Biofuels

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Efficient Production of the Liquid Fuel 2,5-Dimethylfuran from Fructose Using Formic Acid as a Reagent**

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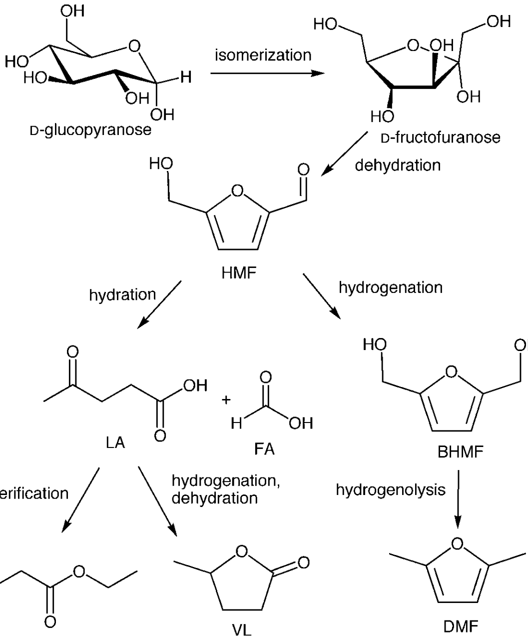
Biofuels that are obtainable from renewable sources have attracted recent interest.[1] The ultimate goal of current research is the conversion of our most abundant renewable hydrocarbons, lignocellulose, into liquid fuels for motor vehicles.[2] Such carbon-neutral resources, in addition to being more geographically disperse than petroleum reserves, promise to minimize the emission of greenhouse gases. The majority of lignocellulose is cellulose, a polymer derived from glucose. The main approaches to the utilization of cellulose involves acid-catalyzed hydrolysis[3] followed by either chemical or biological conversions of glucose.[4] Glucose readily isomerizes into fructose, from which one can envision a number of promising liquid fuels such as 2,5-dimethylfuran (DMF),[5] γ-valerolactone (VL),[6] and ethyl levulinate (EL)[7] (Scheme 1).

DMF is particularly attractive because of its nearly ideal boiling point (92–94 °C), its high energy density (30 kJ cm^{-3}), and its high research octane number (RON = 119).[5] Furthermore it is immiscible with water and is easier to blend with gasoline than ethanol. 5-(Hydroxymethyl)furfural (HMF)[8] is a compound of interest since it is an intermediate in biofuel conversions as well as a valued fine chemical.[9] HMF can either undergo hydrogenation/hydrogenolysis to form DMF or acid-catalyzed conversion into levulinic acid (LA), a precursor to VL.

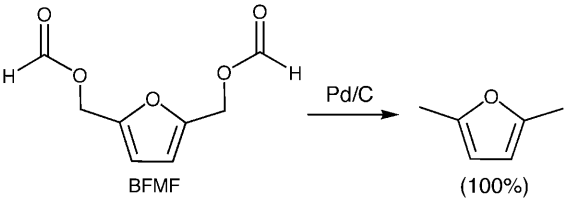
In considering alternative conversions[10,11] of fructose that ultimately lead to DMF, we conceived of a process whereby several steps could be conducted in one pot. Key to our strategy is the use of formic acid (FA), which has the potential to serve as an acid catalyst, a source of hydrogen (H_2), and a deoxygenation agent.[12] FA has attracted much recent interest in the area of green chemistry because of its potential as a hydrogen carrier and as a means of utilizing carbon dioxide.[13] FA is currently produced industrially by the hydration of carbon monoxide as well as the hydrogenation of carbon dioxide.[14] FA is also generated as a by-product from biomass degradation processes.[6a,15]

Initial experiments were aimed at evaluating the usefulness of formic acid for conversions of HMF. As expected, HMF can be readily hydrogenated into bis(hydroxymethyl)furan (BHMF) using formic acid (4 equiv) in the presence of Pd/C. The conversion is essentially quantitative in refluxing tetrahydrofuran (THF). No additional reactions occurred even after prolonged reaction times. Featuring two benzylic-like alcohol groups, BHMF is well suited for hydrogenolysis to deliver DMF.[16] Indeed, the gas-phase conversion of BHMF into DMF has been conducted at 220 °C with 6.8 bar H_2 over a copper/ruthenium catalyst.[5] Formic acid provides a milder pathway for this conversion. Specifically, we found that the diformate ester of BHMF (BFMF) is quantitatively converted into DMF in refluxing THF upon the addition of Pd/C [Eq. (1)].



Scheme 1. Conversions of glucose into liquid fuels.

Given the lability of BFMF, we turned our attention to conditions for the formation of BFMF from BHMF. We found that a THF solution of BHMF and formic acid (10 equiv) converted into BFMF at 120 °C upon the addition of small amounts (0.13 equiv) of H_2SO_4. The intermediate monoester was observed spectroscopically.[17]



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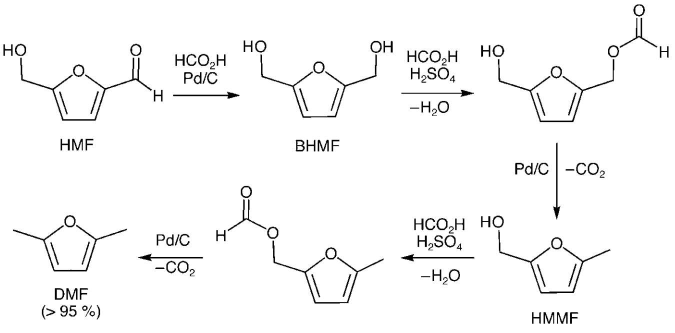
The utility of FA as both a hydrogen source and a deoxygenating agent encouraged efforts to combine several of the aforementioned steps. Gratifyingly, heating a solution of HMF in refluxing THF with formic acid, H_2SO_4, and Pd/C gave DMF. The reaction proceeded in excellent yield (> 95 %, 15 h). NMR analysis of the reaction revealed signals that were assigned to 2-hydroxymethyl-5-methylfuran (HMMF) as an intermediate, thus implicating step-wise hydrogenolysis of BHMF (Scheme 2).

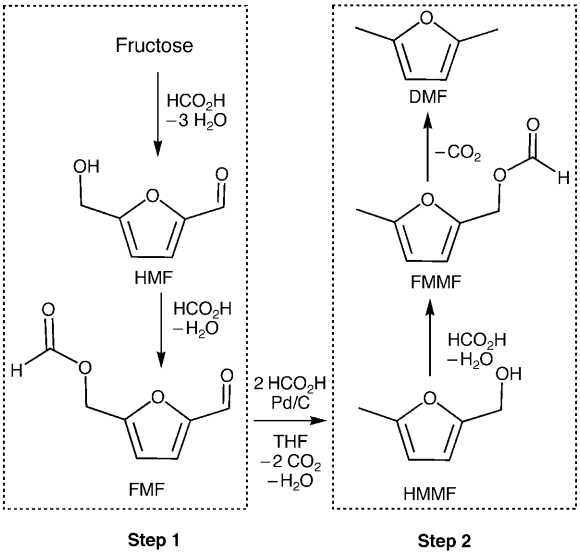


Scheme 2. Pathway for dimethylfuran from HMF. See the Supporting Information for details.

Table 1: Dehydration of fructose with formic acid.[a]

Entry	Solvent	Additive	T [°C]	t [h]	Selectivity [%][c] $\frac{HMF+FMF}{HMF+FMF+LA} \times 100$
1	FA	none	120	10	56
2	FA	1 mol% H_2SO_4	120	1	65
3	FA	10 mol% H_2SO_4	120	0.5	52
4	FA	none	150	2	73
5[b]	DMSO	10 mol% H_2SO_4	100	5	93

[a] Typical reaction conditions: fructose (3.6 g), FA (20 mL), additive. [b] 10 mL DMSO used. [c] Selectivity determined by ^1H NMR analysis. DMSO = dimethylsulfoxide.



Scheme 3. One-pot process to generate DMF from fructose. The conversions were carried out at about 150 °C (left box) and 70 °C (right box).

Deoxygenation of benzylic-like alcohols by in situ generation of formate esters was verified in control experiments. Neither furfuryl alcohol nor benzyl alcohol undergoes hydrogenolysis in the presence of formic acid and Pd/C in THF. However, addition of a catalytic amount of H_2SO_4 (0.065 equiv/ROH) to such solutions resulted in clean conversions into 2-methylfuran and toluene.

In view of the conversion of HMF into DMF, we investigated the use of formic acid for conversions of fructose. Therefore, by using 2.8 mL of formic acid per gram of fructose, we obtained HMF and its formate ester (FMF), as well as LA. HMF and FMF are equivalent precursors to DMF. LA, which is also a promising precursor for biofuels (Scheme 1),[6b,c,d] does not interfere with subsequent reactions. Considerable control of the selectivity toward HMF/FMF versus LA is possible by varying the temperature, reaction time, and strong acid additives (Table 1). For example, HMF formed in 95 % yield when the dehydration was conducted in DMSO.

Solutions of FMF and HMF in FA were found to undergo hydrogenation and hydrogenolysis into DMF upon addition of a THF slurry of the Pd/C catalyst. The conversion is proposed to proceed through the intermediacy of 2-hydroxymethyl-5-methylfuran (HMMF) and its monoformate ester (FMMF; Scheme 3). LA was unreactive under these conditions and thus remained in the solution at the end of the reaction. Pd/C and formic acid were recovered by filtration and distillation. Control experiments confirmed that a solution of FMF in formic acid (2.46 mL$\,g^{-1}$) and H_2SO_4 (0.13 equiv) and subsequent addition of THF with Pd/C yielded DMF quantitatively upon heating to reflux.

Use of acetic acid in the above processes highlights a number of advantages for formic acid. Being a weaker acid, acetic acid is ineffective for the dehydration of fructose into HMF. The diacetate ester of BHMF is unreactive toward Pd/C except in the presence of H_2 wherein we observe formation of significant amounts of 2,5-dimethyltetrahydrofuran. The use of formic acid completely avoids ring hydrogenation.

In summary, formic acid, a potentially renewable carrier of hydrogen, enables an efficient one-pot synthesis of the promising liquid fuel 2,5-dimethylfuran from fructose. Formic acid serves three distinct functions: as an acid catalyst for dehydration of fructose to HMF, a hydrogen source for one hydrogenation (HMF to BHMF), and as a reagent for the deoxygenation of furanylmethanols. Additional flexibility in the transformation is possible if the initially produced HMF is isolated; the HMF can then be subjected to palladium-catalyzed decarbonylation[18] (CO is a precursor to formic acid[14]), and the resulting furfuryl alcohol then undergoes hydrogenolysis with formic acid to give 2-methylfuran.

Experimental Section

Synthesis of DMF from HMF: A suspension of HMF (0.25 g, 2 mmol), FA (0.78 mL, 20 mmol), H_2SO_4 (14 μL, 0.26 mmol), THF (10 mL), and Pd/C (0.4 g) was stirred at reflux for 15 h. ^1H and

^{13}C NMR analyses confirmed full conversion of HMF into DMF. See the Supporting Information for details.

One-pot synthesis of DMF from fructose: A suspension of fructose (3.6 g, 20 mmol) and formic acid (10 mL, 265 mmol) was stirred at 150 °C for 2 h. The resulting dark solution was then cooled to room temperature and diluted with THF (20 mL), after which H_2SO_4 (0.138 mL, 2.6 mmol) and Pd/C (4 g) were added. The resulting solution was then stirred at 70 °C for an additional 15 h. The Pd/C was then recovered by filtration and the filtrate was diluted with 20 mL H_2O, and extracted with diethyl ether (15 mL x 3). The THF and diethyl ether were removed by distillation at 90 °C. Yield of the isolated DMF: 1.1 mL (51 %).

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