, gave low yields for both benzene and phenol. This result suggests that there is an isomerization process to afford a *cis*-1,2-diol intermediate

benzene yield / phenol yield

allo-inositol (**23**)[a]   D-*chiro*-inositol (**24**)   *muco*-inositol (**25**)   *myo*-inositol (**26**)
46% / 14%   52% / 37%   64% / 32%   17% / 7%

Scheme 11. Deoxygenation of inositols to aromatics. [a] 3-octanol was used instead of 3-pentanol.

at the third DODH step, which could proceed through an oxorhenium-assisted mechanism (see the Supporting Information).

We are currently investigating the application of this method to sugars, the most-direct feedstock from biomass but arguably the most-challenging substrate owing to their thermal instability as well as the complexity associated with the equilibrium between multiple isomeric forms (furanose/pyranose, aldose/ketose, α isomer/β isomer); this equilibrium is a critical consideration given the *cis*-diol specificity of our oxorhenium-catalyzed DODH reaction. When we first examined tetroses to assess the effect of aldose functionality, both D-erythrose (**27**) and L-threose (**28**) afforded furan (through a DODH reaction and subsequent dehydration) in comparable yields (Scheme 12). The high reactivity of **28** in our
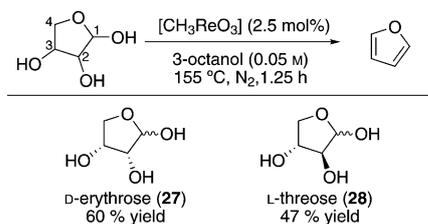
Scheme 12. Deoxygenation of tetroses to furan.

DODH process can have two plausible explanations; a) DODH of the C1 and C2 hydroxy groups, b) the epimerization of the C2 hydroxy group via erythrulose. The DODH of the internal diol (C2 and C3 hydroxy groups) in the open-chain form is unlikely because **28** would then yield (*E*)-4-hydroxybut-2-enal, which cannot re-cyclize because of the *trans* geometry. Although this experiment alone could not specify the exact DODH pathway, it suggested that the *cis*-stereochemistry requirement of DODH is not necessarily stringent for sugar substrates when the epimerization on C1 and C2 hydroxy groups can provide access to the desired product. Similar to the inositol case, once the first DODH reaction occurs, the resulting alkene directs the dehydration reaction to produce a stable compound (in this case furan) given the appropriate structure. This appears a very effective strategy to achieve a good selectivity in the DODH-based sugar deoxygenation reaction. The DODH reaction of pentoses (ribose, lyxose, arabinose, xylose) produced 2-(alkoxymethyl)furan but suffered from low yields, presumably owing to the high reactivity of furfuryl alcohol (see the Supporting Information for details). However, our preliminary results from applying the DODH reaction to hexoses are highly promising (Scheme 13): 2-vinylfuran (**29**), which is another interesting chemical candidate for material application,[29] was obtained along with furan. We assume the retro-aldol reaction of the common intermediate accounts for the furan formation (see the Supporting Information), but owing to volatility, the side product acetaldehyde could not be quantified.

In summary, we have developed an oxorhenium-catalyzed DODH reaction using alcohol as a reductant and successfully
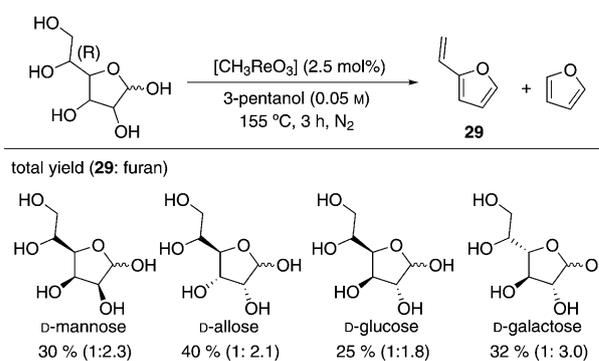
Scheme 13. Deoxygenation of hexoses to 2-vinylfuran and furan.

applied it to sugars and sugar alcohols with a view to biomass conversion. Oxorhenium compounds, namely MTO, showed much higher activity than the previously reported rhenium carbonyl catalysts and enabled the DODH reaction to be applied to unstable polyol substrates. In addition, mechanistic insights were acquired by studying the isolated Re^V species. Besides being *cis*-diol specific, the DODH reaction provided a strong differentiation among diol moieties and this stereospecificity was the key to obtaining the high yields. Although secondary alcohols were more favorable as reductants, we demonstrated the viability of the use of bio-derived alcohols such as 1-butanol in this reaction. Sugar alcohols yielded linear polyene products, possible feedstock for polymers and fuels. When DODH was combined with a subsequent dehydration reaction, stable aromatic compounds with a low oxygen content were obtained from sugars (benzene, phenol, and furan moieties). Future work will include increasing the efficiency of sugar DODH, the application to polysaccharides, and immobilization/recycling of the catalyst.

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[12] As most products were volatile, yields and conversions were determined by ^{1}H NMR spectroscopy using mesitylene as an internal standard, unless otherwise noted.

[13] a) B. G. Harvey, H. A. Meylemans, *J. Chem. Technol. Biotechnol.* **2011**, *86*, 2–9; b) M. Kumar, K. Gayen, *Appl. Energy* **2011**, *88*, 1999–2012.

[14] No catalytic DODH reaction was observed when **1** was reacted with oxorhenium catalyst in the absence of alcohols. See the Supporting Information.

[15] Although water is produced from DODH reaction and the reaction was tolerant to moisture in the air, the reaction was inhibited when a significant amount of water was initially present. No conversion of **1** was observed in 3-octanol/H_2O = 5:1 or 1-butanol/H_2O = 10:1 with 2.5 mol% of MTO, 170°C, 1 h.

[16] A. Cann, J. Liao, *Appl. Microbiol. Biotechnol.* **2010**, *85*, 893–899.

[17] Secondary alcohols also underwent dehydration to produce alkenes (e.g. *cis*- and *trans*-pentenes from 3-pentanol). However, this reaction did not interfere with the desired DODH reaction.

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[21] When MTO and 3-pentanol were heated at 155°C in the absence of 3-hexyne, a black insoluble material resulted. The organic phase contained 3-pentanone (^{1}H and ^{13}C NMR analysis).

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[23] No reaction was observed at room temperature over 3 days or at 100°C over 1 h. A trace amount of **12** (5% yield) was observed at 125°C after 1 h.

[24] No reaction was observed at temperatures of up to 100°C by VT-NMR analysis. Note that only a simplified structure is depicted in the scheme: **13** is not *Cs* symmetric. For details, see Supporting Information.

[25] When penta-1,4-dien-3-ol was heated in 3-octanol with 2.5 mol% of MTO, (*E*)-3-(penta-2,4-dienyloxy)octane was obtained (see the Supporting Information). For a related rhenium-catalyzed etherification of alcohols, see: B. D. Sherry, A. T. Radosevich, F. D. Toste, *J. Am. Chem. Soc.* **2003**, *125*, 6076–6077.

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[28] (Pentan-3-yloxy)benzene, hydroquinone and catechol were detected by GC-MS but yields were insignificant (^{1}H NMR and GC-FID analysis).

[29] a) A. Gandini, *The Behavior of Furan Derivatives in Polymerization Reactions, Vol. 25*, Springer, Berlin, **1977**, pp. 47–96; b) S. Höhne, S. Spange, *Macromol. Chem. Phys.* **2003**, *204*, 841–849.