Simple Chemical Transformation of Lignocellulosic Biomass into Furans for Fuels and Chemicals

Joseph B. Binder[†] and Ronald T. Raines[*,†,‡]

Departments of Chemistry and Biochemistry, University of Wisconsin—Madison, Madison, Wisconsin 53706

Received October 30, 2008; E-mail: rtraines@wisc.edu

Abstract: Lignocellulosic biomass is a plentiful and renewable resource for fuels and chemicals. Despite this potential, nearly all renewable fuels and chemicals are now produced from edible resources, such as starch, sugars, and oils; the challenges imposed by notoriously recalcitrant and heterogeneous lignocellulosic feedstocks have made their production from nonfood biomass inefficient and uneconomical. Here, we report that *N,N*-dimethylacetamide (DMA) containing lithium chloride (LiCl) is a privileged solvent that enables the synthesis of the renewable platform chemical 5-hydroxymethylfurfural (HMF) in a single step and unprecedented yield from untreated lignocellulosic biomass, as well as from purified cellulose, glucose, and fructose. The conversion of cellulose into HMF is unabated by the presence of other biomass components, such as lignin and protein. Mechanistic analyses reveal that loosely ion-paired halide ions in DMA−LiCl are critical for the remarkable rapidity (1−5 h) and yield (up to 92%) of this low-temperature (≤140 °C) process. The simplicity of this chemical transformation of lignocellulose contrasts markedly with the complexity of extant bioprocesses and provides a new paradigm for the use of biomass as a raw material for a renewable energy and chemical industries.

Introduction

Throughout most of human history, renewable biomass resources have been the primary industrial and consumer feedstocks. Only in the past 150 years have coal, natural gas, and petroleum grown into their dominant roles as sources for energy and chemicals.[1] Today these fossil resources supply approximately 86% of energy and 96% of organic chemicals, but in as soon as two decades petroleum production is unlikely to meet the growing needs of humanity and natural gas resources will be increasingly inaccessible.[2] Moreover, consumers and governments concerned about CO_2 emissions and other environmental impacts are demanding renewable power and products.

With advances in conversion technology, plentiful biomass resources have the potential to regain their central position as feedstocks for civilization, particularly as renewable carbon sources for transportation fuels and chemicals.[3] A hexose dehydration product, the platform chemical 5-hydroxymethylfurfural (HMF), will be a key player in the biobased renaissance. This six-carbon analogue of commodity chemicals like terephthalic acid and hexamethylenediamine can be converted by straightforward methods into a variety of useful acids, aldehydes, alcohols, and amines, as well as the promising fuel 2,5-dimethylfuran (DMF).[4,5] The energy content of DMF (31.5 MJ/L) is similar to that of gasoline (35 MJ/L) and 40% greater than that of ethanol (23 MJ/L).[6,7] Moreover, DMF (bp 92−94 °C) is less volatile than ethanol (bp 78 °C) and is immiscible

with water. These attributes bode well for the use of DMF as an alternative liquid fuel for transportation.

Despite the potential for HMF-based fuels and chemicals, most efforts toward HMF production have used edible starting materials, primarily fructose and glucose. In fact, almost all renewable fuels and chemicals are usually based on food resources such as starch, sugars, and oils. These simple starting materials are easy to convert into valuable products, while inedible lignocellulosic biomass is relatively recalcitrant and heterogeneous, making its conversion typically inefficient and uneconomical.[8] In the case of HMF, its formation by the dehydration of fructofuranose is straightforward and has been demonstrated in water, traditional organic solvents,[9] multiphase

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systems,[10,11] and ionic liquids.[12−14] Zhao et al.[13] reported that chromium catalysts in alkylimidazolium chloride ionic liquids, such as 1-ethyl-3-methylimidazolium chloride ([EMIM]Cl), enable synthesis of HMF from glucose, a less expensive feedstock, in good yield. While promising, this method depends on expensive ionic liquid solvents and still uses starch-derived glucose. In our research, we sought to address these concerns by *both* minimizing the use of ionic liquids *and* utilizing authentic lignocellulosic biomass as the starting material for HMF production.
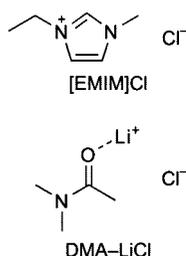
Noting that the chloride counterions in [EMIM]Cl form only weak ion pairs,[15] we reasoned that other nonaqueous solvents containing a high concentration of chloride ions could be as effective as [EMIM]Cl for HMF synthesis. We were aware that DMA containing LiCl is one of few solvents that can dissolve purified cellulose without modifying its chemical structure and can do so to a concentration of up to 15 wt %, and that DMA−LiCl can also dissolve simple sugars.[16,17] These useful properties likely stem from the association of lithium ions with DMA to form DMA·Li$^+$ macrocations, resulting in a high concentration of weakly ion-paired chloride ions (2.0 M in saturated anhydrous DMA−LiCl versus 6.8 M in [EMIM]Cl). These chloride ions can form hydrogen bonds with the hydroxyl groups of cellulose, disrupting its otherwise extensive network of intra- and interchain hydrogen bonds. Here, we report that using DMA−LiCl as a solvent enables the efficient synthesis of HMF in a single step from cellulose and even lignocellulosic biomass, as well as glucose and fructose. This discovery facilitates access to fuels and chemicals derived from HMF.

Results and Discussion

Synthesis of HMF from Fructose in DMA with Halide Additives. We began by exploring the reactivity of fructose in DMA−LiCl, both alone and with added catalysts. When mixed with DMA−LiCl and heated to sufficiently high temperatures (80−140 °C), fructose is converted to HMF in moderate yields (55−65%; Table 1). Increased yields up to 71% can be obtained

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Table 1. Synthesis of HMF from Fructose^a

solvent	catalyst, mol %	additives, wt %	T (°C)	time (h)	molar yield (%)
DMA−LiCl (10%)			120	2	65
DMA−LiCl (10%)	H$_2$SO$_4$, 6		80	4	66
DMA−LiCl (10%)	CuCl, 6		80	5	62
DMA−LiCl (10%)	H$_2$SO$_4$, 6		100	5	63
DMA−LiCl (10%)	CuCl, 6		100	5	62
DMA−LiCl (10%)	H$_2$SO$_4$, 6		120	1	68
DMA−LiCl (10%)	CuCl, 6		120	3	71
DMA−LiCl (10%)	H$_2$SO$_4$, 6		140	0.5	66
DMA−LiCl (10%)	CuCl, 6		140	0.5	58
DMA−LiCl (10%)	H$_2$SO$_4$, 6	[EMIM]Cl, 5	80	4	70
DMA−LiCl (10%)	H$_2$SO$_4$, 6	[EMIM]Cl, 10	80	4	72
DMA−LiCl (10%)	H$_2$SO$_4$, 6	[EMIM]Cl, 20	80	4	78
DMA−LiCl (10%)	CuCl, 6	[EMIM]Cl, 20	120	1	67
DMA−LiCl (10%)	CuCl, 6	[EMIM]Cl, 40	120	1.5	83
DMA	H$_2$SO$_4$, 6	[EMIM]Cl, 20	100	2	84
DMA−LiCl (10%)	H$_2$SO$_4$, 6	[EMIM]BF$_4$, 20	100	2	71
DMA	H$_2$SO$_4$, 6	[EMIM]BF$_4$, 20	100	4	59
DMA−LiCl (10%)	H$_2$SO$_4$, 6	[EMIM]OTf, 20	100	1	71
DMA	H$_2$SO$_4$, 6	[EMIM]OTf, 20	100	2	48
DMA	H$_2$SO$_4$, 6	[EtPy]Cl, 20	100	2	81
DMA	H$_2$SO$_4$, 6	KCl, 1.5	80	2	56
DMA	H$_2$SO$_4$, 6	KCl, 1.5; 18-crown-6, 5.6	80	2	63
DMA	H$_2$SO$_4$, 6	LiF, 10	80	2	0
DMA	H$_2$SO$_4$, 6	LiBr, 10	100	4	92
DMA	H$_2$SO$_4$, 6	NaBr, 10	100	2	93
DMA	H$_2$SO$_4$, 6	KBr, 10	100	2	92
DMA	H$_2$SO$_4$, 6	LiI, 10	100	6	89
DMA	H$_2$SO$_4$, 6	NaI, 10	100	5	91
DMA	H$_2$SO$_4$, 6	KI, 10	100	5	92

^{a} Fructose was reacted at a concentration of 10 wt % relative to the total mass of the reaction mixture. The solvent composition is indicated by the weight percent of LiCl relative to DMA with additive concentrations relative to the total mass of the reaction mixture. Catalyst loading is relative to fructose. Yields are based on HPLC analysis.

through catalysis by Brønsted acids (e.g., H$_2$SO$_4$) and metal chlorides (e.g., CuCl, CuCl$_2$, and PdCl$_2$). Nonetheless, these yields of HMF are moderate when compared to the yields of up to 85% achieved in solvents such as DMSO and [EMIM]Cl.[9,13] In an effort to favor the formation of HMF, we added increasing amounts of [EMIM]Cl to the DMA−LiCl medium (Table 1). In general, the addition of ionic liquid improved yields. For example, [EMIM]Cl in combination with CuCl bolstered the yield of HMF up to 83%.

Intrigued by the effect of [EMIM]Cl, we investigated the influence of other additives on the dehydration of fructose in DMA as catalyzed by H$_2$SO$_4$ (Table 1). The trifluoromethane-sulfonate and tetrafluoroborate salts of EMIM delivered modest HMF yields, which were increased by the addition of LiCl. Adding ionic liquids with a variety of cationic counterions for chloride delivered HMF in yields around 80%. These results suggested that chloride ion mediated the crucial advantage of [EMIM]Cl as an additive. Furthermore, the reaction appeared to proceed better with the loosely ion-paired chloride afforded by ionic liquids than with lithium chloride. We also observed that the potassium-complexing agent 18-crown-6 increased the yield of HMF in reactions utilizing potassium chloride. These results indicate that weakly ion-paired halide ions[18] favor the reaction.

We found distinct differences in the ability of halide ions to mediate the formation of HMF from fructose in DMA containing

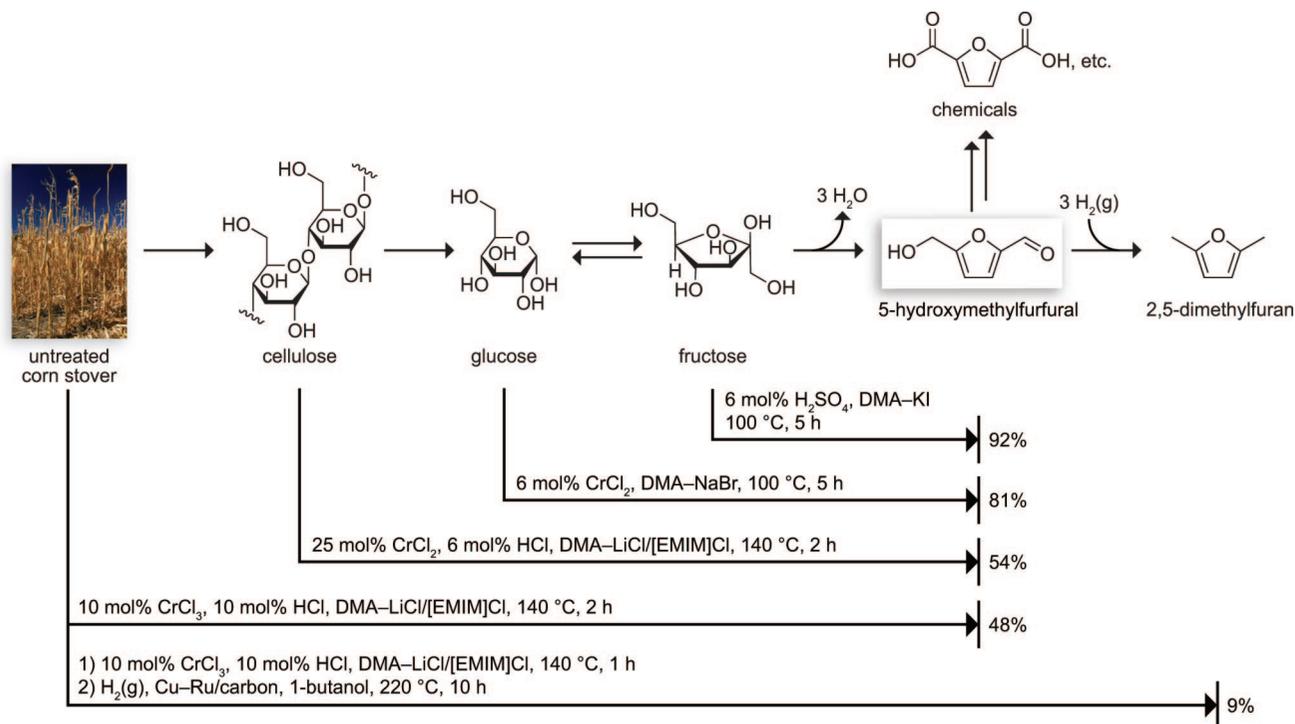(18) Weaver, W. M.; Hutchison, J. D. *J. Am. Chem. Soc.* **1964**, *86*, 261–265.

Figure 1. Halide salts in DMA enable previously elusive yields of bio-based chemicals from a variety of carbohydrates. Conditions are optimized for the conversion of carbohydrates into HMF (1 step) and DMF (2 steps). (Photograph courtesy of Department of Energy/National Renewable Energy Laboratory.)

H_2SO_4. As expected from their low nucleophilicity and high basicity, fluoride ions were completely ineffective. On the other hand, bromide and iodide ions, which tend to be less ion-paired than fluoride or chloride, enabled exceptionally high HMF yields in DMA. For example, adding 10 wt % lithium bromide or potassium iodide enabled the conversion of 92% of fructose to HMF in 4−5 h at 100 °C (Figure 1). These reactions were highly selective, resulting in only low levels of the colored byproducts and insoluble polymeric products (i.e., humins) often formed concurrently with HMF.[4] Kinetic analyses indicate that the rate of HMF formation has a first-order dependence on halide concentration (Figure 2).

Influence of Halides on the Formation of HMF from Fructose. Our results provide mechanistic insights regarding the conversion of fructose into HMF. In most depictions of this process,[19] a fructofuranosyl oxocarbenium ion forms first and then deprotonates spontaneously at C-1 to form an enol. To account for the dramatic influence of halide on yield and rate, we propose two variations on this mechanism (Figure 3A). In one, a halide ion (X^-) attacks the oxocarbenium ion to form a 2-deoxy-2-halo intermediate that is less prone to side reactions as well as reversion to fructose. This intermediate then loses HX to form the enol (nucleophile pathway). Alternatively, a halide ion could form the enol merely by acting as a base that deprotonates C-1 (base pathway).

The known reactivity of sugars as well as our observations of fructose reactivity support the nucleophile pathway. The fructofuranosyl oxocarbenium ion is known to be attacked readily by alcohols,[20] borohydrides,[21] and even fluoride,[22] so it

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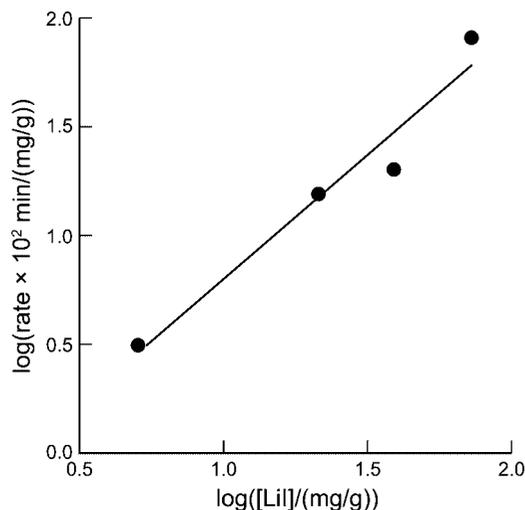(22) Defaye, J.; Gadelle, A. *Carbohydr. Res.* **1985**, *136*, 53–65.

Figure 2. Log−log plot of initial rates of HMF formation from fructose vs [LiI]. Linear regression analysis of the data (shown) gives a slope of 1.1, which is consistent with a first-order dependence of the rate of HMF formation on [I^-].

is reasonable to expect its being attacked by chloride, bromide, and iodide. Bromide and iodide, which are better nucleophiles and leaving groups than chloride, are also more effective as ionic additives. A mechanism that required the halide ion to act only as a base would invert the order of halide reactivity.

Synthesis of HMF from Glucose in DMA. Next, we sought to utilize the DMA−halide system to convert glucose into HMF. As in [EMIM]Cl, $CrCl_2$ and $CrCl_3$ in DMA enable the conversion of glucose into HMF in yields up to 69% (Table 2). We found negligible HMF yields (<1%) from glucose in the absence of chromium salts. With the addition of $CrCl_2$ to DMA or DMA−LiCl, we obtained substantial yields of HMF (47−60%), which were improved further by adding [EMIM]Cl
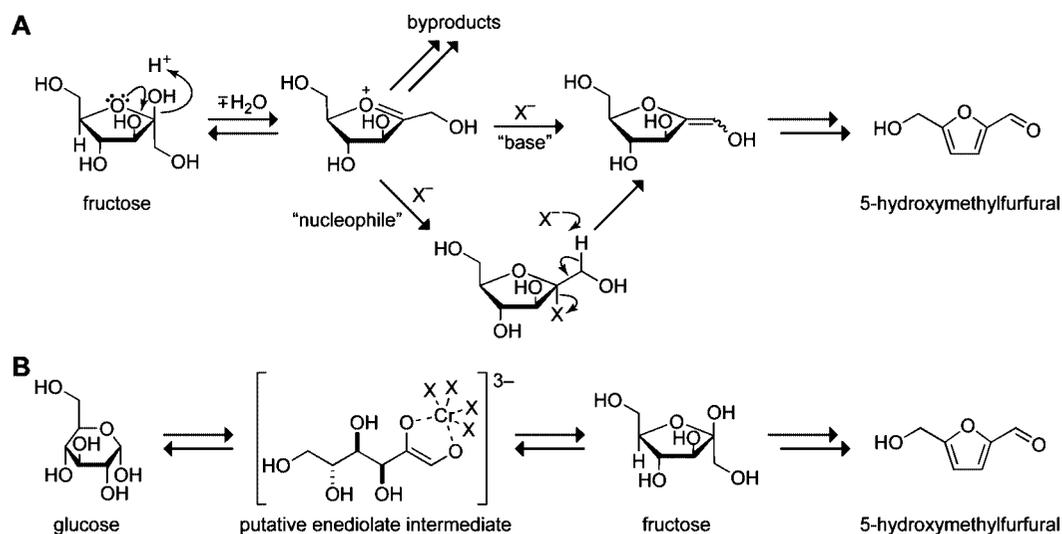
Figure 3. Putative mechanisms for the dehydration of fructose and isomerization of glucose. (A) Putative nucleophilic and basic mechanisms for halide participation in the conversion of fructose into HMF. X^- represents a halide ion. (B) Putative mechanism for the chromium-catalyzed transformation of glucose into HMF. Chromium species, depicted here as a hexacoordinate chromium(II) complex, catalyze the isomerization of glucose into fructose through a putative enediolate intermediate.[13] Fructose is then converted rapidly into HMF.

Table 2. Synthesis of HMF from Glucose[a]

solvent	catalyst, mol %	additive, wt %	T (°C)	time (h)	molar yield (%)
DMA−LiCl (10%)			100	6	<1
DMA−LiCl (10%)		[EMIM]Cl, 20	100	6	<1
DMA	CrCl₂, 6		100	4	60
DMA	CrCl₂, 6		120	3	47
DMA−LiCl (10%)	CrCl₂, 6		100	5	60
DMA−LiCl (10%)	CrCl₂, 6		120	3	53
DMA−LiCl (10%)	CrCl₃, 6		120	2	55
DMA	CrCl₂, 6	[EMIM]Cl, 5	100	6	64
DMA	CrCl₂, 6	[EMIM]Cl, 10	100	6	67
DMA	CrCl₂, 6	[EMIM]Cl, 20	100	6	67
DMA−LiCl (10%)	CrCl₂, 6	[EMIM]Cl, 5	100	6	58
DMA−LiCl (10%)	CrCl₂, 6	[EMIM]Cl, 10	100	6	61
DMA−LiCl (10%)	CrCl₂, 6	[EMIM]Cl, 20	100	6	62
DMA	CrCl₃, 6	[EMIM]Cl, 5	100	6	59
DMA	CrCl₃, 6	[EMIM]Cl, 10	100	6	63
DMA	CrCl₃, 6	[EMIM]Cl, 20	100	6	67
DMA	CrCl₂, 6	LiBr, 10	100	4	79
DMA−LiCl (5%)	CrCl₂, 6	LiBr, 5	100	4	56
DMA	CrCl₂, 6	LiI, 10	100	4	54
DMA	CrCl₃, 6	LiBr, 10	100	6	79
DMA	CrBr₃, 6	LiBr, 10	100	6	80
DMA	CrBr₃, 2	LiBr, 10	100	6	76
DMA	CrBr₃, 1	LiBr, 10	100	6	66
DMA−LiCl (10%)[b]	CrCl₂, 6	[EMIM]Cl, 20	100	6	62
DMA−LiCl (10%)	CrCl₂, 6	TMEDA, 1	120	3	28
DMA−LiCl (10%)	CrCl₂, 6	pyridine, 1	120	3	43

[a] Glucose was reacted at a concentration of 10 wt % relative to the total mass of the reaction mixture. The solvent composition is indicated by the weight percent of LiCl relative to DMA with additive concentrations relative to the total mass of the reaction mixture. Catalyst loading is relative to glucose. Yields are based on HPLC analysis. [b] In this case, glucose was 45% in water.

to the reaction mixture. Supplementing the solvent with up to 20% [EMIM]Cl allows HMF yields up to 69%, comparable to those obtained by Zhao et al.[13] in [EMIM]Cl alone. As with fructose, we observed a marked halide effect. Although addition of iodide salts to the chromium chloride reaction mixture did not greatly change the HMF yield, using 10 wt % lithium or sodium bromide increased the HMF yield to 79−81% after 5−6 h at 100 °C. These yields of HMF from glucose exceed those reported previously, approach typical yields of HMF from

fructose, and do not require ionic liquid solvents. Moreover, glucose syrups like those readily available from corn are also excellent feedstocks for HMF synthesis by our methods.

Further investigation of the generality of chromium-catalyzed HMF synthesis revealed that a wide range of polar aprotic solvents afforded HMF from glucose in yields higher than those commonly achieved (Table S4 in Supporting Information).[11] On the other hand, some coordinating classes of solvents, such as amines and alcohols, prevent formation of HMF, perhaps because of their interactions with the chromium salts. No HMF was formed upon reaction of glucose in pyridine, and adding several equivalents (based on chromium) of pyridine or *N,N,N′,N′*-tetramethylethylenediamine markedly decreased HMF formation in DMA−LiCl (Table 2). The basicity of these amines might also disfavor HMF formation. Although Zhao et al.[13] reported that CrCl₂ was markedly less effective than CrCl₃, we found that chromium in either oxidation state gave a similar yield.

Chromium likely enables conversion of glucose to HMF by catalyzing the isomerization of glucose into fructose (Figure 3B).[13] The fructose is then converted to HMF. Our observations suggest that the yield of HMF from glucose in reactions utilizing chromium correlates with metal coordination. Highly coordinating ligands such as amines decrease the yield of HMF. On the other hand, halide ligands enhance HMF yields, with bromide being the most effective. Our data suggest that the halide additives must balance two roles in the conversion of glucose into HMF: serving as ligands for chromium and facilitating the selective conversion of fructose. Although iodide excels in the latter role, its large size or low electronegativity could compromise its ability as a ligand. In contrast, bromide potentially offers the optimal balance of nucleophilicity and coordinating ability, enabling unparalleled transformation of glucose into HMF.

Synthesis of HMF from Cellulose. HMF has been traditionally obtained from monosaccharides. Cellulosic biomass is, however, an especially promising source because of its inexpensive availability from nonfood resources. Unfortunately, the typical aqueous acid hydrolysis methods for producing HMF from cellulose rely on high temperatures and pressures (250−400 °C,

Table 3. Synthesis of HMF from Cellulose and Lignocellulosic Biomass[a]

biomass	solvent	catalyst, mol %	additives, wt %	T (°C)	time (h)	HMF yield[b] (%)	furfural yield[c] (%)
cellulose	DMA−LiCl (10%)		[EMIM]Cl, 40	140	2	4	
cellulose	DMA−LiCl (10%)	CrCl₂, 25		140	6	15	
cellulose	DMA−LiCl (15%)	CrCl₃, 36		140	6	17	
cellulose	DMA−LiCl (10%)	CrCl₂, 25; HCl, 10		140	2	22	
cellulose	DMA−LiCl (10%)	CrCl₃, 25; HCl, 10		140	2	33	
cellulose	DMA−LiCl (10%)	CrCl₂, 25; HCl, 6	[EMIM]Cl, 20	140	4	33	
cellulose	DMA−LiCl (10%)	CrCl₂, 25; HCl, 6	[EMIM]Cl, 40	140	1	43	
cellulose	DMA−LiCl (10%)	CrCl₂, 25; HCl, 6	[EMIM]Cl, 60	140	2	54	
cellulose	DMA−LiCl (10%)	CrCl₂, 25; HCl, 6	[EMIM]Cl, 80	140	2	47	
cellulose	DMA−LiCl (10%)	CrCl₃, 25; HCl, 6	[EMIM]Cl, 40	140	4	38	
cellulose	[EMIM]Cl	CrCl₂, 25; HCl, 6		140	1	53	
cellulose	DMA	CrCl₂, 25; HCl, 10	LiI, 10	140	3	<1	
cellulose	DMA	CrCl₂, 25; HCl, 10	LiBr, 10	140	3	<1	
cellulose	DMA−LiCl (10%)	CrCl₃, 25; HCl, 10	LiBr, 3	140	2	37	
corn stover	DMA−LiCl (10%)	CrCl₂, 38	[EMIM]Cl, 10	140	6	16	ND
AFEX corn stover	DMA−LiCl (10%)	CrCl₂, 38	[EMIM]Cl, 10	140	6	16	ND
pine sawdust	DMA−LiCl (10%)	CrCl₂, 33	[EMIM]Cl, 15	140	5	19	ND
corn stover	DMA−LiCl (10%)	CrCl₂, 10; HCl, 10	[EMIM]Cl, 20	140	3	23	ND
corn stover	DMA−LiCl (10%)	CrCl₂, 10; HCl, 10	[EMIM]Cl, 40	140	3	24	ND
corn stover	DMA−LiCl (10%)	CrCl₂, 10; HCl, 10	[EMIM]Cl, 60	140	3	36	ND
corn stover	DMA−LiCl (10%)	CrCl₂, 10; HCl, 10	[EMIM]Cl, 80	140	3	31	ND
corn stover	[EMIM]Cl	CrCl₂, 10; HCl, 10		140	3	29	ND
corn stover	DMA−LiCl (10%)	CrCl₃, 10; HCl, 10	[EMIM]Cl, 20	140	3	26	ND
corn stover	DMA−LiCl (10%)	CrCl₃, 10; HCl, 10	[EMIM]Cl, 40	140	1	39	ND
corn stover	DMA−LiCl (10%)	CrCl₃, 10; HCl, 10	[EMIM]Cl, 60	140	2	48	34
corn stover	DMA−LiCl (10%)	CrCl₃, 10; HCl, 10	[EMIM]Cl, 80	140	2	47	37
corn stover	[EMIM]Cl	CrCl₃, 10; HCl, 10		140	1	42	ND

[a] Cellulose was reacted at a concentration of 4 wt % relative to the total mass of the reaction mixture. Biomass was reacted at a concentration of 10 wt % relative to the total mass of the reaction mixture. Solvent composition is indicated by weight percent of LiCl relative to DMA with additive concentrations relative to the total mass of the reaction mixture. Catalyst loading and molar yield are relative to moles of glucose monomers contained in the cellulose in the starting material. Yields are based on HPLC analysis. [b] Molar yield from pine sawdust assumes a typical cellulose content of 40%; yields from corn stover are based on cellulose analysis of 34.4%. [c] Molar yields from corn stover are based on xylan analysis of 22.8% for untreated stover. ND, not determined.

10 MPa) and result in yields of 30%, at most.[23] We suspected that the solubility of cellulose in DMA−LiCl and the efficient conversion of glucose into HMF with chromium would enable superior results. Dissolution of purified cellulose in a mixture of DMA−LiCl and [EMIM]Cl and addition of CrCl₂ or CrCl₃ produced HMF from cellulose in up to 54% yield within 2 h at 140 °C (Table 3). These yields compare well with reports of HMF synthesis from cellulose in the patent literature using aqueous acid and ionic liquids.[23,14] Neither lithium iodide nor lithium bromide alone produced high yields of HMF because these salts in DMA do not dissolve cellulose.[16] Using lithium bromide along with DMA−LiCl did enable modest improvements in yield. Likewise, using hydrochloric acid as a cocatalyst boosted yields.

Recently, Mascal and Nikitin[24] reported an alternative method for producing furanic products, chiefly 5-chloromethylfurfural (CMF), from purified cellulose. Heating a solution of highly purified cellulose in concentrated hydrochloric acid and lithium chloride and then extracting the products with 1,2-dichloroethane yielded this chlorinated relative of HMF in 71% isolated yield. CMF can be converted subsequently to potential fuels like DMF and 5-ethoxymethylfurfural. Although this process avoids the use of chromium and results in higher yields (84% isolated yield of furanic products versus 54%), it has notable drawbacks relative to our DMA−LiCl system. Mascal and Nikitin use chloride stoichiometrically and produce potentially hazardous

chlorinated organic products,[25] which are not observed in our system. In addition, the weight of their reaction mixture is nearly 150-fold greater than that of the cellulose reactant. Their 1,2-dichloroethane extractant, which is likewise used in a large excess relative to cellulose, is a possible carcinogen, and the concentrated hydrochloric acid presents its own hazards.[25] By comparison, DMA is a common industrial solvent that, along with LiCl, enables the processing of cellulose at far higher concentrations (≤15 vs ≤0.7 wt %).

Synthesis of HMF and Furfural from Lignocellulosic Biomass. We discovered another desirable attribute of our process: the ready conversion of lignocellulosic biomass. Efficient production of fuels or chemicals from crude biomass often requires pretreatment processes.[26,27] In contrast, HMF can be produced readily from untreated lignocellulosic biomass such as corn stover or pine sawdust under conditions similar to those used for cellulose (Table 3). Yields of HMF from corn stover subjected to ammonia fiber expansion (AFEX) pretreatment[26] were nearly identical to those for untreated stover. Other biomass components, such as lignin and protein, did not interfere substantially in the process, as yields of HMF based on the cellulose content of the biomass were comparable to those from purified cellulose. To be highly efficient, a process for biomass

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conversion should also utilize the pentoses present in hemicellulose. Notably, the industrial chemical furfural is formed from the hemicellulose component of biomass under our reaction conditions in yields similar to those obtained in industrial processes (34−37% vs ∼50%).[28]

We propose that the formation of HMF from cellulose in DMA−LiCl occurs via saccharification followed by isomerization of the glucose monomers into fructose and dehydration of fructose to form HMF. The saccharification of cellulose in water is thought to occur via Brønsted acid-catalyzed hydrolysis of its glycosidic bonds.[29] A similar Lewis acid-catalyzed process could be responsible for the hydrolysis activity of chromium halides. Additionally, the improved HMF yield with addition of hydrochloric acid suggests that Brønsted acid catalysis also occurs in DMA−LiCl. This area of cellulose chemistry offers rich opportunities for mechanistic understanding in addition to enabling HMF synthesis and possibly offering an alternative to enzymatic or aqueous acid-catalyzed hydrolysis for saccharification of lignocellulosic biomass.

Conversion of Lignocellulosic Biomass into 2,5-Dimethylfuran. The conversion of lignocellulosic biomass to HMF in a single step offers straightforward access to a wide variety of useful HMF derivatives, such as DMF. Dumesic and co-workers have shown that DMF, a promising HMF-derived fuel,[6,7] can be prepared by hydrogenolysis of fully purified HMF using copper catalysts.[30] We sought instead a process to synthesize DMF in two chemical reactions from lignocellulosic biomass.

In the first step of our process, we formed HMF from untreated corn stover in DMA−LiCl. We then removed the chloride ions from the crude HMF by ion-exclusion chromatography in water.[31] This separation step prevented the chloride from poisoning the copper hydrogenolysis catalyst. Finally, we subjected the crude HMF from corn stover to hydrogenolysis in 1-butanol with a carbon-supported copper−ruthenium catalyst and obtained a 49% molar yield of DMF, similar to that obtained by Dumesic and co-workers[7] using HMF that contained trace chloride. The overall molar yield of DMF based on the cellulose content of the stover was 9% (Figure 1). We expect that optimization of the process could readily improve upon this result.

Conclusions

Our two-step process represents a low-temperature (<250 °C), nonenzymic route from lignocellulosic biomass to fuels. Most other chemical methods for the conversion of lignocellulosic biomass to fuels use extreme temperatures to produce pyrolysis oil or synthesis gas, incurring substantial energy costs. Our low-temperature chemical conversion also has inherent advantages over bioprocessing for cellulosic fuels and chemicals. Fermentation of lignocellulosic feedstocks requires saccharification through extensive pretreatment, fragile enzymes, and engineered organisms. In contrast, our chemical process uses simple,

inexpensive catalysts to transform cellulose into a valuable product in an ample yield. In addition, our privileged solvents enable rapid biomass conversion at useful solid loadings (10 wt %). Under our best conditions, we transform 42% of the dry weight of cellulose into HMF and 19% of the dry weight of corn stover into HMF and furfural in one step. For comparison, cellulosic ethanol technology, which has been optimized extensively, enables the conversion of 24% of the dry weight of corn stover into ethanol in a complex process involving multiple chemical, biochemical, and microbiological steps.[27]

Our process is also competitive on the basis of energy yield. The HMF and furfural products contain 43% of the combustion energy available from cellulose and xylan in the corn stover starting material, whereas ethanol from corn stover preserves 62% of the sugar combustion energy (see Supporting Information). Biomass components that cannot be converted into HMF, such as lignin, could be reformed to produce H_2 for HMF hydrogenolysis (Figure 1) or burned to provide process heat.[32]

Realizing all of the intrinsic advantages of our process requires additional improvements. The high loading of the chromium catalyst and the toxicity of this metal could be barriers to its large-scale use. To address this issue, we have already found that decreasing chromium loading by two-thirds decreases the yield of HMF from glucose only slightly (Table 2). Additionally, the yields of HMF from cellulose and lignocellulosic biomass are still modest. Finally, methods for recycling solvents and salts would make the process more economical. We also anticipate that further mechanistic studies of this fascinating reaction cascade will enable the design of enhanced, chromium-free catalysts that can accomplish the transformation of cellulose into HMF in higher yield. With these types of improvements, this selective chemistry could become a highly attractive process for the conversion of lignocellulosic biomass into an array of fuels and chemicals.

Experimental Methods

General. Commercial chemicals were of reagent grade or better and were used without further purification. With the exception of hydrogenolysis, reactions were performed in glass vessels heated in a temperature-controlled oil bath with magnetic stirring. The term "concentrated under high vacuum" refers to the removal of solvents and other volatile materials using a rotary evaporator at vacuum attained by a mechanical belt-drive oil pump while the water-bath temperature was maintained below 30 °C. Conductivity was measured with an Extech Instruments ExStik II conductivity meter.

1-Ethyl-3-methylimidazolium chloride (99.5%, [EMIM]Cl) was from Solvent-Innovation (Cologne, Germany). 1-Ethyl-3-methylimidazolium tetrafluoroborate (97%, [EMIM]BF$_4$), 5-hydroxymethylfurfural, and 2,5-dimethylfuran were from Aldrich (Milwaukee, WI). 1-Ethyl-3-methylimidazolium triflate (98.5%, [EMIM]OTf), 1-butyl-3-methylpyridinium chloride (97%, [BMPy]Cl), 1-ethyl-3-methylimidazolium bromide (97%, [EMIM]Br), and 1-propyl-3-methylimidazolium iodide (97%, [PMIM]I) were from Fluka (Geel, Belgium). 1-Ethylpyridinium chloride (98%, [EtPy]Cl), 1-ethyl-2,3-dimethylimidazolium chloride (98%, [MMEIM]Cl), and furfural were from Acros (Buchs, Switzerland). Cu−Ru/carbon catalyst (3:2 mol ratio Cu:Ru) was prepared by the method of Dumesic and co-workers[7] using 5% Ru/carbon from Aldrich (Milwaukee, WI). Cellulose (medium cotton linters, C6288) was from Sigma (St. Louis, MO). Milled and sieved corn stover and AFEX-treated corn stover were generously provided by B. E. Dale

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and co-workers (Michigan State University).[26] Cellulose and corn stover were dried to constant weight at 120 °C prior to use.

Analytical Methods. All reaction products were analyzed by HPLC and quantified with calibration curves generated from commercially available standards. Following a typical reaction, the product mixture was diluted with a known mass of deionized water, centrifuged to sediment insoluble products, and analyzed. The concentrations of products were calculated from HPLC-peak integrations and used to calculate molar yields. HPLC was performed with either a Waters system equipped with two 515 pumps, a 717 Plus autosampler, and a 996 photodiode array detector or an Agilent 1200 system equipped with refractive index and photodiode array detectors. HMF and furfural were analyzed either by reversed-phase chromatography on a Varian Microsorb-MV 100-5 C18 column (250 × 4.6 mm; 93:7 water/acetonitrile, 1 mL/min, 35 °C) or by ion-exclusion chromatography on a Bio-Rad Aminex HPX-87H column (300 × 7.8 mm; 5 mM H_2SO_4, 0.6 or 0.9 mL/min, 65 °C). DMF was analyzed by reversed-phase chromatography on a Varian Microsorb-MV 100-5 C18 column (250 × 4.6 mm; 55:45 water/acetonitrile, 1 mL/min, 35 °C). Representative ion-exclusion HPLC traces for HMF and furfural analysis are shown in Figures S1 and S2 in Supporting Information.

Representative Procedure for Synthesis of HMF from Sugars. Fructose (27.1 mg, 150 μmol) and LiCl (24 mg) were mixed in DMA (203 mg). Following addition of concentrated H_2SO_4 (0.5 μL, 9 μmol), the reaction mixture was stirred at 80 °C for 5 h. At 1-h intervals, aliquots of the reaction mixture were removed for HPLC analysis. For reactions of glucose that involved [EMIM]Cl, chromium salts were mixed with a portion of the ionic liquid (25 mg) before addition to the reaction mixture. HMF yields for optimized reactions of sugars were reproduced to within 2−3%.

Kinetic Analysis of HMF Formation from Fructose. Fructose (425.6 mg, 2.362 mmol) and concentrated sulfuric acid (7.9 μL, 142 μmol) were dissolved in DMA (3.8185 g). Four known weights of this stock solution (approximately 0.5 g) were combined with four different mixtures of LiI and LiBF$_4$ (added to maintain constant salt concentration of 0.55 mmol/g) with LiI concentrations from 72.7 to 5.1 mg/g. After the salts were dissolved completely, the solutions were heated at 75 °C for 10 min and cooled rapidly on ice prior to HPLC analysis.

Representative Procedure for Synthesis of HMF from Cellulose and Lignocellulose. Cellulose (21.2 mg, 131 μmol of glucose units in cellulose), LiCl (26 mg), [EMIM]Cl (159 mg), and DMA (252 mg) were mixed at 50 °C for 24 h to form a viscous solution. To this cellulose solution were added concentrated HCl (1 μL, 12 μmol) and CrCl$_2$ (4 mg, 30 μmol) in [EMIM]Cl (50 mg), and the reaction mixture was heated to 140 °C with vigorous stirring for 2 h. At 1-h intervals aliquots of the reaction mixture were removed for HPLC analysis. Reactions with lignocellulose were similar except that the dissolution step was performed at 75 °C and the biomass was added at a concentration of 10 wt %. In other cases the cellulose was dissolved according to the methods of McCormick et al.[16] HMF yields for optimized reactions of cellulose were reproduced to within 2−3%.

Ion-Exclusion Chromatographic Separation of HMF. Fructose (1.20 g, 6.67 mmol) and LiCl (600 mg) were mixed in DMA (6.0 g) and stirred at 140 °C for 1 h. Deionized water (1.0 g) was mixed with a portion of this reaction mixture (3.87 g) containing HMF (127 mg). This solution was loaded onto a column of ion-exclusion resin (Dowex 50X8−200, Li$^+$ form, 70 × 1.5 cm) and eluted with deionized water at a rate of 3 cm/min. Fractions (25 mL) were

collected and analyzed by HPLC. HPLC analysis indicated that >75% of the HMF was recovered in the HMF-containing fractions.

Synthesis of DMF from Fructose. Fructose (1.805 g, 10 mmol) and LiCl (1.690 g) were dissolved in DMA (14.67 g). Following addition of concentrated H_2SO_4 (33 μL, 0.6 mmol), the reaction mixture was stirred at 120 °C for 1 h. A portion of the reaction mixture (3.01 g, 16.5%) was then diluted with deionized water (2 g), loaded onto a column of ion-exclusion resin (Dowex 50X8−200, Li$^+$ form, 70 × 1.5 cm), and eluted with deionized water at a rate of 2 cm/min. HMF-containing fractions with conductivity <50 μS were pooled and concentrated under high vacuum. The residue was taken up in 1-butanol (45 g) and placed in a Parr reactor with Cu−Ru/carbon catalyst (100 mg). The reactor was purged three times with H$_2$(g), pressurized with 6.8 bar of H$_2$(g), and heated to 220 °C with stirring. After 10 h, the reactor was cooled and vented. The contents were analyzed by HPLC for DMF (51.6 mg, 537 μmol, 32.5% based on fructose).

Synthesis of DMF from Corn Stover. Corn stover (1.504 g, 3.19 mmol of glucose units in cellulose), LiCl (0.755 g), [EMIM]Cl (5.630 g), and DMA (6.756 g) were mixed at 75 °C for 24 h. To this viscous mixture were added concentrated HCl (26 μL, 310 μmol) and CrCl$_3$ (50.5 mg, 319 μmol) in [EMIM]Cl (0.55 g), and the reaction mixture was heated with 140 °C with vigorous stirring. After 2 h, the reaction mixture was cooled to room temperature, diluted with deionized water (7 g), and subjected to centrifugation to sediment insoluble material. After removal of the supernatant, the pellet was resuspended in deionized water (3 g), and the process was repeated. The combined supernatant solutions were loaded onto a column of ion-exclusion resin (Dowex 50X8−200, Li$^+$ form, 70 × 1.5 cm), and eluted with deionized water at a rate of 3 cm/min. HMF-containing fractions with conductivity <50 μS were pooled and concentrated under high vacuum. After they were concentrated under high vacuum, the pooled HMF-containing fractions with conductivity >50 μS were loaded a second time on the ion-exchange column and eluted with deionized water. HMF-containing fractions from the second pass with conductivity <50 μS were pooled, concentrated under high vacuum, and combined with the earlier HMF concentrate. This residue was taken up in 1-butanol (45 g) and placed in a Parr reactor with Cu−Ru/carbon catalyst (79 mg). The reactor was purged three times with H$_2$(g), pressurized with 6.8 bar of H$_2$(g), and heated to 220 °C with stirring. After 10 h, the reactor was cooled and vented. The contents were analyzed by HPLC for DMF (27.7 mg, 288 μmol, 9.0% based on cellulose).

Supporting Information Available: Calculations of energy yields, two figures, and six tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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