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An efficient didehydroxylation method for the biomass-derived polyols glycerol and erythritol. Mechanistic studies of a formic acid-mediated deoxygenation†

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An efficient 1,2-deoxygenation method, involving an unexpected mechanism, was found for simple diols and for biomass-derived polyols (glycerol and erythritol) that results in the conversion of the 1,2-dihydroxy group to a carbon–carbon double bond.

Biomass is an abundant and readily available feedstock that has great potential as a renewable source of chemical intermediates.¹ Whereas the preparation of useful chemicals from petroleum has historically been accomplished by *adding* heteroatom functionality to unfunctionalized starting materials, the conversion of biomass commonly requires the *removal* of oxygen atoms from the natural precursors. In this context, the deoxygenation of polyhydroxy compounds, especially biomass-derived carbohydrates, is an important target.

Glycerol (**1**) is the main byproduct in the triglyceride transesterification process for biodiesel manufacture. The recent market expansion of biofuels has made glycerol attractive as a starting material for the synthesis of more valuable chemicals.² We describe in this paper an improved and efficient method for the formic acid-mediated conversion of glycerol into allyl alcohol (**3**) (Fig. 1). Allyl alcohol is a large-scale industrial chemical, presently produced from propene, which is used as a starting material in the manufacture of various polymers and other allyl compounds, and has also a great potential as a precursor of 3-hydroxypropionic acid,³ an important building block for the development of bio-refinery processes. Ours is a solvent-free procedure that employs formic acid, a high-volume commodity chemical. Formic acid has recently shown significant potential as a low-cost renewable chemical because of its occurrence in bio-oils from biomass pyrolysis⁴ and because of its promising role in hydrogen storage through the fixation of CO₂ with H₂.⁵

Glycerol is known to undergo proton-catalyzed dehydration reactions in the presence of solid acid catalysts⁶ and in supercritical aqueous media⁷ to afford the unsaturated aldehyde acrolein, usually with low selectivity. In the course of our investigation of the acid-catalyzed dehydration of glycerol, we observed production of allyl alcohol instead of the aldehyde.

Earlier studies⁸ reported substantial charring during the treatment of glycerol with formic acid. We have now found that the simple expedient of protecting this reaction from air provides a much more tractable process. Specifically, treating glycerol with formic acid while directing a stream of nitrogen through the reaction mixture completely eliminates charring, which is mainly responsible for the formation of undesired products. The method thus substantially improves the yield and selectivity of the process. A description of our reaction conditions and full experimental details are presented in the supplementary information.†

By continuously removing the sensitive product alcohol (the most volatile component of the reaction mixture) by distillation, the high temperature can be maintained while allowing the reaction to proceed nearly to completion, resulting in a yield of 80% after purification by distillation over K₂CO₃. Besides protecting the product from atmospheric oxidation, the nitrogen bubbling facilitates distillation of the alcohol.

With respect to the mechanism of this reaction, our first hypothesis was that it involved initial acid-induced dehydration of glycerol to acrolein *via* a 1,2-hydrogen shift pathway, followed by reduction of the aldehyde carbonyl group consistent with the well-documented role of formic acid as a hydride donor.⁹ In order to test this hypothesis, we carried out isotopic labeling experiments using d₅-glycerol (**1-d₅**) and perdeuterated formic acid (**2-d₂**) (Scheme 1). The incorporation of deuterium in the final product was monitored by ²H-NMR.

First, d₅-glycerol was treated with undeuterated formic acid and, surprisingly, *no* protons were incorporated from the supposed reducing agent formic acid into the product alcohol. Instead, the allyl alcohol product was completely deuterated at all carbon positions (**3-d₅**). When **2-d₂** was employed in the

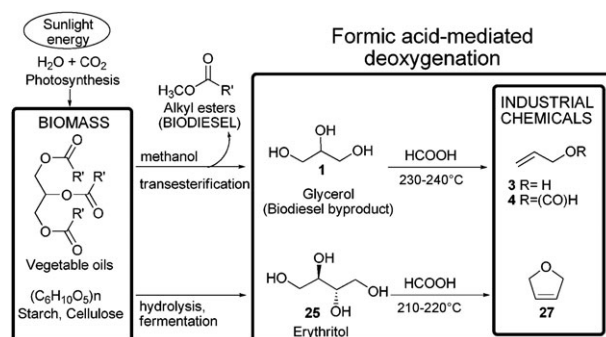


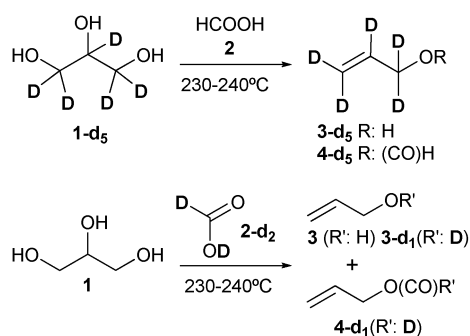
Fig. 1 Formic acid-mediated deoxygenation of the biomass-derived polyols glycerol and erythritol.

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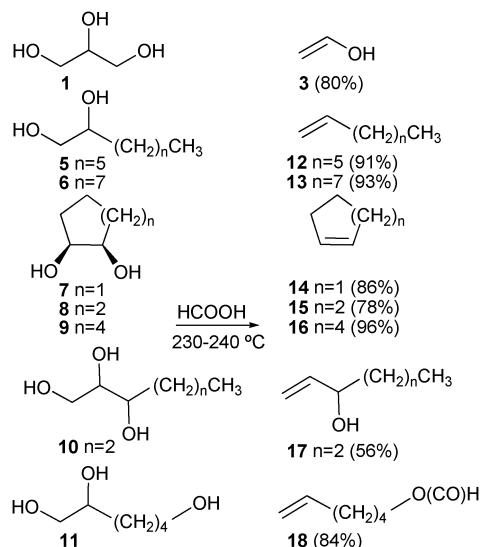
Scheme 1 Isotopic labeling experiments.

reaction with non-labeled **1**, no deuterium was incorporated in the final product (**3**), except for the exchange of deuterium into the hydroxyl group (**3-d₁**) and the formyl proton of the minor allyl ester **4-d₁**. Thus, there is no hydride transfer from formic acid, ruling out the intervention of the expected acrolein intermediate.

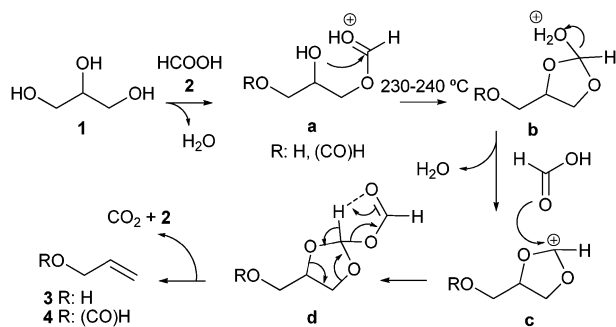
We concluded from the above experiments that formic acid was somehow inducing a direct removal of two hydroxy groups (didehydroxylation reaction) from glycerol. To examine the generality of this process, we studied the reaction of several simple diols (Scheme 2) following the same procedure.

The reaction was found applicable in the case of 1,2-diols such as 1,2-octanediol (**5**) and 1,2-decanediol (**6**) which smoothly underwent this conversion to the corresponding alkenes in yields over 90%. Cyclic diols including *cis*-1,2-cyclopentanediol (**7**), *cis*-1,2-cyclohexanediol (**8**) and *cis*-1,2-cyclooctanediol (**9**) afforded the corresponding cyclic olefins in high yields. Trihydroxy compounds such as 1,2,3-hexanetriol (**10**) and 1,2,6-trihydroxyhexane (**11**) led as well to the corresponding alkenes **17** and **18**.

Deoxygenation of diols to produce olefins is a useful synthetic transformation that typically requires initial conversion of the vicinal diol into an activated group, which is subsequently transformed into an olefin in a further step.¹⁰ The formic acid-mediated didehydroxylation provides a



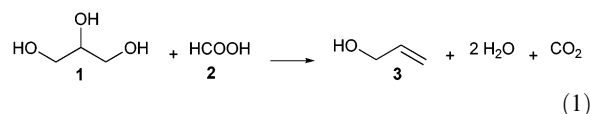
Scheme 2 Formic acid-mediated didehydroxylation of diols and triols.



Scheme 3 Mechanism proposed for the formic acid-mediated didehydroxylation.

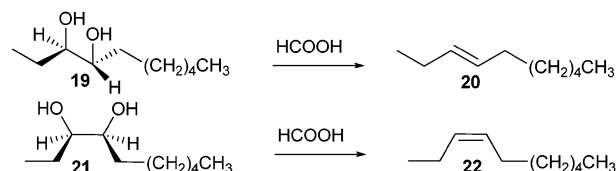
one-step procedure that directly affords the alkenes in high yield and purity.

We suggest that these reactions proceed through an orthoester-type intermediate, inspired by Eastwood's procedure for the conversion of vicinal diols to olefins using triethyl orthoformate and acetic anhydride¹¹ and by the thermal decomposition observed for 2-acetoxy-1,3-dioxolanes.¹² A proposed mechanism for the formic acid-mediated didehydroxylation of glycerol (eqn (1)) is given in Scheme 3.

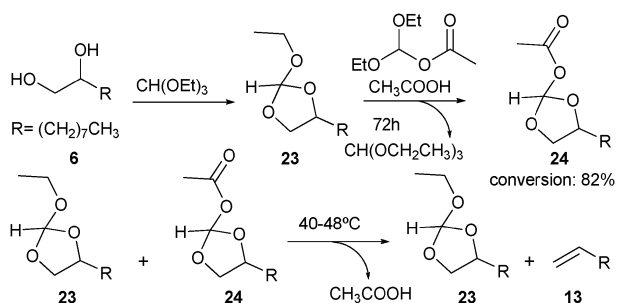


We suggest that the reaction involves the transient formation of a cyclic carbocation intermediate (**c**, Scheme 3) which is resonance-stabilized by the two oxygen atoms vicinal to the cationic center. The preparation and characterization of 1,3-dioxolan-2-ylum ions from *alpha* glycols has been previously described.¹³ The most plausible route from the 1,3-dioxolan-2-ylum carbocation to the observed product involves attack of the carbonyl oxygen of formic acid to provide a 2-acyloxy-1,3-dioxolane (**d**, Scheme 3), which then undergoes thermal carbon dioxide elimination and hydrogen transfer to give an olefin and formic acid.

The fact that *cis*-1,2-cyclopentanediol (**7**) reacted cleanly with formic acid at high temperature to yield cyclopentene (**14**), while *trans*-1,2-cyclopentanediol did not form the olefin, suggested that the formic acid-mediated deoxygenation is a highly stereospecific *syn* elimination, which is in accordance with the pathway proposed above. In order to confirm this supposition, we subjected two stereoisomeric internal acyclic 1,2-diols to the reaction. Thus, treatment of (3*R**,4*R**)-decane-3,4-diol (**19**) and (3*S**,4*R**)-decane-3,4-diol (**21**) with formic acid (**2**) proceeded readily, generating the *trans* (**20**) and *cis* (**22**) isomers of 3-decene respectively (Scheme 4). The diol substrates and the deoxygenation products have magnetically different protons that lead to specific and distinguishable



Scheme 4 Stereospecific deoxygenation of diols **19** and **21**.



Scheme 5 Synthesis and thermal transformation of 2-acetoxy-1,3-dioxolane **24**.

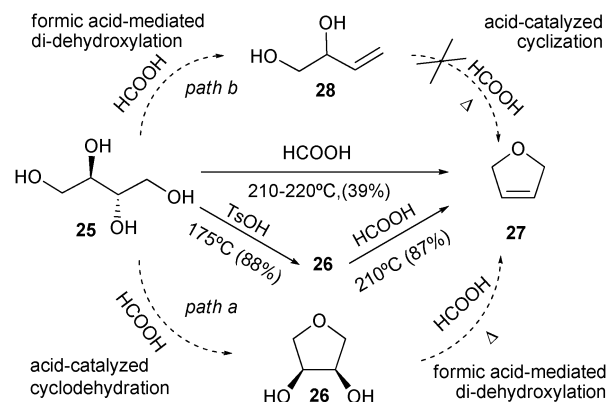
patterns. Both reactions were stereospecific as observed by NMR analysis of the crude distillates, in which no signals (<1%) due to the alkene with the opposite stereochemistry were detected in the spectra.

In order to demonstrate the capability of thermal transformation of the cyclic orthoesters of type **b** (Scheme 3) to generate a double bond, the synthesis of a 2-acyloxy-1,3-dioxolane from a 2-alkoxy-1,3-dioxolane was carried out. 1,2-Decanediol (**6**) was used as a model system for this study. The 2-ethoxy-1,3-dioxolane derivative **23** was prepared and subsequently converted¹² to the 2-acetoxy-1,3-dioxolane **24** (Scheme 5). When a mixture of dioxolanes **23** and **24** was carefully heated, the 2-acetoxy-1,3-dioxolane **24** was transformed into the olefin **13** at 40–48 °C, while compound **23** was unaffected.

The above results suggest that the formic acid-mediated didehydroxylation might be extendable to carbohydrates, an economically and environmentally important target. Preliminary results with sugar polyols are very promising. Erythritol (**25**) is a four-carbon sugar alcohol that is accessible through yeast or fungal fermentation of glucose from corn starch (Fig. 1). The reaction of **25** with formic acid at 210–220 °C, following the procedure described above for glycerol (**1**), gave a distillate that contained 2,5-dihydrofuran (**27**) along with water and formic acid. A 39% yield of the pure dihydrofuran **27** was isolated after purification by fractional distillation (Scheme 6).

To investigate the course of this reaction, *cis*-1,4-anhydroerythritol (**26**) was prepared by acid-catalyzed cyclodehydration of erythritol with *p*-toluenesulfonic acid¹⁴ in 88% yield. Formic acid-mediated didehydroxylation of the cyclic product **26** afforded the corresponding olefin **27** in 87% yield after purification by redistillation. The reaction of 3,4-dihydroxybutene (**28**) with formic acid was also investigated, since it is a reasonable potential intermediate in the conversion of erythritol to 2,5-dihydrofuran. If deoxygenation of the vicinal primary and secondary hydroxy groups (through an orthoester type intermediate) occurred, the diol **28** could possibly provide the product **27** by acid-catalyzed cyclodehydration (Scheme 6, path b). However, as shown in Scheme 6, **28** did not yield 2,5-dihydrofuran when submitted to our standard formic acid-mediated didehydroxylation conditions, pointing to *path a* as the most plausible reaction pathway.

2,5-Dihydrofuran (**27**) is presently prepared by ring closing metathesis or by catalytic rearrangement of vinyl oxirane.



Scheme 6 Synthesis of 2,5-dihydrofuran (**27**) from erythritol (**25**) and possible intermediates **26** and **28** (pathways a and b, respectively).

The transformation of erythritol (**25**) to 2,5-dihydrofuran (**27**) is a good example of how this reaction could offer an efficient approach to the conversion of biomass to value-added chemicals.

In conclusion, we have uncovered an improved selective one-pot, one-reagent deoxygenation technique for converting vicinal diols to unsaturated systems in high yields, and provide evidence for an unexpected concerted mechanism for the critical bond-changing processes in this transformation. Our preliminary results with inexpensive biomass-derived polyols suggest that the reaction of polyhydroxy compounds with formic acid will be a valuable alternative for the manufacture of reduced oxygen content products.

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