Direct conversion of glucose and cellulose to 5-hydroxymethylfurfural in ionic liquid under microwave irradiation

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ABSTRACT

An efficient strategy for $CrCl_3$-mediated production of 5-hydroxymethylfurfural (HMF) in ca. 60% and 90% isolated yields from cellulose and glucose, respectively, in ionic liquid under microwave irradiation is presented.

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Studies on conversion of cellulose into biofuels and other bio-materials have been currently one of the most intensive pursuits worldwide.[1] One major approach is to hydrolyze cellulose to glucose followed by fermentation for biofuels and related chemicals. However, the overall energy efficiency of these biochemical routes is under debate.[2] Thus, a workable non-fermentative process for the conversion of cellulose to bio-based products remains imperative.

The five-membered ring compound, 5-hydroxy-methylfurfural (HMF), is one of the top bio-based platform compounds. HMF can be converted to a novel biofuel molecule 2,5-dimethylfuran[3] via selective hydrogenation. Thus, making HMF with renewable feedstock is highly demanding. Because glucose is liable to form a stable six-membered pyranoside structure,[4] it failed to form HMF with satisfactory yields under those known conditions.[5] Furthermore, a direct cellulose-to-HMF process (Scheme 1), which is economically more attractive, has yet to be developed.

We present herein an efficient strategy for direct production of HMF in ca. 90% and 60% isolated yields from glucose and cellulose, respectively, in ionic liquids under microwave irradiation (MI) in the presence of $CrCl_3$. This approach greatly advanced our utilization of lignocellulose for bioenergy through a chemical transformation strategy.

After a solution of glucose and $CrCl_3$ (3.6 wt%) in [C₄mim]Cl was subjected to MI at 400 W for 1 min, the entire reaction mixture was purified by column chromatography on silica gel (ethyl acetate:petroleum ether = 1:10 to 1:1), affording HMF in 91% yield (Table 1, entry 1). In contrast, HMF was obtained in 17% yield if the reaction was done under oil-bath heating at 100 °C for 60 min (entry 2). If water was used as the solvent, glucose dehydration was essentially suffocated (entry 3). When sulfuric acid

was employed in lieu of $CrCl_3$, the dehydration reaction afforded HMF in only 49% yield (entry 4), and formation of insoluble humins was observed in this case. Careful comparison of these data indicated that (1) MI had a drastic effect on HMF formation; (2) [C₄mim]Cl was a solvent superior to water, and (3) $CrCl_3$ was a powerful catalyst for selective dehydration of glucose. More detailed explanation will be discussed thereafter. Taken together, efficient dehydration of glucose to HMF was achieved in [C₄mim]Cl with a catalytic amount of $CrCl_3$ under MI.

We have demonstrated recently that cellulose could be effectively hydrolyzed in ionic liquids to produce glucose.[6] It was thus logic to pursue a direct transformation of cellulose into HMF. Indeed, we were able to obtain HMF in 61% isolated yield and total reducing sugars (TRS) in 16% yield when Avicel cellulose and $CrCl_3 \cdot 6H_2O$ (10 wt%) were mixed in [C₄mim]Cl and irradiated at 400 W for 2 min (Table 2, entry 1). These data are close to the best known result from glucose.[5b] Other cellulose samples showed similar results in the range of 53–62% (entries 2–4). Apparently, this method worked almost equally well regardless of the cellulose type and the degree of polymerization. Although our method afforded TRS in around 20% yield based on analysis with the 3,5-dinitrosalicylic acid (DNS) reagent,[7] further analysis revealed that glucose had little contribution, indicating that other byproducts or sugar oligomers might be formed. In sharp contrast, when an identical reaction of Avicel cellulose was heated with oil-bath at 100 °C for 240 min, HMF and TRS were obtained in 17% and 45% yields, respectively (entry 5). It should be noted that the initial water content in the system was estimated about 170 mM, a quite low concentration compared to about 1000 mM in our early cellulose hydrolysis work.[6a] Yet, as there are three water molecules released for the formation of one HMF molecule, cellulose hydrolysis is expected auto-accelerated during the process. On the other hand, a lower water concentration would also slow down HMF rehydration and humins formation.[4]

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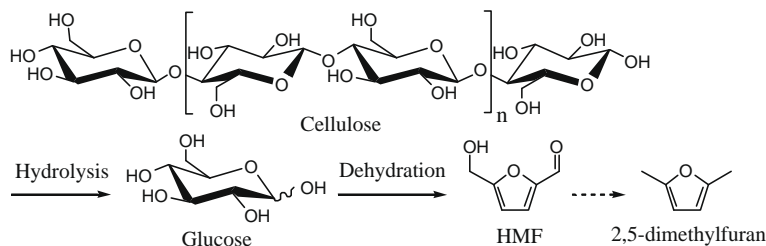
Scheme 1. Schematic illustration of the steps for cellulose-to-HMF.

Table 1
HMF production from glucose under various conditions[a]

Entry	Catalyst	Catalyst loading (wt%)	Time (min)	Yield[b] (%)
1	CrCl$_3$	3.6	1	91
2[c]	CrCl$_3$	3.6	60	17
3[d]	CrCl$_3$	3.6	10	<1
4	H$_2$SO$_4$	10	1	49

[a] Unless otherwise specified, conditions were glucose (100 mg) in [C$_4$mim]Cl (1.0 g) under MI at 400 W.
[b] Isolated yields.
[c] Heated with an oil-bath at 100 °C.
[d] Water (1.0 g) was used in lieu of [C$_4$mim]Cl as the solvent.

Table 2
HMF production from cellulose in [C$_4$mim]Cl under MI[a]

Entry	Substrate	Time (min)	Yield$_{HMF}$[b] (%)	Yield$_{TRS}$[c] (%)
1	Avicel	2	61	16
2	Spruce	2	53	26
3	Sigmacell	2	55	23
4	a-Cellulose	2	62	20
5[d]	Avicel	240	17[e]	45
6[d,f]	Avicel	240	2.0[e]	15
7[f]	Avicel	2	1.6[e]	9.7

[a] Unless otherwise specified, reaction conditions were cellulose (100 mg) and CrCl$_3$·6H$_2$O (10 mg) in [C$_4$mim]Cl (2.0 g) under 400 W MI.
[b] Isolated yield unless otherwise specified.
[c] Determined by the DNS method.[7]
[d] Heated by oil-bath at 100 °C.
[e] Determined spectrophotometrically at 282 nm.
[f] Three equiv of 2,2'-bipyridine (17.5 mg) were introduced thereafter the addition of CrCl$_3$·6H$_2$O (10 mg).

Based on current data, the reasons that a combination of [C$_4$mim]Cl, CrCl$_3$, and MI generates the magic power for conversion of cellulose into HMF may be imagined. First, complete dissolution of cellulose in [C$_4$mim]Cl leaves the cellulose chains accessible to chemical transformation.[8] Second, [C$_4$mim]Cl has excellent dielectric properties for transformation of microwave into heat.[9] Under MI, alternating electric field induces vibrational motion of ions, and resistance of the reaction mixture to ion flux leads to heat evolution, the higher the concentration of ions, the stronger the heating effect.[10] Because the reaction in ionic liquids had nearly a pure ionic circumstance, it was heated up rapidly, volumetrically and simultaneously by this 'specific microwave effects'. Therefore, it circumvented some known problems such as partly overheating under conventional oil-bath conditions.[11] Other microwave effects,[12] such as lowering activation energy or increasing the pre-exponential factor in the Arrhenius law due to orientation effect of polar species in an electromagnetic field,[13] might also contribute. Moreover, [C$_4$mim]Cl may also act as a water scavenger by dilution, circumventing water-associated HMF decomposition as found in these aqueous systems.[14] Thus, a combination of ionic liquid and MI might be an interesting condition to try new chemistry.

Although an exact catalytic mechanism for the exceptional effectiveness of CrCl$_3$ in the conversion of cellulose remains elusive, we would like to offer some insights into the reaction. As illustrated in Scheme 2, we imagined that CrCl$_3$ in [C$_4$mim]Cl might form complexes [C$_4$mim]$_n$[CrCl$_{3+n}$] (n = 1–3) in a way similar to LnCl$_3$ reported by Rogers and co-workers.[15] In the cellulose hydrolysis step, the 1,4-glucosidic bonds were weakened partially because of coordination with [CrCl$_{3+n}$]$^{n-}$, resulting in more liable to water attack to form glucose and oligomers. Then, the complex promoted rapid mutarotation of the a-anomer of glucose to the β-one through hydrogen bonds of chloride anions with the hydroxyl groups similar to what was proposed for CrCl$_2$ in an early work.[5b] The hemiacetal portion of β-glucopyranose then forms Cr(III) enolate anion complex leading to isomerization of glucose to fructose, which would be dehydrated to HMF simultaneously in the reaction condition (vide ante). There are additional data supporting our speculation. We found that a strong coordinating ligand, 2,2'-bipyridine, strongly inhibited the reaction, as HMF yield dropped from 61% to 1.6% (Table 2, entry 1 vs entry 7). Moreover, under oil-bath heating conditions, both HMF yield and TRS yield dropped substantially in the presence of 2,2'-bipyridine (Table 2, entry 5 vs entry 6). These results suggested that 2,2'-bipyridine restrained both cellulose hydrolysis and glucose dehydration reactions. Thus, coordination chemistry involving CrCl$_3$ played a key role not only for glucose dehydration but also for cellulose hydrolysis.

Zhang and co-workers reported a method for dehydration of glucose to HMF and claimed that CrCl$_2$ was more efficient as a catalyst than CrCl$_3$ under conventional heating condition.[5b] However, near identical HMF yields were observed in our system, that is, when the reaction was heated under MI, implying that the valence state of Cr is not the determinant in the transformation. Moreover, one might consider to formulate complexes [C$_4$mim]$_n$[CrCl$_{2+n}$] (n = 1–4) for CrCl$_2$ in [C$_4$mim]Cl according to Scheme 2. We also noticed that in Zhang's work, glucose was introduced into the mixture of CrCl$_2$ and ionic liquid pretreated at 150 °C for 20 min with vigorous stirring in a sealed tube because CrCl$_2$ could not be easily solubilized in [C$_4$mim]Cl. When CrCl$_3$ was used in our method, in contrast, stirring at 80 °C for 1 min under ambient pressure ensured a solution of CrCl$_3$ in [C$_4$mim]Cl. Thus, it was more practical.[16] More significantly, for the glucose-to-HMF process, our method afforded 91% isolated yield whereas a 68% HPLC yield was reported in the literature.[5b] When cellulose was employed as the substrate, we also obtained HMF in over 60% isolated yield.

As very high isolated yield for HMF was realized with our method, it was appealing to envision a more practical process. Noting that ionic liquids have little vapor pressure, and HMF has a boiling point of 85–88 °C at 0.01 torr,[17] one can take the advantages of this system and engineer a continuous reaction-distillation process to produce HMF using carbohydrates as the feedstock. In this scenario, both ionic liquids and catalyst may be recycled.

In conclusion, we showed multiple beneficiary effects under MI in ionic liquid for carbohydrate chemistry. For the conversion of
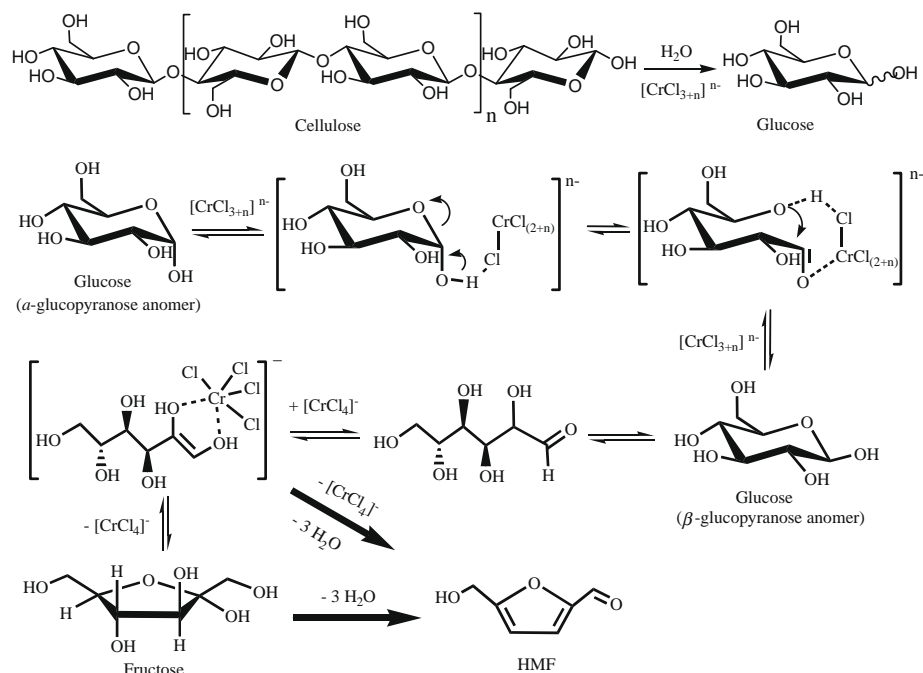
Scheme 2. Direct conversion of cellulose to HMF catalyzed with $CrCl_3$ in [C_4mim]Cl (n = 1–3).

glucose and cellulose, respectively, HMF was obtained in 91% and 61% isolated yields in the presence of a catalytic amount of $CrCl_3$. Thus, this work achieved a direct transformation of cellulose into HMF technically escaping a sugar separation step. Our method provided a new opportunity for transformation of abundant and inexpensive cellulosic biomass through a non-fermentative process into biofuels and bio-based products.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2009.07.053.

References and notes

1. (a) Suganuma, S.; Nakajima, K.; Kitano, M.; Yamaguchi, D.; Kato, H.; Hayashi, S.; Hara, M. *J. Am. Chem. Soc.* **2008**, *130*, 12787–12793; (b) Schmidt, L. D.; Dauenhauer, P. J. *Nature* **2007**, *447*, 914–915; (c) Rinaldi, R.; Palkovits, R.; Schüth, F. *Angew. Chem., Int. Ed.* **2008**, *47*, 8047–8050.
2. Klemm, D.; Heublein, B.; Fink, H.-P.; Bohn, A. *Angew. Chem., Int. Ed.* **2005**, *44*, 3358–3393.
3. Román-Leshkov, Y.; Barrett, C. J.; Liu, Z. Y.; Dumesic, J. A. *Nature* **2007**, *447*, 982–985.
4. Kuster, B. M. F. *Starch* **1990**, *42*, 314–321.
5. (a) Qi, X.; Watanabe, M.; Aida, M. T. *Green Chem.* **2008**, *10*, 799–805; (b) Zhao, H.; Holladay, J. E.; Brown, H.; Zhang, Z. C. *Science* **2007**, *316*, 1597; (c) Chheda, J. N.; Román-Leshkov, Y.; Dumesic, J. A. *Green Chem.* **2007**, *9*, 342–350; (d) Seri, K.; Inoue, Y.; Ishida, H. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 1145–1150.
6. (a) Li, C. Z.; Zhao, Z. K. B. *Adv. Synth. Catal.* **2007**, *349*, 1847–1850; (b) Li, C. Z.; Wang, Q.; Zhao, Z. K. *Green Chem.* **2008**, *10*, 177–182.
7. Miller, G. L. *Anal. Chem.* **1959**, *31*, 426–428.
8. Swatloski, R. P.; Spear, S. K.; Holbrey, J. D.; Rogers, R. D. *J. Am. Chem. Soc.* **2002**, *124*, 4974–4975.
9. de la Hoz, A.; Diaz-Ortiz, A.; Moreno, A. *Chem. Soc. Rev.* **2005**, *34*, 164–178.
10. Kappe, C. O. *Chem. Soc. Rev.* **2008**, *37*, 1127–1139.
11. Nuchter, M.; Ondruschka, B.; Bonrath, W.; Gum, A. *Green Chem.* **2004**, *6*, 128–141.
12. Kappe, C. O. *Angew. Chem., Int. Ed.* **2004**, *43*, 6250–6284.
13. Hosseini, M.; Stiasni, N.; Barbieri, V.; Kappe, C. O. *J. Org. Chem.* **2007**, *72*, 1417–1424.
14. Asghari, F. S.; Yoshida, H. *Ind. Eng. Chem. Res.* **2007**, *46*, 7703–7710.
15. Hines, C. C.; Cordes, D. B.; Griffin, S. T.; Watts, S. I.; Cocalia, V. A.; Rogers, R. D. *New J. Chem.* **2008**, *32*, 872–877.
16. A recent publication reported similar observations: Binder, J. B.; Raines, R. T. *J. Am. Chem. Soc.* **2009**, *131*, 1979–1985.
17. Fayet, C.; Gelas, J. *Carbohydr. Res.* **1983**, *122*, 59–68.