DOI: 10.1002/cssc.201200718



Production of Hybrid Diesel Fuel Precursors from Carbohydrates and Petrochemicals Using Formic Acid as a Reactive Solvent

Xiaoyuan Zhou and Thomas B. Rauchfuss*^[a]

We report the one-pot alkylation of mesitylene with carbohydrate-derived 5-(hydroxymethyl)furfural (HMF) as a step toward diesel-range liquids. Using FeCl₃ as a catalyst, HMF is shown to alkylate toluene, xylene, and mesitylene in high yields in CH₂Cl₂ and MeNO₂ solvents. Efforts to extend this reaction to greener or safer solvents showed that most ether-based solvents are unsatisfactory. Acid catalysts (e.g, *p*-TsOH) also proved to be ineffective. Using formic acid as a reactive solvent, mesitylene could be alkylated to give mesitylmethylfurfural (MMF) starting from fructose with yields up to approximate-

Introduction

The conversion of lignocellulosic biomass into liquid fuels has attracted tremendous interest across the world.^[1] The traditional approach entails the conversion of cellulose, the most abundant component of lignocellulosic biomass, to glucose, which is enzymatically digested to ethanol, and CO₂. The main alternative approach to such biofuels is purely chemical. It again begins with the hydrolysis of cellulose to glucose, which is subsequently isomerized and dehydrated into 5-(hydroxymethyl)furfural (HMF), which retains all six carbon centers. HMF is a platform compound as a precursor of diverse liquid fuels such as 2,5-dimethylfuran (DMF),^[2] γ -valerolactone (GVL),^[3] 2,5-dimethyltetrahydrofuran (MTHF),^[4] and 5-(alkoxymethyl)furfurals.^[5] HMF has also been discussed as a commodity chemical as a precursor to furandicarboxylic acid, a potential replacement for terephthalic acid.^[6]

The attractiveness of HMF as a building block has increased with continuing advances in its production from carbohydrates. Systems that employ DMSO, *N*,*N*-dimethylacetamide (DMA), biphasic mixtures, and ionic liquids as solvents have been well studied.^[7] Recently, Zhang and Lai showed that fructose could be efficiently converted to HMF by using isopropyl alcohol as the solvent and HCl as the catalyst.^[8] In addition to HMF, another furanic product, chloromethylfurfural (CMF), serves as a versatile precursor to various chlorine-free deriva-

[a]	Dr. X. Zhou, Prof. T. B. Rauchfuss
	Department of Chemistry
	University of Illinois at Urbana-Champaign
	600 South Mathews Avenue, Urbana, IL 61801 (USA)
	Fax: (+ 1)217-244-3186
	E-mail: rauchfuz@illinois.edu
	Supporting Information for this article is available on the WWW under
	http://dx.doi.org/10.1002/cssc.201200718.

ly 70%. The reaction of fructose with formic acid in the absence of mesitylene gave rise to low yields of the formate ester of HMF, which indicates the stabilizing effect of replacing the hydroxyl substituent with mesityl. The arene also serves as a second phase into which the product is extracted. Even by using formic acid, the mesitylation of less expensive precursors such as glucose and cellulose proceeded only in modest yields (ca. 20%). These simpler substrates were found to undergo mesitylation by using hydrogen chloride/formic acid via the intermediate chloromethylfurfural.

tives. CMF can be produced in good yields from glucose, cellulose, or even raw biomass.^[5a,9] Furthermore, our group has shown that fructose can be converted to dimethylfuran (DMF) via HMF as an intermediate by using formic acid as a hydrogen donor and acid catalyst.^[10]

This report focuses on HMF as a building block for the production of precursors to diesel fuels. Petroleum-derived diesel is a mixture of C₁₁-C₁₅ alkanes, cycloalkanes, and aromatic compounds.[11] To convert lignocellulosic biomass, which is mainly composed of C₅-C₆ carbohydrates, into diesel-range fuels, C-C bond formation is necessary. Several strategies have been reported. Dumesic and co-workers used the aldol condensation of furfurals with acetone or its derivatives to generate C_9-C_{15} molecules, which were subjected to hydrodeoxygenation (HDO) to generate linear alkanes.^[12] Dumesic's group has also introduced an alternative approach starting from GVL, which comes from biomass-derived carbohydrates via levulinic acid. GVL undergoes decarboxylation over a silica/alumina catalyst to produce butene and CO₂. Butene is then oligomerized to produce alkenes suitable for gasoline and/or jet fuel applications.^[13] Recently, Corma and co-workers demonstrated that 2methylfuran, derived from hemicellulose, could be condensed with itself or 5-methylfurfural under acidic conditions followed by HDO to produce diesel-like 6-alkyl undecanes.^[14] A similar strategy was applied to the condensation reaction with furan by Huber and co-workers.^[12d]

Related to the theme of converting C_5 and C_6 platform molecules into diesel-range intermediates, we conceived a process that involves Friedel–Crafts coupling between HMF and petrochemically derived arenes. We have previously shown that several steps in the conversions of fructose can be conducted in one pot^[10] and we were attracted to the idea that similar pro-



Scheme 1. Conversion of sugars to diesel-like compounds.

cess efficiencies could be realized in the Friedel-Crafts approach (Scheme 1).

Results and Discussion

Arylation of HMF by using an FeCl₃ catalyst

Beller and co-workers briefly reported the FeCl₃-catalyzed solvent-free Friedel-Crafts reaction of HMF with o-xylene, which provides a 37% yield of the coupled product.^[15] Our studies have focused on reactions with mesitylene, which was expected to generate only one isomer and will thus simplify product analysis (Scheme 2). As shown in Table 1, the coupled product, 5-(mesitylmethyl)furfural (MMF), was obtained in high yields (> 90%) when the reaction was conducted in MeNO₂. This conversion was completed in 1 h, and longer reaction times had little influence on the yield (Table 1, entries 1-3). Similar yields were achieved when the solvent was switched to CH₂Cl₂. The



Scheme 2. FeCl₃-catalyzed arylation of HMF with mesitylene.

of HMF. ^[a]				,
Entry	Arene	Solvent	t	Yield
			[h]	[%] ^[b]
1	mesitylene	MeNO ₂	1	94
2	mesitylene	MeNO ₂	6	92
3	mesitylene	MeNO ₂	20	96
4	mesitylene	CH_2CI_2	12	92
5	<i>p</i> -xylene	MeNO ₂	2	95
6	toluene	MeNO ₂	2	87
7	mesitylene	THF	16	0
8	mesitylene	<i>i</i> PrOH	6	0
9	mesitylene	<i>n</i> BuOH	15	0
10	mesitylene	H₂O	5	0
[a] Reaction conditions: HMF (1.0 mmol), arene (5 mL), FeCl ₃ (0.10 mmol), solvent (5 mL), $T=80$ °C. [b] Yields were determined by using ¹ H NMR				
spectrosco	py using MeNO ₂ as th	ne integration stan	dard.	



generality of this method was demonstrated with different arenes, including *p*-xylene and toluene. Under similar conditions, these arenes gave rise to good yields of the coupled products (Table 1, entries 5 and 6).

With the goal of converting sugars into MMF, we explored potentially greener solvents that would dissolve sugars. Neither MeNO₂ nor CH₂Cl₂ are attractive solvents in the biofuels area. Tests using THF, iPrOH, nBuOH, and H₂O were unsuccessful. The formation of MMF was not observed in any of these solvents under the conditions used for MeNO₂ or CH₂Cl₂ (Table 1, entries 7-10).

Arylation of HMF by using Brønsted acid catalysts

The poor conversions of FeCl₃-catalyzed reactions in oxygenated solvents is attributed to the basicity of the solvent, which competes with HMF for the Lewis acid catalyst. A solution to this problem was suggested by our finding that the Brønsted acid p-toluenesulfonic acid (p-TsOH) could be used in place of FeCl₃ as the catalyst for the Friedel–Crafts reaction. Thus, MMF was produced in good yields in both MeNO₂ and CH₂Cl₂ (Table 2, entries 1 and 2). In oxygenated solvents, however, p-

Table 2. p-Tssolvents.	sOH-catalyzed arylation of HMF	with mesity	/lene in various
Entry	Solvent	<i>t</i> [h]	Yield ^[b] [%]
1	MeNO ₂ (5 mL)	2	76
2	CH_2CI_2 (5 mL)	16	84
3	<i>i</i> PrOH (5 mL)	3	0
4	THF (5 mL)	22	0
5	CH ₂ Cl ₂ (5 mL)+H ₂ O (5 mL)	5	0
6	MeNO ₂ (5 mL)+H ₂ O (5 mL)	12	0
[a] Reaction	conditions: HMF (1.0 mmol),	mesitylene	(5 mL), <i>p</i> -TsOH

(0.10 mmol), T = 80 °C. [b] Yields were determined by using ¹H NMR spectroscopy using MeNO₂ as the integration standard.

TsOH is an ineffective catalyst (Table 2, entries 3 and 4). Furthermore, the addition of H₂O to the reactions with MeNO₂ or CH₂Cl₂ inhibited the reaction (Table 2, entries 5 and 6).

Formic acid as a reactive solvent

As the oxygenated solvents that are suitable for sugars inhibit the Friedel-Crafts reaction, we tried the synthesis of MMF starting from fructose in MeNO_2 . In the presence of $\mathsf{HCI},^{\scriptscriptstyle[16]}$ the yields of MMF were modest (Table 3).

The preceding results highlight problems with the low solubility of fructose in MeNO₂ and the ineffectiveness of conventional acid catalysts. These considerations led us to explore the use of formic acid (FA) as a reactive solvent. FA is an excellent solvent for fructose, 0.9 g mL⁻¹ of which dissolves in FA at room temperature. FA is also a relatively strong acid with a pK_a of 3.77.^[17] Initial experiments examined the FA-catalyzed alkylation of mesitylene with HMF. As summarized in Table 4, the results were promising although the yields are highly dependent

CHEMSUSCHEM Full papers

Table 3. One-pot synthesis of MMF from fructose. ^[a]					
Entry	Solvent	HCl [μL]	<i>T</i> [°C]	<i>t</i> [h]	Yield ^[b] [%]
1	MeNO ₂	20	80	48	0
2	MeNO ₂	20	120	4	23
3	-	20	120	4	22
4	MeNO ₂	0	120	4	17
[a] Reaction	conditions:	fructose	(1.0 mmol),	mesitylene	(5 mL), FeCl ₃

(0.10 mmol), HCI (3.8 m). [b] Yields were determined by using $^1{\rm H}$ NMR spectroscopy using ${\rm MeNO}_2$ as the integration standard.

Table 4. One-pot synthesis of MMF in FA. ^[a]					
Entry	Substrate	HCI [µL]	<i>T</i> [°C]	t [h]	Yield ^[b] [%] []]
1	HMF	0	80	6	33
2	HMF	0	80	22	66
3 ^[c]	HMF	0	80	4	55
4	HMF	0	120	2	79
5	HMF	0	120	4	94
6	FMF	0	120	4	90
7	fructose	0	120	5	36
8	fructose	0	120	12	53
9	fructose	20	120	2	72
10	fructose	20	120	4	68
11	fructose	0	150	2	66
12	fructose	0	150	4	58
13	fructose	20	100	2	62
14	fructose	20	100	4	63
15	fructose	20	100	12	72
[a] Reaction conditions: substrate (1.0 mmol), FA (5 mL), mesitylene (5 mL), HCl (3.8 μ). [b] Yield was determined by using ¹ H NMR spectrosco-					

(5 mL), HCI (3.8 m). [b] Yield was determined by using 'H NMR spectroscopy using MeNO₂ as the integration standard. [c] FeCl₃ (0.1 mmol) was added.

on temperature, time, and additives. At 80 °C, up to a 66% yield of MMF was achieved (Table 4, entries 1 and 2). The reaction accelerated in the presence of FeCl₃ (Table 4, entry 3). Omitting FeCl₃ but at 120 °C, we generated MMF almost quantitatively after 4 h (Table 4, entries 4 and 5).

A plausible mechanism for the Friedel–Crafts arylation of HMF is illustrated in Scheme 3. A control experiment showed that FA solutions of HMF produced 5-(formyloxymethyl)furfural (FMF) quantitatively in 10 min at 120 °C. This result suggests that the arylation of HMF proceeds via FMF. This pathway was confirmed by the synthesis of MMF from FMF (Table 4, entry 6).

Encouraged by the effectiveness of FA as a reactive solvent, we next examined the one-pot dehydration/arylation reaction starting from fructose. Under conditions similar to those for HMF but starting with fructose, MMF was formed in yields up to 53% by using FA (Table 4, entries 7 and 8). These yields exceed those discussed above if MeNO₂/FeCl₃ was employed as the solvent in place of FA. Small amounts of HCl further accelerate the conversion (Table 4, entries 9 and 10). In the absence of HCl, similarly good yields of MMF could be achieved at elevated temperatures (Table 4, entries 11 and 12). A reduction of the reaction temperature from 120 to $100^{\circ}C$ decelerat



Scheme 3. Pathway for the arylation of HMF to MMF in FA.

ed the conversion, which, however, could be compensated for by prolonged reaction times (Table 4, entries 13–15).

Production of MMF from glucose and cellulose

We investigated the production of MMF from glucose and cellulose in place of fructose. Such a process would require the isomerization of glucose to fructose. As summarized in Table 5,

Table 5. One-pot synthesis of MMF in FA starting from glucose. ^[a]					
Entry	CrCl₃·6H₂O [mol%]	<i>Т</i> [°С]	t [h]	Yield ^[b] [%]	
1	0	120	4	10	
2	5	120	4	11	
3	10	120	4	20	
4	20	120	4	23	
5	10	100	4	4	
6	10	150	4	19	
7	10	120	12	22	
8 ^[c]	0	120	5	52	
[a] Reaction conditions: glucose (1.0 mmol), FA (5 mL), mesitylene (5 mL), HCI (3.8 μ , 20 μ L). [b] Yield was determined by using ¹ H NMR spectroscopy using MeNO ₂ as the integration standard. [c] Reaction conditions: glucose (0.39 mmol), FA (7 mL), mesitylene (15 mL), 1,2-dichloroethane (15 mL), concentrated HCI (1 mL).					

the reaction conditions that generate MMF from fructose in good yields gave rise to only low yields from glucose (Table 5, entry 1). This problem is attributed to the sluggish isomerization of glucose to fructose. As chromium chlorides catalyze the isomerization of glucose to fructose,^[18] experiments were conducted with CrCl₃·6H₂O, but the yield of MMF improved only by 10% (Table 5, entries 2 and 3). A further increase of the catalyst loading had a very limited effect on the yield of MMF (Table 5, entry 4). This one-pot synthesis of MMF from glucose is also significantly influenced by temperature. The reaction conducted at 100 °C resulted in a much lower yield than that at 120 °C (Table 5, entries 3 and 5), whereas a higher reaction temperature (150 °C) led to a negligible change in the yield of MMF (Table 5, entry 6). Attempts to enhance the yield by extending the reaction time were unsatisfactory (Table 5, entry 7).

CHEMSUSCHEM FULL PAPERS

A further objective was to convert cellulose directly to MMF. The propose conversion would involve the initial depolymerization of cellulose followed by the conversion of glucose to MMF via fructose and HMF. As anticipated from experiments with glucose, only small amounts of MMF were produced from cellulose (Table 6, entry 1). The poor conversions are attributed to the slow depolymerization of cellulose. Indeed, the best yields required a long reaction time (8 h) and a high temperature (150 °C; Table 6, entries 2 and 3).

Table 6. One-pot synthesis of MMF in FA starting from cellulose. ^[a]					
Entry	<i>Т</i> [°С]	<i>t</i> [h]	Yield ^[b] [%]		
1	120	4	2		
2	120	8	10		
3	150	8	19		
4 ^[c]	120	5	37		

[a] Reaction conditions: cellulose (1.0 mmol, determined by moles of glucose monomers contained in cellulose), FA (5 mL), mesitylene (5 mL), HCI (3.8 m, 20 μ L), CrCl₃·6H₂O (0.1 mmol). [b] Yield was determined by using ¹H NMR spectroscopy using MeNO₂ as the integration standard. [c] Reaction conditions: cellulose (0.39 mmol, determined by moles of glucose monomers contained in cellulose), FA (7 mL), mesitylene (15 mL), 1,2-di-chloroethane (15 mL), concentrated HCI (1 mL).

Mascal and Nikitin reported that glucose and cellulose could be converted into 5-(chloromethyl)furfural (CMF) with yields up to 80% in a biphasic system by employing only aqueous HCl as a reagent.^[5a, 9a] This method inspired us to produce MMF from glucose and cellulose via CMF as the intermediate in a two-pot procedure (Scheme 4). In one reactor, glucose and cellulose were converted into a 1,2-dichloroethane solution of CMF in one reactor, which was separated from the aqueous phase and subsequently treated with FeCl₃ and mesitylene in a separate reactor. In this way, MMF was generated from glucose and cellulose with yields of 68 and 36%, respectively.



Scheme 4. Generation of MMF from glucose and cellulose.

We further simplified the process in a one-pot reaction by using concentrated HCl, 1,2-dichloroethane, FA, and mesitylene (Scheme 5). This mixture consists of two liquid phases of which the main components are $H_2O/HCl/FA$ and 1,2-dichloroethane/ mesitylene. By using this blend, MMF was produced from glucose and cellulose with yields up to 52 (Table 5, entry 8) and 37% (Table 6, entry 4).



Scheme 5. Simplified synthesis of MMF from glucose and cellulose.

Experiments on the function of mesitylene

A common side-reaction that plagues the acid-catalyzed conversion of fructose into HMF is the competing formation of intractable polymers called humins.^[19] In terms of their structure and mechanism of formation, these dark, insoluble species are poorly understood. Humins result from the polymerization/oligomerization of furanic compounds,^[20] it has been proposed that they also arise through the condensation of sugars with their dehydration products.^[21] Experiments that involve fructose in the absence of mesitylene yield only small amounts of FMF (Table 7, entry 1), even under conditions that otherwise produce MMF in nearly 70% yield (Table 4, entry 10). Such experiments produce large amounts of humins, which indicates that the presence of mesitylene suppresses the formation of humins.

Table 7. Reactions of various substrates in FA in the absence of mesityle-ne. $^{[a]}$					
Entry	Substrate	Yield ^[b] [%]	Products		
1	fructose	21	FMF		
2	HMF	70	FMF		
3	MMF	95	MMF		
4 ^[c]	HMF+fructose	33	FMF		
5 ^[c]	MMF+fructose	62	FMF (0.02 mmol)		
MMF (0.60 mmol)					
[a] Reaction conditions: substrate (1.0 mmol), FA (5 mL), HCI (3.8 M, 20 μ L), 120 °C, 4 h. [b] Yield was determined by using ¹ H NMR spectroscopy using MeNO ₂ as the integration standard. [c] The substrate was a mix-					

ture of HMF or MMF (0.66 mmol) and fructose (0.34 mmol).

We considered two possible beneficial roles for mesitylene on the formation of furans from fructose. In the first hypothesis, mesitylene removes the most reactive functional group from HMF, the hydroxyl group. According to the second hypothesis, as it is immiscible with FA, mesitylene functions as a second phase to extract the products into a more benign environment. Related biphasic systems have been applied for the in situ extraction of furfurals to minimize the formation of humins in the dehydration process.^[22] A series of experiments were conducted to investigate the first hypothesis (Table 7). In the absence of mesitylene, HMF led to the formation of FMF in FA with a yield of 70%, and MMF was recycled quantitatively under identical conditions (Table 7, entries 2 and 3). This result is consistent with our hypothesis that the replacement of the -OH group with an aryl group stabilizes the furanic compound in FA and inhibits its condensation to produce humins. Moreover, as noted above, humins are also proposed to form from the condensation of sugars with their dehydration products. To understand the function of the aryl group in MMF and the formation of humins in this system, the conversion of mixtures of monosaccharides and furanic compounds were studied (Table 7, entries 4 and 5). The addition of fructose to HMF reduced the yield of FMF to 33%, concomitant with a significant, albeit qualitative, increased yield of humins. In contrast, MMF was recycled quantitatively from an FA solution even in the presence of fructose. Based on these results, we conclude that humins mainly arise through the cross-polymerization of sugars and their dehydration products. The homopolymerization of HMF or FMF to form humins may also occur, but to a much lesser extent. The conversion of HMF to MMF inhibits the formation of humins from both of the pathways proposed above.

In addition to the stabilizing effect of mesitylene, in this case, this Friedel–Crafts arylation reagent may also serve as a second phase solvent in which the products are more stable than in FA with a catalytic amount of HCI. To probe this possibility, the partition coefficients of HMF, FMF, and MMF in a mixture of FA and mesitylene were determined (Table 8). HMF and

Table 8. Partition coefficients (P) of HMF, FMF, and MMF in FA/mesityle-ne. ^[a]				
Entry	Substrate	P ^[b]		
1 ^[c]	HMF	>19		
2	FMF	>19		
3	MMF	0.41		
[a] Conditions: substrate (1.0 mmol), FA (5 mL), mesitylene (5 mL). [b] $P = $ [substrate] _{FA} /[substrate] _{mesitylene} . [c] The formation of FMF (16%) from HMF was observed.				

FMF are much more soluble in FA than in mesitylene, with more than 95% of these solutes in the FA phase. In comparison, mesitylene is a better solvent than FA for MMF. These results suggest that the FA/mesitylene mixture is not an effective biphasic system for the generation of HMF or FMF. However, the solubilities of HMF (or FMF) could be modified dramatically by substituting the hydroxyl (or formyl) group with an aryl group, which makes them more soluble in the mesitylene phase in which they are more stable.

Conclusions

This work describes an approach for the production of hybrid fuels from readily available precursors derived from both biological sources and the benzene-toluene-xylene (BTX) stream of petrochemicals.^[23] The transformations examined involve the Friedel-Crafts reactions of 5-(hydroxymethyl)furfural (HMF), the principal intermediate obtained from the dehydration of fructose. This sugar is obtained from glucose, which in turn is the monomer in cellulose and amylose. Our alkylations were optimized with mesitylene, although other arenes were also shown to be suitable substrates.

Our major finding is that formic acid (FA) functions effectively as both solvent and catalyst for the reactions of fructose, glucose, and even cellulose. The dehydration of the sugar and alkylation of the aromatic compound were combined in a onepot synthesis to give mesitylmethylfurfural (MMF) in yields of 20–70% under mild reaction conditions. Glucose and cellulose, which are both more attractive and challenging substrates, gave rise to only modest yields even with a CrCl₃·6H₂O/FA system. A new biphasic system of concentrated HCl/FA and 1,2-dichloroethane/mesitylene substantially improved the yields of MMF from glucose and cellulose. We propose that this process involves chloromethylfurfural (CMF) as an intermediate, which alkylates the mesitylene. As CMF can be obtained in yields up to 80% from cellulose,^[9] it is likely that the yields of MMF from cellulose could be further optimized.

The new methodology minimizes the formation of humins, which complicates conversions that involve polysaccharides. This undesirable cross-polymerization reaction is inhibited by the enhanced stability of MMF (vs. HMF) and the biphasic nature of the reaction medium. Together with our previous report,^[10] these results further demonstrate the attractiveness of formic acid in the processing of biomass.

Experimental Section

All reactions were performed without the exclusion of air. Unless otherwise stated, starting materials and reagents were purchased from Aldrich and used as received. Throughout this report, fructose refers to D-(–)-fructose and glucose refers to D-glucose. FA (99%) was purchased from Acros. NMR spectra were recorded by using a Varian Unity 400 spectrometer. FTIR spectra were recorded by using a Perkin–Elmer Spectrum 100 FTIR spectrometer. Chromatography was conducted with Siliaflash P60 from Silicycle (230–400 mesh). Yields were determined by ¹H NMR spectroscopy with MeNO₂ as the integration standard unless otherwise indicated. ¹H and ¹³C NMR chemical shifts are reported relative to SiMe₄ and were determined by reference to the residual ¹H and ¹³C solvent resonances. Coupling constants are given in Hz.

Synthesis of MMF from HMF

A pressure reactor was charged with HMF (10.0 mmol, 1.26 g), FeCl₃ (1.0 mmol, 0.16 g), mesitylene (25 mL), and MeNO₂ (25 mL). The reaction mixture was stirred at 80 °C for 1 h. After cooling to 25° C, the suspension was mixed with H₂O (150 mL) and CH₂Cl₂ (100 mL). The aqueous phase was re-extracted with CH_2CI_2 (2× 100 mL). The combined organic phases were dried over MgSO₄, filtered, and concentrated under vacuum. The residue was purified by flash chromatography (10% Et₂O/pentane) to give a yellow solid. Yield: 1.80 g (79%); m.p. 58–60 °C; ¹H NMR ([D₆]acetone): $\delta =$ 9.51 (s, 1H; -C(=0)H), 7.30 (d, ${}^{3}J_{HH} = 4.0$, 1H; furan ring protons), 6.88 (s, 2H; mesityl ring protons), 6.11 (d, $^3\!J_{\rm HH}\!=\!4.0,\,1\,\rm H;$ furan ring protons), 4.08 (s, 2H; -CH₂-), 2.29 (s, 6H; o-CH₃), 2.23 ppm (s, 3H; *p*-CH₃); ¹³C{¹H} NMR ([D₆]acetone): $\delta = 177.4$, 162.2, 153.2, 137.5, 137.0, 131.0, 129.8, 124.1, 109.8, 28.9, 20.9, 20.1 ppm; GC-MS: m/z: calcd for C₁₅H₁₆O₂: 228.29; found: 228; elemental analysis calcd (%) for C₁₅H₁₆O₂: C 78.92, H 7.06; found: C 79.03, H 7.12.

Synthesis of MMF from Fructose

A pressure reactor was charged with fructose (10.0 mmol, 1.80 g), mesitylene (50 mL), FA (50 mL), and HCl (3.8 m, 0.2 mL). The reaction mixture was stirred at 120 °C for 2 h. After cooling to 25 °C, the suspension was mixed with H₂O (150 mL) and CH₂Cl₂ (100 mL). The aqueous phase was re-extracted with CH₂Cl₂ (2×100 mL). The combined organic phases were dried over MgSO₄, filtered, and concentrated under vacuum. The residue was purified by flash chromatography (10% Et₂O/pentane) to give a yellow solid. Yield: 1.18 g (52%).

Synthesis of FMF from HMF

A solution of HMF (10.0 mmol, 1.26 g) and FA (25 mL) was stirred at 25 °C for 3 h before the volatiles were removed under vacuum to yield an orange oil without purification. Yield: 1.48 g (96%); ¹H NMR ([D₆]acetone): δ = 9.65 (s, 1 H; -C(=O)H), 8.24 (s, 1 H; -OC(=O)H), 7.43 (s, 1 H; furan ring protons), 6.79 (s, 1 H; furan ring protons), 5.28 ppm (s, 2 H; -CH₂--); ¹³C{¹H} NMR ([D₆]acetone): δ = 178.5, 161.3, 155.9, 154.1, 123.1, 113.7, 57.5 ppm; FTIR: $\tilde{\nu}_{C=0}$ = 1731, 1684 cm⁻¹. GC-MS: *m/z*: calcd for C₇H₆O₄: 154.12; found: 154; elemental analysis calcd (%) for C₇H₆O₄: C 54.55, H 3.92; found: C 53.96, H 3.71.

Acknowledgements

This research was supported by BP through the Energy Biosciences Institute and in part under contract from the U.S. Department of Energy by its Division of Chemical Sciences, Office of Basic Energy Sciences (DEFG02-90ER14146).

Keywords: arenes · biomass · homogeneous catalysis · synthesis design · sustainable chemistry

- a) D. L. Klass, Biomass for the Renewable Energy and Fuels in Encyclopedia of Energy (Eds.: C. J. Cleveland), Elsevier, London, 2004; b) B. A. Tokay, Biomass Chemicals in Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, Weinheim, 2005; c) G. W. Huber, S. Iborra, A. Corma, Chem. Rev. 2006, 106, 4044–4098; d) J. O. Metzger, Angew. Chem. 2006, 118, 710–713; Angew. Chem. Int. Ed. 2006, 45, 696–698; e) J. C. Serrano-Ruiz, J. A. Dumesic, Energy Environ. Sci. 2011, 4, 83–99.
- [2] M. Chidambaram, A. T. Bell, Green Chem. 2010, 12, 1253-1262.
- [3] E. I. Gürbüz, D. M. Alonso, J. Q. Bond, J. A. Dumesic, ChemSusChem 2011, 4, 357-361.
- [4] W. Yang, A. Sen, ChemSusChem 2010, 3, 597-603.
- [5] a) M. Mascal, E. B. Nikitin, Angew. Chem. 2008, 120, 8042–8044; Angew. Chem. Int. Ed. 2008, 47, 7924–7926; b) M. Balakrishnan, E. R. Sacia, A. T. Bell, Green Chem. 2012, 14, 1626–1634.
- [6] C. Moreau, M. N. Belgacem, A. Gandini, Top. Catal. 2004, 27, 11.
- [7] Reviews: a) A. A. Rosatella, S. P. Simeonov, R. F. M. Frade, C. A. M. Afonso, Green Chem. 2011, 13, 754–793; b) P. Gallezot, Chem. Soc. Rev. 2012, 41,

1538–1558; Recent advances: c) Y. Yang, C. W. Hu, M. M. Abu-Omar, Green Chem. 2012, 14, 509–513; d) F. Liu, J. Barrault, K. D. O. Vigier, F. Jérôme, ChemSusChem 2012, 5, 1223–1226; e) S. P. Simeonov, J. A. S. Coelho, C. A. M. Afonso, ChemSusChem 2012, 5, 1388–1391; f) C. Aellig, I. Hermans, ChemSusChem 2012, 5, 1737–1742.

- [8] L. Lai, Y. Zhang, ChemSusChem 2011, 4, 1745-1748.
- [9] a) H. H. Szamant, D. D. Chundary, J. Chem. Tech. Biotechnol. 1981, 31, 205–212; b) M. Mascal, E. B. Nikitin, ChemSusChem 2009, 2, 423–426; c) M. Mascal, E. B. Nikitin, ChemSusChem 2009, 2, 859–861.
- [10] T. Thananatthanachon, T. B. Rauchfuss, Angew. Chem. 2010, 122, 6766– 6768; Angew. Chem. Int. Ed. 2010, 49, 6616–6618.
- [11] W. Dabelstein, A. Reglitzky, A. Schütze, K. Reders, Automotive Fuels in Ullmann's Encyclopedia of Industrial Chemistry, 2000, Wiley-VCH, Weinheim. .
- [12] a) G. W. Huber, J. N. Chheda, C. J. Barrett, J. A. Dumesic, *Science* 2005, 308, 1446–1450; b) C. J. Barrett, J. N. Chheda, G. W. Huber, J. A. Dumesic, *Appl. Catal. B* 2006, 66, 111–118; c) D. M. Alonso, J. Q. Bond, J. A. Dumesic, *Green Chem.* 2010, *12*, 1493–1513; d) A. V. Subrahmanyam, S. Thayumanavan, G. W. Huber, *ChemSusChem* 2010, *3*, 1158–1161.
- [13] J. Q. Bond, D. M. Alonso, D. Wang, R. M. West, J. A. Dumesic, Science 2010, 327, 1110–1114.
- [14] a) A. Corma, O. de La Torre, M. Renz, N. Villandier, Angew. Chem. 2011, 123, 2423–2426; Angew. Chem. Int. Ed. 2011, 50, 2375–2378; b) A. Corma, O. de La Torre, M. Renz, ChemSusChem 2011, 4, 1574–1577.
- [15] I. lovel, K. Mertins, J. Kischel, A. Zapf, M. Beller, Angew. Chem. 2005, 117, 3981–3985; Angew. Chem. Int. Ed. 2005, 44, 3913–3917.
- [16] a) H. E. van Dam, A. P. G. Kieboom, H. Vanbekkum, *Starch/Staerke* 1986, 38, 95–101; b) J. D. Chen, B. F. M. Kuster, K. Vanderwiele, *Biomass Bioenergy* 1991, 1, 217–223; c) T. S. Hansen, J. M. Woodley, A. Riisager, *Carbohydr. Res.* 2009, 344, 2568–2572; d) C. Sievers, I. Musin, T. Marzialetti, M. B. V. Olarte, P. K. Agrawal, C. W. Jones, *ChemSusChem* 2009, 2, 665–671; e) T. Tuercke, S. Panic, S. Loebbecke, *Chem. Eng. Technol.* 2009, 32, 1815.
- [17] www2.lsdiv.harvard.edu/labs/evans/pdf/evans_pKa_table.pdf.
- [18] a) H. Zhao, J. E. Holladay, H. Brown, Z. C. Zhang, *Science* 2007, *316*, 1597–1600; b) J. B. Binder, R. T. Raines, *J. Am. Chem. Soc.* 2009, *131*, 1979–1985.
- [19] H. E. van Dam, A. P. G. Kieboom, H. van Bekkum, *Starch/Staerke* **1986**, *38*, 95–101.
- [20] a) F. S. Asghari, H. Yoshida, *Ind. Eng. Chem. Res.* 2007, *46*, 7703-7710;
 b) R. Hashaikeh, I. S. Butler, J. A. Kozinski, *Energy Fuels* 2006, *20*, 2743-2747.
- [21] a) C. Sievers, M. B. V. Olarte, T. Marzialetti, D. Musin, P. K. Agrawal, C. W. Jones, *Ind. Eng. Chem. Res.* **2009**, *48*, 1277–1286; b) R. Weingarten, J. Cho, W. C. Conner, G. W. Huber, *Green Chem.* **2010**, *12*, 1423–1429; c) S. J. Dee, A. T. Bell, *ChemSusChem* **2011**, *4*, 1166–1173.
- [22] a) Y. Román-Leshkov, J. N. Chheda, J. A. Dumesic, *Science* 2006, *312*, 1933–1937; b) J. N. Chheda, Y. Román-Leshkov, J. A. Dumesic, *Green Chem.* 2007, *9*, 342–350; c) R. Xing, A. V. Subrahmanyam, H. Oclay, W. Qi, G. P. van Walsum, H. Pendse, G. W. Huber, *Green Chem.* 2010, *12*, 1933–1946; d) T. vom Stein, P. M. Grande, W. Leitner, P. Domínguez de María, *ChemSusChem* 2011, *4*, 1592–1594.
- [23] G. Alfke, W. W. Irion, O. S. Neuwirth, Oil Refining in Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, Weinheim, 2007.

Received: September 24, 2012 Published online on December 23, 2012