Solvent Mediation for Enhanced Separation of 5-Hydroxymethylfurfural from 1-Butyl-3-Methylimidazolium Chloride

Jinxia Zhou,[†,‡] Tingyu Huang,[†] Yuling Zhao,[§] Zhi Xia,[†] Zhanwei Xu,[†] Songyan Jia,[†] Jianji Wang,[§] and Z. Conrad Zhang*,[†]

[†]Dalian National Laboratory of Clean Energy and State Key Laboratory of Catalysis, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian, China

[‡]College of Environmental and Chemical Engineering, Dalian University, Dalian, China

[§]School of Chemistry and Chemical Engineering, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, Henan Normal University, Xinxiang, Henan, China

ABSTRACT: Ionic liquids have been widely studied as effective reaction media for the conversion of glucose or cellulose to 5-hydroxymethhyl-furfural (5-HMF). However, the recovery of 5-HMF from ionic liquids, typically carried out by extraction, has been encountered with very low extraction efficiency, which limited the reusability of the solvents. Through this work, based on the model biphasic system that consists of 1-butyl-3-methylimidazolium chloride ([BMIM]Cl) as the ionic liquid phase and methyl isobutyl ketone (MIBK) as the extractant phase, the dominant force that suppresses the extraction efficiency of 5-HMF was identified as being the strong hydrogen bonding between 5-HMF and [BMIM]Cl. Solvent mediation with functional promoters have been established as a new strategy to shift this force, resulting in improved extraction efficiency of 5-HMF from the ionic liquid. For example, with ethanol as a promoter, the distribution coefficient of 5-HMF was about 10 times higher than that without a promoter.
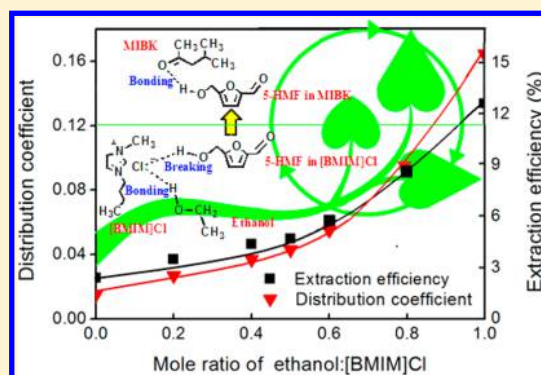
INTRODUCTION

Developing platform chemicals from biomass have been considered a viable approach for the utilization of biomass feedstocks.[1] 5-HMF as a versatile platform chemical[2] can be synthesized from C-6 carbohydrates, the dominant monomers in biomass. Until now, the synthesis of 5-HMF from mono- and polysaccharides has been widely studied, and many studies adopted fructose as a starting material by acid catalyzed dehydration.[3] However, fructose is not an abundant carbohydrate in most biomass. Producing 5-HMF from cellulose and its structural building block, glucose, is particularly attractive from the perspective of sustainability as cellulose is the most abundant carbohydrate polymer in nature.[4]

The synthesis of 5-HMF from cellulose and glucose has been met with a great technical challenge.[5] A technically viable route for the conversion of glucose to 5-HMF would be via isomerization of glucose to fructose, followed by subsequent dehydration of fructose to 5-HMF. Great efforts have been focused on one-pot tandem conversion strategies.[3] Recently, some ionic liquids have been reported to be highly effective reaction media for one-pot conversion of glucose to 5-HMF, and such media were also shown to be promising for producing 5-HMF from polysaccharides under mild conditions.[6,7] The first major breakthrough was reported based on the discovery in 1-ethyl-3-methylimidazolium chloride ([EMIM]Cl) ionic liquid

solvent.[8] A 5-HMF yield of up to 70% was obtained in these solvents with CrCl₂ and CrCl₃ as catalysts. Other forms of chloride salt or chromium ion based catalysts in 1-alkyl-3-methylimidazolium chloride, [AMIM]Cl, were also effective catalysts.[9] Besides enabling high conversion of glucose to 5-HMF, some [AMIM]Cl compounds were also reported capable of dissolving and depolymerizing cellulosic biomass polymer.[10] Cellulose conversions were near 100% in [BMIM]Cl and [EMIM]Cl solvents, with 83.7% and 87.1% to glucose and 12.6% and 12.5% to cellobiose, in 1-butyl-3-methylimidazolium chloride ([BMIM]Cl) and [EMIM]Cl, respectively.[11] Moreover, the pretreated cellulose in the solvents was converted into 5-HMF by suitable catalysts in a single-step process under mild temperatures.[12] The 5-HMF yield of 53% with 95% cellulose conversion was achieved at 120 °C in [BMIM]Cl/Cr ([PSMIM]HSO₄)₃ reaction media.[12] Despite the significant progress over the recent years, isolation of 5-HMF from the ionic liquids remains a great challenge and is a major hurdle for recycled use of the ionic liquid solvents. Separation of 5-HMF from [BMIM]Cl solvent by distillation is not practical due to

the very low vapor pressure of 5-HMF. The strong interaction between 5-HMF and the solvent further reduces the 5-HMF vapor pressure. The chemical nature of such interaction remains unclear and has received little attention according to published literature. The recovery of 5-HMF by extraction with a less polar organic solvent was an alternative choice. However, although some biphasic systems involving an aqueous reaction phase have been shown moderate extraction effects,[13] extraction of 5-HMF over an ionic liquid phase was encountered with very low extraction efficiency.[14−16]

We hypothesized that the strong interaction between 5-HMF and the ionic liquids may be the main underlying cause for the poor effectiveness of the extraction phase for 5-HMF separation. We investigated this hypothesis by identifying the primary cause for the poor 5-HMF extraction efficiency in a model biphasic system that contains [BMIM]Cl as the solvent phase and methyl isobutyl ketone (MIBK) as the extract phase. The possible interaction forces between 5-HMF and [BMIM]-Cl were first studied in detail. On the basis of the fundamental understanding of this dominant interaction force, a method for promoting extraction of 5-HMF from the [BMIM]Cl phase by MIBK solvent was investigated by using appropriate promoters.

■ EXPERIMENTAL SECTION

Materials. 5-Hydroxymethylfurfural (5-HMF, 98%) was obtained from Aladdin. Furfuralcohol (99%) was purchased from Sigma-Aldrich. Methanol (99%), ethanol (99%), glycerol (99%), acetonitrile (99%), methyl isobutyl ketone (MIBK, 99%), and D-glucose (99%) were purchased from Sinopharm (China). Furfural (99%) was obtained from TCI Chemical Co., LTD (Shanghai, China). Deionized water (DI H$_2$O) was supplied by Hangzhou Wahaha Group Co., Ltd. All the chemicals above were used as received. [BMIM]Cl was purchased from Lanzhou Greenchem ILS, LICP (China). It was degassed through online-vacuum at 100 °C for 10 h. ^{1}H NMR spectral data of the [BMIM]Cl were determined by using an AV-400 Bruker spectrometer and was found in good agreement with those reported in the literature.[17]

Viscosity Measurement. Capillary viscosities of [BMIM]-Cl and its mixtures at atmospheric pressure were measured using an GB/T265 Kinematic viscosity measuring unit (Dalian Zhineng Instrument Group Co., Ltd., China) fitted with flat open Abramovich Standard viscometers. The temperature of the thermostatic glycerol bath was measured with a 100 Ω platinum resistance thermometer with an overall estimated uncertainty of ±0.1 K. The viscosity measurement for each sample was repeated five times, and the overall maximum uncertainty of these viscosity measurements was estimated as ≤1%.

Extraction Methods. For each extraction sample, a specified amount of [BMIM]Cl (preheated at 100 °C and kept in liquid state before dispensing), MIBK, the solutes to be extracted, and promoter were added into a glass vial with scale lines. The relative proportions of the compounds are listed in the titles of figures or in the footnote of the table in the discussion of the results. The glass vial was sealed with a cap, and its volume was calibrated with scale lines on its wall. Chemical dispense was conducted on a Core Module 3 (CM3) high-throughput instrument (Freeslate Corporation), a bench-top platform system that performs complex automated liquid and powder weighing, mixture stirring, and temperature monitoring. Except for special testing conditions at higher temperature, the extraction experiments were operated at room

temperature, 24−26 °C. The compounds in the vial were mixed by manually shaking for 30 min with about 100 oscillating times per minute, and at last, the vial was settled in the static stage for phase separation for 3 h or longer. After several experiments and taking samples at different time intervals, it was found that increasing the agitation time (minimum time 30 min) and rest time (minimum time 3 h) had no effect on equilibrium phase compositions. Some samples, of which the bottom ionic liquids were initially highly viscous with poor fluidity, were preheated at 50 °C on the CM3 heating bath for 10−15 min before shaking. The heat treatment reduced the viscosity for the subsequent extraction. The experiments for testing the extraction temperature at 50−75 °C were conducted as follows: the compounds loaded in the vial were preheated to a specified temperature on the CM3 heating bath for 0.5 h. They were then shaken sufficiently to become well-mixed. At last the vial was put on the heating bath again to allow static settlement of the contents inside the vial. After complete phase segregation, the volumes of the extract and raffinate phases were measured according to the scale lines on the wall of the vial, and the samples with specified volumes from the two phases were collected with a pipet. Then glycerol as an internal analytical standard was added to the extracted samples, and the mixtures were further diluted and analyzed by HPLC. A mass balance was made between the initial mass of 5-HMF and the amounts in the upper and lower phases on the basis of equilibrium compositions. The relative error in the mass balance was within 2%.

All samples collected from the extract and raffinate phases were analyzed on an Agilent 1260 HPLC equipped with a refractive index detector (RID) and a diode array detector (DAD). Components were separated with a Hi−Piex H (300 × 7.7 mm) column and an H$_2$SO$_4$ (5 mM) eluent at a flow rate of 0.6 mL min^{-1}, and the column temperature was maintained at 65 °C. Glycerol was added as an internal standard for quantitative calculations.

The characteristics of the distributions of solutes in both phases were determined by the following parameters.[18,19]

The distribution coefficient was determined as the ratio of the equilibrium concentrations of the distributed solute in the extract phase and the raffinate phase. It was calculated according to eq 1:

$$\text{distribution coefficient} = C_e/C_r \qquad (1)$$

where C_e and C_r are the equilibrium concentrations of the distributed solute in the extract phase and the raffinate phase, respectively.

The phase volume ratio was defined as the volume ratio of the extract phase to the raffinate phase. It was calculated according to eq 2:

$$\text{phase volume ratio} = V_e/V_r \qquad (2)$$

where V_e and V_r stand for the volumes of the extract phase and the raffinate phase, respectively.

The extraction efficiency, E, was the ratio of the 5-HMF distributed in the extract phase and the total 5-HMF in the biphasic system. It was calculated according to eq 3:

$$\text{extraction efficiency} = C_e V_e/(C_e V_e + C_r V_r) \times 100\% \qquad (3)$$

Calculation Methods. Molecular dynamics simulations were performed with MDynaMix 5.2[20] by using an all-atom force field. For 5-HMF, ethanol, and [BMIM]Cl, the reported parameters of AMBER force field were always used.[21]

Optimization of the isolated ion structures was performed by using Gaussian 09 B.01[22] at the B3LYP/6-31+G* level. Atom charges were obtained by fitting the electrostatic potentials calculated at the B3LYP/6-311++G* level, and the one-conformation, two-step restraint electrostatic potential method was used for this purpose. The double time-step algorithm[23] was adopted with long and short time steps of 2 and 0.5 fs, respectively.

The mixtures of [BMIM]Cl and 5-HMF with and without the ethanol promoter were performed at 298 K. The molecule numbers of [BMIM]Cl, 5-HMF, and ethanol in the simulation system were 240, 100, and 240, respectively. The initial configuration was prepared by PACKMOL[24] in a square box, typically larger than the "real" size to make the packing easier. A starting simulation was carried out at 700 K in NVE ensemble. After a relaxation for a few MD steps to reduce the possible overlapping in the initial configuration, the Nose-Hoover NPT ensemble simulation was performed. Descending from 700 K to the sampling temperature at 298 K, the NPT simulations were carried out under the standard atmospheric conditions. At the sampling temperature point, the system was equilibrated for at least 6 ns, and then the production phase lasted for 4 ns. The conformations in trajectories were dumped with an interval of 20 fs for further analysis. The energies were collected every 10 ps for averaging.

■ RESULTS AND DISCUSSION

Dominant Force between [BMIM]Cl and 5-HMF. 5-HMF, furfural, and furfuralcohol all belong to furan compounds with structural variations in the functional groups. 5-HMF has a carbonyl group and a hydroxymethyl group, while furfural has only a carbonyl group and furfuralcohol only a hydroxymethyl group. When the three substrates were evaluated as the solutes, distinctive differences among these compounds were observed during their extractions. Figure 1 shows that the distribution coefficient and the extraction efficiency values of furfuralcohol and 5-HMF are much lower than that of furfural, and the values of furfuralcohol are a little higher than the values of 5-HMF. A higher distribution coefficient or extraction efficiency means a more efficient extraction of a solute, due to a weaker interaction of the solute with [BMIM]Cl. Therefore, according to the
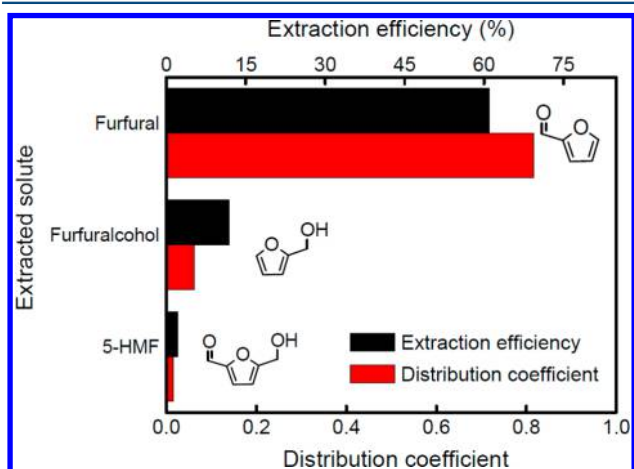
Figure 1. Extraction parameters of furfural, furfuralcohol, and 5-HMF from [BMIM]Cl by MIBK (experimental conditions: 1 g [BMIM]Cl and 2.4 g MIBK; mole ratio of evaluated solute:[BMIM]Cl = 0.5:1; 25 °C).

results shown in Figure 1, it is evident that the interaction strengths of the three solutes with [BMIM]Cl follow the order: furfural ≪ furfuralcohol <5-HMF. Both 5-HMF and furfuralcohol have hydroxyl groups and are capable of forming hydrogen bonding with the Cl⁻ of [BMIM]Cl. Besides the hydrogen bond interactions, other interactions [i.e., p- and π-electron dispersion interaction and van-der-Waals interaction (nonelectrostatic interaction) also exist].[25] In accordance with the extraction properties in Figure 1 and the differences among the molecular structures of the solutes, there is little doubt that the hydrogen bonding exerts as the dominant force in the interaction between 5-HMF and [BMIM]Cl. Hence, weakening the hydrogen bonding between hydroxymethyl group of 5-HMF and Cl⁻ of [BMIM]Cl served as the basis of our design strategy for the selection of promoters in our subsequent experiments.

Ethanol Promoted 5-HMF Extraction. Extraction of 5-HMF by MIBK from [BMIM]Cl with increasing ethanol loading was studied to verify and elucidate the fundamental role of ethanol as a promoter (Figure 2). The molar ratio of 5-HMF
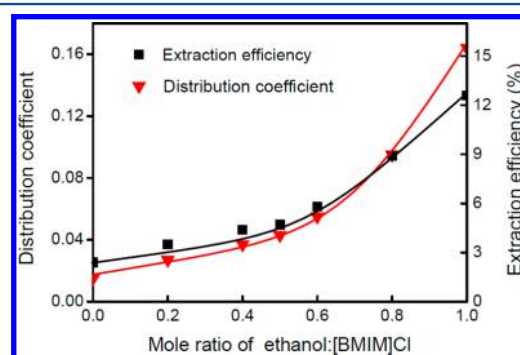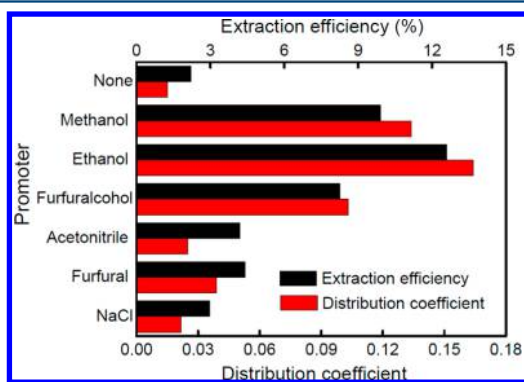

Figure 2. Extraction parameters of 5-HMF from [BMIM]Cl by MIBK with different ethanol loading (experimental conditions: 1 g [BMIM]Cl and 2.4 g MIBK; mole ratio of 5-HMF:[BMIM]Cl = 0.5:1; 25 °C).

solute to [BMIM]Cl solvent is fixed at 0.5:1 for this particularly study. The distribution coefficient and the extraction efficiency values are plotted to manifest the amount of extractable 5-HMF from [BMIM]Cl. As shown in Figure 2, when the extraction is performed at a relatively low ethanol loading of no more than 0.5:1 mol ratio of ethanol:[BMIM]Cl, the increase in the distribution coefficient value was not significant. However, with further increase in ethanol loading from 0.5:1 up to 1.0:1 in the mole ratio of ethanol:[BMIM]Cl, the distribution coefficient value showed a dramatic increase with ethanol loading, reaching 0.16 at the 1.0:1 mol ratio. The extraction efficiency of 5-HMF followed the same trend as the distribution coefficient value. The turning point at 0.5:1 mol ratio of ethanol:[BMIM]Cl, from the slow increase to the sharp increase in the fitted curve of the distribution coefficient and the extraction efficiency, reflects the precise initial molar ratio of 5-HMF to [BMIM]Cl. The results indicate that the added ethanol molecules to the system were first associated with the available [BMIM]Cl not yet bonded by 5-HMF. When these free [BMIM]Cl compounds have been fully saturated by ethanol, extra ethanol molecules compete for the [BMIM]Cl molecules associated with 5-HMF. Only then can the promoter effectively interfere and disrupt the interaction between 5-HMF and [BMIM]Cl, thus releasing 5-HMF from the [BMIM]Cl. These experimental results demonstrate the positive role of ethanol in promoting 5-HMF extraction.

Because each ethanol molecule, C_2H_5OH, has a hydroxyl group, the results suggest that hydrogen bonding may be a dominant interaction force for proton bearing molecules to interact with [BMIM]Cl, by forming hydrogen bonding with a Cl⁻ anion of the [BMIM]Cl. The results in Figure 2 can be well-explained by the hydrogen-bonding model. Assuming each Cl⁻ anion of the [BMIM]Cl solvent forms a hydrogen bond with the H⁺ of a HO group, the initial 50% of 5-HMF with respect to the [BMIM]Cl would interact with equal moles of [BMIM]Cl by hydrogen-bonding formation. This leaves 50% of the [BMIM]Cl free of the hydrogen bonding. Adding ethanol in a molar amount that was equivalent to the free [BMIM]Cl only marginally promoted the distribution coefficient and the extraction efficiency values. Further increase in the ethanol molar concentration resulted in competitive displacement of 5-HMF from the [BMIM]Cl solvent, resulting in the rapid increase in the distribution coefficient and the extraction efficiency values.

Effects of Other Molecules and NaCl Salt. To further verify the hypothesis on the importance of hydrogen bonding interaction between 5-HMF and [BMIM]Cl, other molecules with and without H-bonding capabilities are quantitatively studied for their promotional effect as the extraction parameters in the [BMIM]Cl and MIBK biphasic systems. In Figure 3, the

Figure 3. Extraction parameters of 5-HMF from [BMIM]Cl by MIBK with different promoters (experimental conditions: 1 g [BMIM]Cl and 2.4 g MIBK; mole ratio of 5-HMF:[BMIM]Cl = 0.5:1; mole ratio of promoter:[BMIM]Cl = 1:1; 25 °C).

promoting effects of other selected molecules and salt species are compared in order to gain insight on the mechanism of promoted 5-HMF extraction. Considerable variations in the extraction efficiency of 5-HMF are observed when the values of the distribution coefficient and the extraction efficiency are compared across different promoters. For the system without a promoter, the distribution coefficient of the 5-HMF was about 0.02. In comparison, the distribution coefficient values were increased about 6, 11, and 7 times with methanol, ethanol, and furfuralcohol as promoters, respectively. Similarly, the extraction efficiency values of 5-HMF were also largely increased when the three protic promoters were used. Thus, addition of the substrates with hydrogen donors displayed positive promoting effects on the extraction of 5-HMF by MIBK. The polarity index of methanol, ethanol, and acetonitrile are 5.1, 5.2, and 5.8, respectively. However, the promoting effect of the strongly polar molecule, acetonitrile is much weaker than that of the two alcohols. It can therefore be deduced that polarity does not play a crucial role in the promoting effect. Furfural may undergo π-electron dispersion interaction with the

[BMIM]Cl molecules. In accordance with Table 2, such interaction offers a much weaker promoting effect compared with the hydrogen bonding. It has been reported that the presence of an inorganic salt (e.g. NaCl) in the aqueous phase played an important role in improving the extraction efficiency of 5-HMF.[26] However, the salt did not improve the 5-HMF extraction from [BMIM]Cl/MIBK phase. This difference could be rationalized on the basis that [BMIM]Cl is already a salt, and additional salt should not be expected to enhance the 5-HMF extraction.

Behaviors of Low Molecular Alcohols. Methanol and ethanol are miscible with [BMIM]Cl in any ratio and cannot form two phases. Stark et al.[25] reported the complete miscibility of the alcohols like methanol in 1-butyl-3-methylimidazolium methanesulfonate ([BMIM][CH$_3$SO$_3$]) ionic liquid and concluded that such alcohols were not suitable agents for the extraction of 5-HMF from the ionic liquid. However, as demonstrated in this work, these alcohols played a favorable role as promoters in disrupting the hydrogen-bonding interaction between 5-HMF and [BMIM]Cl, resulting in enhanced extraction of 5-HMF by MIBK. To establish the role of methanol and ethanol as promoters, it is important to determine the distribution properties of the methanol and ethanol promoters between the [BMIM]Cl and the MIBK phases.

As shown in Table 1, when methanol or ethanol is added into a [BMIM]Cl/MIBK biphasic system, the low values of the

Table 1. Distribution Properties of Methanol and Ethanol As Solutes in the [BMIM]Cl/MIBK Biphasic System[a]

entry	solute	distribution coefficient	extraction efficiency (%)
1	methanol	0.048	7.9
2	ethanol	0.125	15.1

[a]Experimental conditions: 1 g [BMIM]Cl and 3 mL MIBK; mole ratio of extracted solute:[BMIM]Cl = 0.5:1; 25 °C.

distribution coefficient and the extraction efficiency manifest the low proportion of methanol or ethanol in the MIBK phase. In accordance with the extraction efficiency value, it may be deduced that nearly 92% of methanol is dissolved in [BMIM]Cl phase, and the value for ethanol is 85%. Dumesic et al.[27] used 2-butanol as a phase modifier to promote efficient production of 5-HMF from fructose in a two-phase system involving an aqueous phase and a MIBK phase. However, the role of 2-butanol in that system is quite different from that of these lower alcohols, such as methanol and ethanol used in our study, because most of the 2-butanol (>95%) is partitioned effectively into the MIBK layer and acts as an extractant together with MIBK. In this work, the methanol or ethanol added in the MIBK/[BMIM]Cl two-phase system is mainly affiliated with the bottom ionic liquid phase. Therefore, these lower alcohols can hardly be considered coextractants with MIBK. For the special roles of methanol and ethanol as revealed by the present study, it is appropriate to define them as promoters.

Besides the positive roles in promoting extraction of 5-HMF from the [AMIM]Cl ionic liquids, methanol and ethanol also offer potential for optimization of the reaction system. When used as reaction solvents, the ionic liquids can cause negative impact on heat and mass transfers because of high viscosities. It was found that addition of methanol and ethanol helped to reduce [BMIM]Cl viscosity significantly. When the alcohols were used as the promoters, the kinematic viscosities of the

[BMIM]Cl-methanol and [BMIM]Cl-ethanol mixtures (mole ratio of promoter:[BMIM]Cl = 1:1) at 80 °C were reduced to 8.8 and 9.6 mm^2/s, respectively, which are more than an order of magnitude lower than that of pure [BMIM]Cl (109.4 mm^2/s). The reduced viscosity is highly favorable for the process as the rates of heat and mass transfers and chemical reaction are largely dependent on the fluid flow phenomena of the system.

Because of their low boiling points, the lower molecular alcohols like ethanol and methanol can readily be recovered from the ionic liquid by distillation. More than 95% ethanol was removed from the [BMIM]Cl-ethanol mixtures (mole ratio of ethanol:[BMIM]Cl = 1:1) after 30 min atmospheric distillation at 100 °C or reduced pressure distillation at 55 °C.

Support by Molecular Dynamics Simulations. Molecular dynamics simulations were performed on the mixtures of [BMIM]Cl/5-HMF with and without ethanol promoter. The interaction energies of [BMIM]Cl with 5-HMF and with the promoter in different systems are listed in Table 2. An

Table 2. Interaction Energies of [BMIM]Cl with 5-HMF and with Ethanol in Different Simulation Systems (kJ/mol)

interaction system	[BMIM]$^+$–5-HMF	Cl$^-$–5-HMF	[BMIM]$^+$–ethanol	Cl$^-$–ethanol
[BMIMCl]/5-HMF	−68.8	−128.1	–	–
[BMIMCl]/5-HMF/Ethanol	−64.5	−90.3	−71.2	−135.6

interaction energy with a larger absolute value manifests a stronger interaction force. In accordance with the data in Table 2, it can be deduced that the interaction between Cl$^-$ and 5-HMF is much stronger than that between [BMIM]$^+$ and 5-HMF in the [BMIM]Cl/5-HMF mixture system. This result is consistent with our initial hypothesis that the dominant interaction between [BMIM]Cl and 5-HMF is the hydrogen-bonding interaction between the Cl$^-$ of [BMIM]Cl and hydroxyl H of 5-HMF, as discussed on the basis of Figure 1. The interaction energies in the [BMIM]Cl/5-HMF/ethanol mixture system manifest that the ethanol forms a strong interaction with the Cl$^-$ of [BMIM]Cl, and at the same time the interaction force between Cl$^-$ and 5-HMF is decreased markedly compared to the system without ethanol. These results indicate that a strong interference force of ethanol is exerted on [BMIM]Cl.

The above results indicate that the strong hydrogen bonding between the hydroxyl group of 5-HMF and the Cl$^-$ anion of [BMIM]Cl is the dominant force that suppresses the extraction efficiency of 5-HMF, and the promoters that contain hydroxyl protons can effectively improve the extraction efficiency. The possible promoting mechanism is deduced as follows: in the [BMIMCl]/5-HMF mixture, 5-HMF is strongly associated with [BMIM]Cl mainly through hydrogen bonding. When a promoter (e.g., ethanol) is added, its hydroxyl proton can also form hydrogen bonding with the Cl$^-$ of [BMIM]Cl. The promoter with a stronger H-bonding ability can effectively compete with the 5-HMF and weaken the Cl$^-$-5-HMF H-bonding interaction force. As a result, 5-HMF is liberated from the [BMIM]Cl phase for a more favorable affinity with the extractant, resulting in the enhanced extraction efficiency by the organic extractant phase.

Effects of 5-HMF Initial Loading. The extraction efficiency of 5-HMF without added ethanol does not vary appreciably with the increasing 5-HMF initial loadings. In contrast, the extraction efficiency of 5-HMF with added ethanol

is concentration-dependent and it increases gradually with the increase of 5-HMF initial loading (Figure 4). Therefore, the
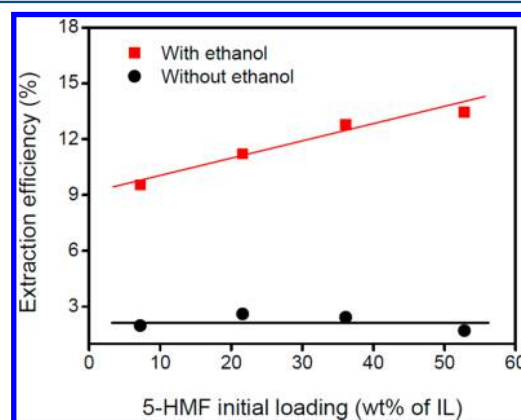
Figure 4. Extraction efficiency of 5-HMF at different 5-HMF initial loadings in [BMIM]Cl (experimental conditions: 1g [BMIM]Cl and 2.4 g MIBK; mole ratio of ethanol:[BMIM]Cl = 1:1; 25 °C).

promoting effect of ethanol is more pronounced with the increase of the 5-HMF initial loading. Because 5-HMF in the extract phase can be recovered by distillation of the extraction solvent, the much increased 5-HMF concentration in the extractant phase can be expected to result in significantly improved economics in the production of 5-HMF. Most importantly, the promoted high extraction efficiency is expected to make it feasible to the recycled use of the ionic liquid and the catalyst. It sould be noted that the amount of ethanol used as promoter is only a fraction of the weight of 5-HMF. For example, under the extraction condition with 1:1 mol ratio of ethanol:[BMIM]Cl and 0.5:1 mol ratio of 5-HMF:[BMIM]Cl, ethanol content is 26.7 wt % with respect to [BMIM]Cl or is 74.0 wt % with respect to 5-HMF.

Effects of Temperature. Figure 5 shows the results of extracting 5-HMF from [BMIM]Cl by MIBK operated at different temperatures with or without ethanol promoter. Both the distribution coefficient and the extraction efficiency values of 5-HMF extraction have a small but not very significant increase in the temperature range of 25−75 °C. This low temperature-sensitivity is beneficial as the biphasic behavior
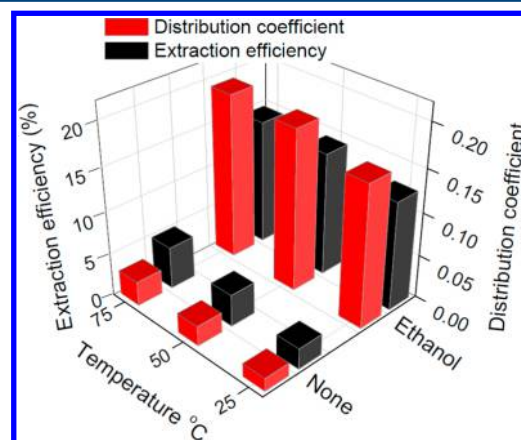
Figure 5. Extraction parameters of 5-HMF at different temperatures (experimental conditions: 1g [BMIM]Cl and 2.4 g MIBK; mole ratio of 5-HMF:[BMIM]Cl = 0.5:1; mole ratio of ethanol:[BMIM]Cl = 1:1).

could be expected to be maintained under reaction conditions. The maintenance of this biphasic behavior is also necessary for continuous separation and reuse of the extractant solvent at the reaction temperature. Therefore, the promoter-modified biphasic system can be expected to be applicable to process conditions.

CONCLUSIONS

In summary, a new method based on the solvent mediation has been established for enhanced 5-HMF extraction from [AMIM]Cl ionic liquids. On the basis of the model [BMIM]Cl/MIBK biphasic system, this work established that the strong hydrogen bonding between the proton of the hydroxyl group of 5-HMF and the Cl⁻ anion of the [BMIM]Cl ionic liquid is the dominant force in suppressing the extraction efficiency. Functional promoters that effectively displace the strong hydrogen bonding between 5-HMF and [BMIM]Cl were found to sufficiently weaken the interaction of 5-HMF with the chloride based ionic liquid, resulting in enhanced extraction efficiency. The feasibility of the strategy was demonstrated by the substantially enhanced extraction efficiency of 5-HMF from the ionic liquid with the use of lower alcohol promoters. When ethanol was used as a promoter, the distribution coefficient of 5-HMF from the ionic liquid by MIBK was increased by over 10 times than that without the promoter. The lower molecular alcohols like ethanol and methanol are particularly effective because of their higher bonding ability with [BMIM]Cl, and their lower affinity with MIBK. Because of their low boiling points, these alcohol promoters can readily be recovered from the ionic liquid by distillation.

AUTHOR INFORMATION

Corresponding Author

*Address: Dalian National Laboratory of Clean Energy, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian, China, 116023. Tel.: +86-411-84379462. Fax: +86-411-84379371. E-mail: zczhang@yahoo.com.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

REFERENCES

(1) Anbarasan, P.; Baer, Z. C.; Sreekumar, S.; Gross, E.; Binder, J. B.; Blanch, H. W.; Clark, D. S.; Toste, F. D. Integration of Chemical Catalysis with Extractive Fermentation to Produce Fuels. *Nature* **2012**, *491*, 235.

(2) Werpy, T.; Petersen, G. Top Value Added Chemicals from Biomass. Volume I: Results of Screening for Potential Candidates from Sugars and Sythesis Gas; Pacific Northwest National Laboratory: Richland, WA, 2004, vol. *1*.10.2172/15008859

(3) van Putten, R. J.; van der Waal, J. C.; de Jong, E.; Rasrendra, C. B.; Heeres, H. J.; de Vries, J. G. Hydroxymethylfurfural, A Versatile Platform Chemical Made from Renewable Resources. *Chem. Rev.* **2013**, *113*, 1499.

(4) Klemm, D.; Heublein, B.; Fink, H.; Bohn, A. Cellulose: Fascinating Biopolymer and Sustainable Raw Material. *Angew. Chem., Int. Ed.* **2005**, *44*, 3358.

(5) James, O. O.; Maity, S.; Usman, L. A.; Ajanaku, K. O.; Ajani, O. O.; Siyanbola, T. O.; Sahu, S.; Chaubey, R. Towards the Conversion of Carbohydrate Biomass Feedstocks to Biofuels via Hydroxylmethylfurfural. *Energy Environ. Sci.* **2010**, *3*, 1833.

(6) Zhang, Z. C. *Interdisciplinary Reviews: Energy and Environment: Catalytic Transformation of Carbohydrates and Lignin in Ionic Liquids.* Wiley: New York, 2013.

(7) Su, Y.; Brown, H. M.; Huang, X. W.; Zhou, X. D.; Amonette, J. E.; Zhang, Z. C. Single-step Conversion of Cellulose to 5-Hydroxymethylfurfural (HMF), A Versatile Platform Chemical. *Appl. Catal., A* **2009**, *361*, 117.

(8) Zhao, H.; Holladay, J. E.; Brown, H.; Zhang, Z. C. Metal Chlorides in Ionic Liquid Solvents Convert Sugars to 5-Hydroxymethylfurfural. *Science* **2007**, *316*, 1597.

(9) Yong, G.; Zhang, Y.; Ying, J. Y. Efficient Catalytic System for the Selective Production of 5-Hydroxymethylfurfural from Glucose and Fructose. *Angew. Chem., Int. Ed.* **2008**, *47*, 9345.

(10) Zhang, Z. C. *In: Suib SL, ed. New and Future Developments in Catalysis: Catalytic Biomass Conversion.* Elsevier: Netherlands, 2013.

(11) Morales-delaRosa, S.; Campos-Martin, J. M.; Fierro, J. L. G. High Glucose Yields from the Hydrolysis of Cellulose Dissolved in Ionic Liquids. *Chem. Eng. J.* **2012**, *181−182*, 538.

(12) Zhou, L.; Liang, R.; Ma, Z.; Wu, T.; Wu, Y. Conversion of Cellulose to HMF in Ionic Liquid Catalyzed by Bifunctional Ionic Liquids. *Bioresour. Technol.* **2013**, *129*, 450.

(13) Saha, B.; Abu-Omar, M. M. Advances in 5-Hydroxymethylfurfural Production from Biomass in Biphasic Solvents. *Green Chem.* **2014**, *16*, 24.

(14) Chan, J. Y. G.; Zhang, Y. Selective Conversion of Fructose to 5-Hydroxymethylfurfural Catalyzed by Tungsten Salts at Low Temperatures. *ChemSusChem* **2009**, *2*, 731.

(15) Lima, S.; Neves, P.; Antunes, M. M.; Pillinger, M.; Ignatyev, N.; Valente, A. A. Conversion of Mono/di/polysaccharides into Furan Compounds Using 1-Alkyl-3-methylimidazolium Ionic Liquids. *Appl. Catal., A* **2009**, *363*, 93.

(16) Tao, F.; Song, H.; Chou, L. Efficient Conversion of Cellulose into Furans Catalyzed by Metal Ions in Ionic Liquids. *J. Mol. Catal. A: Chem.* **2012**, *357*, 11.

(17) Erdmenger, T.; Vitz, J.; Wiesbrock, F.; Schubert, U. S. Influence of Different Branched Alkyl Side Chains on the Properties of Imidazolium-based Ionic Liquids. *J. Mater. Chem.* **2008**, *18*, 5267.

(18) Pei, Y.; Wang, J.; Wu, K.; Xuan, X.; Lu, X. Ionic Liquid-based Aqueous Two-phase Extraction of Selected Proteins. *Sep. Purif. Technol.* **2009**, *64*, 288.

(19) Gao, J.; Chen, L.; Yan, Z. C. Extraction of Dimethyl Sulfoxide Using Ionic-liquid-based Aqueous Biphasic Systems. *Sep. Purif. Technol.* **2014**, *124*, 107.

(20) Lyubartsev, A. P.; Laaksonen, A. M. DynaMix−a Scalable Portable Parallel MD Simulation Package for Arbitrary Molecular Mixtures. *Comput. Phys. Commun.* **2000**, *128*, 565.

(21) Cornell, W. D.; Cieplak, P.; Bayly, C. I.; Gould, I. R.; Merz, K. M.; Ferguson, D. M.; Spellmeyer, D. C.; Fox, T.; Caldwell, J. W.; Kollman, P. A. A Second Generation Force Field for the Simulation of Proteins, Nucleic Acids, and Organic Molecules. *J. Am. Chem. Soc.* **1995**, *117*, 5179.

(22) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A. et al. *Gaussian09 B.01*; Gaussian, Inc.: Wallingford, CT, 2009.

(23) Tuckerman, M.; Berne, B. J.; Martyna, G. J. Reversible Multiple Time Scale Molecular-Dynamics. *J. Chem. Phys.* **1992**, *97*, 1990.

(24) Martinez, L.; Andrade, R.; Birgin, E. G.; Martinez, J. M. Packmol: A Package for Building Initial Configurations for Molecular Dynamics Simulations. *J. Comput. Chem.* **2009**, *30*, 2157.

(25) Stark, A.; Ondruschka, B.; Zaitsau, D. H.; Verevkin, S. P. Biomass-derived Platform Chemicals: Thermodynamic Studies on the Extraction of 5-Hydroxymethylfurfural from Ionic Liquids. *J. Chem. Eng. Data* **2012**, *57*, 2985.

(26) Gürbüz, E. I.; Wettstein, S. G.; Dumesic, J. A. Conversion of Hemicellulose to Furfural and Levulinic Acid Using Biphasic Reactors with Alkylphenol Solvents. *ChemSusChem* **2012**, *5*, 383.

(27) Román-Leshkov, Y.; Chheda, J. N.; Dumesic, J. A. Phase Modifiers Promote Efficient Production of Hydroxymethylfurfural from Fructose. *Science* **2006**, *312*, 1933.