Direct conversion of inulin to 5-hydroxymethylfurfural in biorenewable ionic liquids

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In this work, we found that inulin is soluble in ionic liquids (ILs) choline chloride (ChoCl)/oxalic acid and ChoCl/citric acid, which are prepared entirely from cheap and renewable materials. On the basis of this discovery, we conducted the one pot reaction for the conversion of inulin into 5-hydroxymethylfurfural (HMF), which is a potential substitute for petroleum-based building blocks, using the two ILs as catalysts and solvents. The effects of reaction time, temperature and water added on the reaction were studied. It is demonstrated that the ILs are very efficient for the reaction at relatively lower temperature and could be reused after simple separation.

Introduction

The diminishing availability of petrochemical resources forces human beings to look for sustainable resources.¹ Biomass, as an abundant and widely-distributed sustainable resource, is a promising substitute for fossil-based resources to produce liquid fuels and intermediates for chemical industry.² Carbohydrates comprise the main class of biomass compounds.¹

It is known that the direct production of useful organic compounds from five- and six-carbon carbohydrates is difficult.³ 5-Hydroxymethylfurfural (HMF), which can be obtained from carbohydrates by dehydration, is an important "bridge" for the efficient use of carbohydrates.^{1,4} As a versatile intermediate, HMF can be converted to many value-added compounds⁵ and liquid fuels.^{2a} Fructose can be converted to HMF more efficiently compared with other monosaccharides.⁶ In recent years, many researchers have studied the conversion of fructose to HMF.⁷⁻¹¹ Unfortunately, most fructose is produced by isomerization of glucose in industry and glucose is produced by hydrolysis of starch, which would consume food supply.¹²

Inulin is a non digestible oligosaccharide consisting of glucose–(fructose)_n or (fructose)_m (Scheme 1) which is available in large quantities.¹³ It exists in many plants, such as in the roots of chicory. The yield of inulin in the roots of chicory is approximately 8-12 t ha⁻¹, which can produce 5-7 t ha⁻¹ of



Scheme 1 The pathways for acid-catalyzed hydrolysis and dehydration of inulin to produce HMF.

Beijing National Laboratory for Molecular Sciences, Institute of Chemistry, Chinese Academy of Sciences, Beijing, 100080, China. E-mail: Hanbx@iccas.ac.cn; Fax: +86-10-62562821 HMF.¹⁴ The hydrolysis of inulin can produce fructose that can be further converted to HMF, and starting from inulin to produce fructose or HMF can reduce the expending of the food supply. This hydrolysis processed under enzymatic or acidic conditions with about an 80% fructose yield has been reported, but long reaction times, from 10 h to 10 days, were required.¹⁵ The high cost resulting from complex processes or harsh conditions limits the industrial production of fructose from inulin.

The combination of hydrolysis of inulin and dehydration of fructose in one pot is possible because both processes can be catalyzed by acids (Scheme 1), which avoids the production of fructose and the corresponding cost. Therefore, the one pot reaction is more advantageous for producing HMF. Up to now, the one pot reaction has been carried out in different solvents, such as in water at 80–110 °C with heterogeneous niobium, vanadium, titanium and zirconium based catalysts,¹⁶ and in water–dimethylsulfoxide or water–acetone mixtures at 140–180 °C using mineral acids (*e.g.*, HCl, H₂SO₄) as catalysts.^{4,10} When the reaction takes place in pure water, the yield of HMF is low; and when it takes place in an organic solvent–water mixture, the yield can be improved but the separation is more complex.

Room temperature ionic liquids (ILs), which are organic salts with a melting point lower than 100 °C, have attracted much attention in recent years.^{17,18} ILs have some unusual properties, such as negligible vapor pressure, nonflammability, high thermal and chemical stability, and adjustable solvent power for organic and inorganic substances. Some ILs have been synthesized from biorenewable materials, such as choline chloride (ChoCl)-based ILs.¹⁹ Some eutectic mixtures formed by heating ChoCl with urea, organic acids and metal chlorides, which also belong to the ILs group,²⁰ have been used not only as solvents and /or catalysts in chemical reactions,^{19,21} but also as solvents and templates in the preparation of novel polymorphous materials.²² Among them, ChoCl/oxalic acid dihydrate and ChoCl/citric acid monohydrate are prepared entirely from cheap and renewable materials.

In this work, we found that inulin is soluble in ChoCl/oxalic acid and ChoCl/citric acid ILs. On the basis of this discovery and the fact that these ILs are acidic, we carried out the one

pot reaction for the conversion of inulin using the two ILs as catalysts and solvents. It was demonstrated that the ILs were very efficient for the reaction at relatively low temperature and could be reused after simple separation. As far as we known, this is the first example of converting inulin in ILs.

Experimental

Materials

Inulin was purchased from Alfa Aesar. The average degree of polymerization was about 29. HMF (99%) was purchased from Aldrich. The other starting materials (AR grade) were purchased from Beijing Chemical Reagents Company and used without further purification.

Analysis methods

The amount of HMF was calculated by using an external standard analyzed by HPLC with a Supelcosil LC-18 5 μ m column at 25 °C, a Shimadzu LC-20AT pump, a Sama UV-Vis LC-830 detector at 282.0 nm, and methanol/water (50/50 v/v) as flowing phase at 0.8 mL min⁻¹. The amount of fructose was also calculated by using an external standard analyzed using HPLC with a Hypersil NH₂ 5 μ m column at 40 °C, a Shimadzu LC-20AT pump, a Shimadzu RID-10A detector at 40 °C, and acetonitrile/water (75/25 v/v) as flowing phase at 0.8 mL min⁻¹.

HMF identification

HMF was identified by ¹H NMR spectra which were recorded as solutions in CDCl₃ at room temperature in a 400 MHz Bruker spectrometer, and by GC-MS (GC: Agilent technologies 6890N; MS: Agilent technologies 5973 inert MS Detector) M.S.: m/z (% of max. intensity) 50 (8), 69 (32), 81 (7), 97 (100), 109 (11), 126 (75); ¹H NMR (400 MHz, CDCl₃) δ (ppm): 4.75 (s, 2 H), 6.54 (d, J = 3.4 Hz, 1 H), 7.24 (d, J = 3.4 Hz, 1 H), 9.62 (s, 1 H).

Preparation of the choline chloride-based ILs

The ILs were synthesized following procedures reported in the literature.²² In ChoCl/oxalic acid, the molar ratio of choline chloride to oxalic acid· $2H_2O$ was 1 : 1, and in ChoCl/citric acid, the molar ratio of choline chloride to citric acid· H_2O was 2 : 1.

General procedure for the reaction in ILs

Inulin (81.0 mg) and a known amount of IL were added into the reactor in a constant temperature oil bath, and the reaction system was stirred for the desired time. After reaction, the reactor was cooled to room temperature immediately. The yields were analyzed by HPLC.

Biphasic procedure and reusing of ChoCl/oxalic acid

Inulin (81.0 mg) and a known amount of IL were added into the reactor in a constant temperature oil bath at 80 °C. After stirring for 1 min, the desired amount of ethyl acetate was added into the reactor. After stirring for the desired time, the reaction system was cooled to room temperature immediately. Then, the ethyl acetate phase was poured out from the reactor and collected. The IL phase was extracted with fresh ethyl acetate (1 mL \times 3). The ethyl acetate phases were combined and analyzed by HPLC. Then, the IL phase was used directly for the next run, where the procedure was the same as that described above.

Results and discussion

Effect of the reaction time on the yield

Our experiment in this work showed that the solubility of inulin in the two ILs is very high. For example, at 70 °C the solubilities of inulin in ChoCl/oxalic acid and ChoCl/citric acid are 150 mg g⁻¹ and 28 mg g⁻¹, respectively. We studied the direct conversion of inulin to HMF in ChoCl/oxalic acid and ChoCl/citric acid. The functional parts of the ILs are the dicarboxylic or tricarboxylic acids. The ILs acted as both solvent and catalyst. Fig. 1 shows the results of the reaction at 80 °C. It is well known that in the acid-catalyzed hydrolysis, inulin is broken down to the fructofuranosyl cation in the first step,²³ and this cation is further dehydrated to produce HMF rapidly or reacts with water to form fructose. This is a complex reaction system and many by-products can be formed. For example, di-D-fructose dianhydrides can be produced from the fructofuranosyl cation,24 and levulinic acid may be formed from HMF under aqueous acidic conditions.1c Fig. 1 shows that when the reaction carried out in ChoCl/citric acid, a large amount of fructose was produced within 10 min, then, the fructose was immediately converted to HMF, which resulted in a sharp decrease of the fructose yield and an increase of the HMF yield for 10 to 30 min. After 30 min, the HMF yield increased at a relatively slower rate and reached the maximum at a reaction time of about 120 min. When the reaction was in ChoCl/oxalic acid, 37% of HMF and only 4% of fructose were obtained within 10 min. This was very different from the reaction in ChoCl/citric acid and indicated that fructose was very unstable in ChoCl/oxalic acid and was quickly converted to HMF due to the higher acidity of the oxalic acid. Then, the HMF yield increased slowly and reached the maximum at a reaction time of about 120 min.



Fig. 1 Conversion of inulin to fructose and HMF in ILs at 80 °C: inulin (81.0 mg, 0.5 mmol fructose units), ILs (3 mmol based on acid moieties, 0.80 g for ChoCl/oxalic acid and 1.47 g for ChoCl/citric acid); water was 3 mmol in the ChoCl/citric acid–water mixture.

Effect of additional water in ILs

It was mentioned above that inulin was converted to HMF, fructose and some di-D-fructose dianhydrides catalyzed by acids. The di-D-fructose dianhydrides that cannot be converted further to HMF were easily formed from inulin under anhydrous acidic conditions,²⁴ and the addition of water would reduce their yields. If we can suppress the formation of di-D-fructose dianhydrides by adding water, the HMF yield might be increased. To prove the above argument, we added different amounts of water to the ILs in the reaction.

Fig. 1 shows the yields of HMF and fructose in a mixture of ChoCl/citric acid and water at different reaction times. The molar ratio of the IL and water was 1 : 1. Similar to that in the neat IL, a large amount of fructose was produced within 10 min and, then, it quickly was converted to HMF; but the yield of fructose in the IL–water mixture was always higher than that in neat IL at the same reaction time. The maximum of the HMF yield in the mixture was reached at about 180 min, at which both the yields of HMF and fructose were higher than those in the neat IL, indicating that the addition of suitable amount of water into the IL indeed increased the HMF yield.

Fig. 2 shows the effect of the amount of water added on the yield of HMF. In ChoCl/citric acid, the yield increased with the increase of the amount of water added when R (Ris the molar ratio of the additional water to fructose units in inulin) was less than 25, and then decreased when R exceeded 25. The main reason for this was that too much water would inhibit the dehydration of fructose to produce HMF. Similarly, in ChoCl/oxalic acid, the yield increased when R was in the



Fig. 2 The yields of HMF in the mixture of ILs and water: inulin (81.0 mg, 0.5 mmol fructose units), ILs (3 mmol based on acids moieties), $80 \degree C$, 2 h.

range of 0–20, and then decreased with further increasing of the amount of water added. In short, the values of *R* at which the HMF yield began to decrease in ChoCl/oxalic acid and ChoCl/citric acid ware 20 and 25, respectively. It is known that oxalic acid has two hydrated water molecules and citric acid contains one hydrated water molecule. The molar ratio of the acid moiety in the ILs and the fructose units in inulin was 3/0.5 in the reaction systems (Fig. 1 and 2). Therefore, in ChoCl/oxalic acid and ChoCl/citric acid the total molar ratios of water (hydrated and added) to fructose units in inulin at which the HMF yields began to decrease were $32 (32 = 3/0.5 \times 2 + 20)$ and $31 (31 = 3/0.5 \times 1 + 25)$, respectively. The two numbers are very close. These experiments further suggested that a suitable amount of water was favourable for promoting the yield of HMF.

Effect of reaction temperature

We also studied the effect of the temperature on the reaction. It was found that a higher temperature benefits the formation of HMF, and more fructose was produced at lower temperatures (Table 1, entries 2–6). Especially, 69% fructose yield was obtained in ChoCl/citric acid at 50 °C (Table 1, entry 7). On the basis of these results, we tested the two-temperature step reaction in a one pot reaction. Inulin was first converted at low temperature (50 °C) for 2 h, and then heated to 80 °C for 2 h. Indeed, the yield (57%) and selectivity (65%) were higher than when reacted only at 80 °C (Table 1, entries 2 and 8).

Reaction in an ethyl acetate (AcOEt)/IL biphasic system

Ethyl acetate (AcOEt) is a widely-used solvent in industry because it is cheap and displays low toxicity. It is known that HMF is soluble in AcOEt.^{21a} The above results demonstrated that ChoCl/oxalic acid was the more efficient IL for the reaction. We studied the reaction in a biphasic system consisting of AcOEt and ChoCl/oxalic acid. Our experiments showed that at the reaction conditions of this work the product HMF is soluble in AcOEt while the solubility of the IL, the reactant inulin and fructose in AcOEt is negligible. Moreover, the reactant inulin and fructose are soluble in the IL, and AcOEt is only slightly soluble in the IL. This special phase behavior is favorable for conducting the reaction in the biphasic system. When the reaction was carried out in the biphasic system, the upper AcOEt phase would extract the product HMF from the IL-rich phase

Table 1 The conversion of inulin to HMF in ChoCl based ILs: inulin (81.0 mg, 0.5 mmol fructose units), ILs (3 mmol based on acid moieties)

Entry	Acid in IL	Temperature/°C	Time/h	HMF yield (%)	Fructose yield (%)	Selectivity (%) ^a
1	Oxalic acid	80	2	56	0	56
2	Citric acid	80	2	51	10	56
3	Oxalic acid	50	2	19	38	31
4	Oxalic acid	60	2	28	31	40
5	Oxalic acid	70	2	45	7	49
6	Oxalic acid	90	2	55	0	55
7	Citric acid	50	2	3	69	9
8 ^b	Citric acid	50/80	2/2	57	12	65
9 ^c	Oxalic acid	80	2	64	0	64

^{*a*} Selectivity is equal to HMF yield/(100 – fructose yield). ^{*b*} Entry 8 was first stirred at 50 °C for 2 h, then at 80 °C for the next 2 h. ^{*c*} Entry 9 was the biphasic systems with IL and AcOEt (4.90 mL).

continuously, which would produce more HMF and reduce the by-products. The separation of the product was also easy because the upper phase consisted only of the solvent and the product. A yield of 64% was achieved in the biphasic system with ChoCl/oxalic acid as the solvent and AcOEt as the extraction solvent, which is considerably higher than that in the neat IL (Table 1, entries 1 and 9).

Reusability of the IL

The recycling of ChoCl/oxalic acid in the biphasic system was investigated. The conditions were the same as those of entry 9 in Table 1. After reaction, there were two phases in the reactor. The upper phase consisted of AcOEt and HMF and the other phase was rich in IL. After separation of the two phases, the product in the IL was further extracted using fresh AcOEt and the IL was reused directly. The results of recycling the IL are presented in Fig. 3. It should be indicated that the activity of the recycled IL was still very high after being used six times.



Fig. 3 Results of recycling ChoCl/oxalic acid in the ChoCl/oxalic acid/AcOEt biphasic reaction system. The conditions were the same as those of entry 9 in Table 1.

Our experiment showed that the accumulated residue (mainly di-D-fructose dianhydrides) and the IL in the IL phase could be separated by extraction using ethanol because the IL is soluble in ethanol, while the residue is not soluble in ethanol at room temperature. At room temperature, when 2 mL of ethanol were added into the IL phase which was recycled 6 times, the IL dissolved in the ethanol and the accumulated residue precipitated from the ethanol solution. Then, the precipitate was removed by filtration and the IL was refreshed after removing the ethanol from the filtrate by distillation.

Conclusion

In summary, inulin was efficiently converted to HMF in a onepot reaction in ChoCl/oxalic acid or ChoCl/citric acid, which were prepared from cheap biorenewable materials. Moreover, the yield of HMF in the AcOEt/ChoCl/oxalic acid biphasic system was considerably higher. The IL phase could be recycled directly after removing the AcOEt phase that contained HMF, and the reduction in the yield was not considerable after the IL was recycled 6 times. We believe that this highly efficient and greener route has great potential for application.

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