

# Efficient conversion of glucose into 5-hydroxymethylfurfural catalyzed by a common Lewis acid $\text{SnCl}_4$ in an ionic liquid†

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The common Lewis acid  $\text{SnCl}_4$  could efficiently convert glucose into 5-hydroxymethylfurfural in 1-ethyl-3-methylimidazolium tetrafluoroborate ([EMim]BF<sub>4</sub>). New evidence indicated that the formation of the five-membered-ring chelate complex of the Sn atom and glucose may play a key role for the formation of HMF, and the mechanism for the reaction was proposed. In addition, the [EMim]BF<sub>4</sub>/SnCl<sub>4</sub> system was also suitable for the conversion of fructose, sucrose, inulin, cellobiose and starch.

Biomass is an abundant and the only sustainable carbon resource, and biomass refinery processes must be developed in the next few decades to produce energy and materials which will replace the ones produced from the diminishing fossil-based resources.<sup>1</sup> Carbohydrates represent 75% of the annual renewable biomass.<sup>2</sup> The most widespread monosaccharide is glucose which is produced by photosynthesis of carbon dioxide and water in the plants and is the monomer of cellulose. The utilization of glucose to generate valuable compounds effectively is a very important topic.<sup>3</sup>

5-Hydroxymethylfurfural (HMF) is a versatile compound, which can be used produce very useful furan derivatives.<sup>4</sup> For example, 2,5-furandicarboxylic acid was selected as one of the top 12 biomass-derived building blocks<sup>4a</sup> and 2,5-dimethylfuran was considered as a promising liquid transportation fuel.<sup>4c</sup> Up to now, different feedstocks have been used to produce HMF, such as fructose,<sup>5</sup> cellulose,<sup>6</sup> and inulin.<sup>7</sup>

Glucose is a wonderful candidate as the resource of HMF compared with fructose.<sup>2</sup> Efficient production of HMF from glucose is of great importance.<sup>8</sup> But some hindrances limit the development of the reactions. Firstly, due to the high content of hydroxyl groups, glucose has low volatility and high reactivity, and liquid-phase technologies should be used.<sup>9</sup> The underived glucose can only be dissolved in a few solvents, such as water, dimethylformamide and dimethylsulfoxide (DMSO). But when water is used as solvent the conversion of glucose is inefficient.<sup>10</sup> In the two latter organic solvents, the HMF yield was not high either,<sup>11</sup> and both of them have disadvantages from an environmental point of view. On the other hand, the catalyst must be used in the reaction to induce the formation

of glucose in straight-chain form and the generation of the enediol intermediate.<sup>12</sup> Up to now, almost no catalyst except chromium(II) chloride (CrCl<sub>2</sub>) was effective for this reaction in ionic liquids.<sup>13</sup> Therefore, both catalyst and solvent are crucial in the conversion of glucose into HMF.<sup>14</sup> There is no doubt that developing a cheap, non-toxic or low-toxicity, easily handled catalytic system for this important reaction and getting insight into the mechanism are highly desirable and challenging.

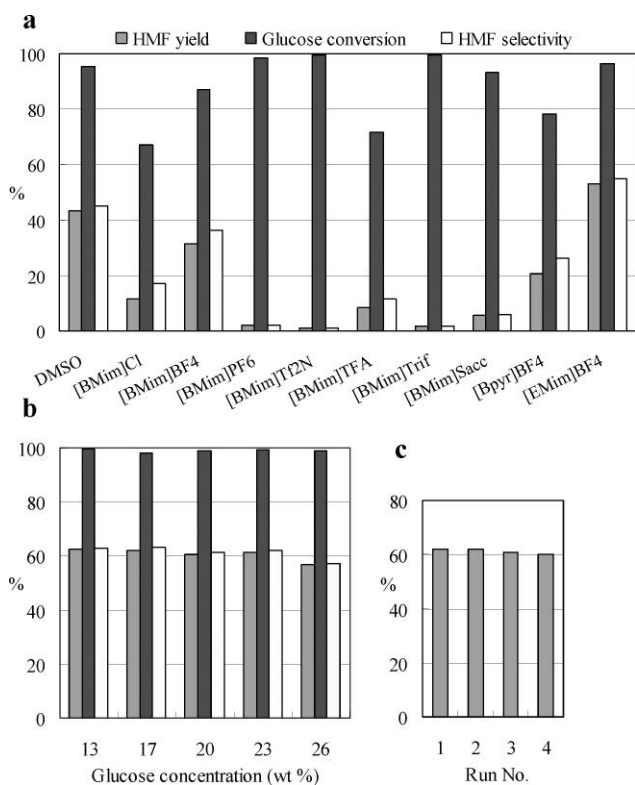
It is well known that SnCl<sub>4</sub> is a common, cheap, easy-handling Lewis acid, and has much lower toxicity. In this work, we found that SnCl<sub>4</sub> in 1-ethyl-3-methylimidazolium tetrafluoroborate ([EMim]BF<sub>4</sub>) was an efficient catalyst to produce HMF from glucose. A detailed study indicated that the formation of the five-membered-ring chelate complex of Sn and glucose may play a key role for the formation of HMF. The catalytic system was still very efficient even when the glucose concentration was as high as 26 wt%, and could be reused for at least four times without considerable reduction in efficiency. In addition, the [EMim]BF<sub>4</sub>/SnCl<sub>4</sub> system was also suitable to the conversion of other sugars such as fructose, sucrose, cellobiose, inulin and starch.

Firstly, we screened a series of metal chlorides, at 10 mol% amount (based on glucose), in DMSO to catalyze the conversion of glucose at 80 °C for 3 h (see ESI, Table S1).† Most of them did not work, and only CrCl<sub>3</sub>·6H<sub>2</sub>O, AlCl<sub>3</sub>·6H<sub>2</sub>O and SnCl<sub>4</sub>·5H<sub>2</sub>O (abbreviated as SnCl<sub>4</sub> in the following) were active. In particular, SnCl<sub>4</sub> was the most efficient and was selected as the catalyst for the following study.

In the next step, different solvents were studied. As we known, some ionic liquids (ILs) have a strong solvent power for many carbohydrates,<sup>15</sup> and some wonderful catalytic results have also been obtained in ILs for different reactions.<sup>16</sup> Besides DMSO, we studied the reaction catalyzed by SnCl<sub>4</sub> at 100 °C for 3 h in a series of ILs, including 1-butyl-3-methylimidazolium chloride ([BMim]Cl), 1-butyl-3-methylimidazolium tetrafluoroborate ([BMim]BF<sub>4</sub>), 1-butyl-3-methylimidazolium hexafluorophosphate ([BMim]PF<sub>6</sub>), 1-butyl-3-methylimidazolium bistriflate imide ([BMim]Tf<sub>2</sub>N), 1-butyl-3-methylimidazolium trifluoroacetate ([BMim]TFA), 1-butyl-3-methylimidazolium trifluoromethylsulfonate ([BMim]Trif), 1-butyl-3-methylimidazolium saccharin ([BMim]Sacc), *N*-butylpyridinium tetrafluoroborate ([Bpyr]BF<sub>4</sub>) and [EMim]BF<sub>4</sub>. The results are given in Fig. 1a. Fixing the cation of the ILs as [BMim]<sup>+</sup>, the best result was obtained when the anion was BF<sub>4</sub><sup>-</sup>. It was observed that lower HMF yields were obtained when the anions of ILs were Cl<sup>-</sup>, Tf<sub>2</sub>N<sup>-</sup>, TFA<sup>-</sup>, Trif<sup>-</sup>, Sacc<sup>-</sup>, all of which have coordination ability. These anions would have stronger interactions with the Sn atom

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† Electronic supplementary information (ESI) available: Materials, analysis methods, experimental procedures, more data of the experiments (Table S1 and S2), and Fig. S1. See DOI: 10.1039/b914601f



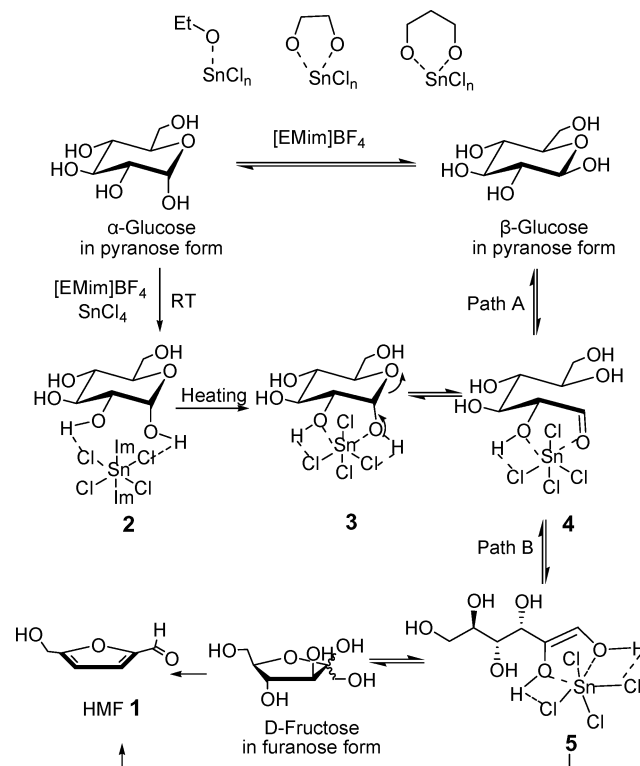
**Fig. 1** **a:** HMF yields in various ILs and DMSO: glucose (100.0 mg, 0.56 mmol), SnCl<sub>4</sub> (19.5 mg, 0.056 mmol), ILs or DMSO (1.0 g), 100 °C, 3 h; **b:** Yields of HMF at different initial glucose concentrations in [EMim]BF<sub>4</sub>: SnCl<sub>4</sub> (10 mol% based on glucose), [EMim]BF<sub>4</sub> (1.0 g), 100 °C, 3 h; **c:** Reuse of SnCl<sub>4</sub>/[EMim]BF<sub>4</sub>: glucose (200.0 mg, 1.11 mmol), SnCl<sub>4</sub> (39.0 mg, 0.111 mmol), [EMim]BF<sub>4</sub> (1.0 g), 100 °C, 3 h.

which competed with the interaction between glucose and Sn atom and inhibited the formation of HMF, resulting in the lower HMF yield. The HMF yield in [BMim]PF<sub>6</sub> was low due to the insoluble nature of glucose in the IL. It can be seen from the above results that when SnCl<sub>4</sub> was used as the catalyst, a suitable medium should have strong solvent power for glucose but low coordination ability to Sn. Thus, fixing the anion of the ILs as BF<sub>4</sub><sup>-</sup>, the highest yield of HMF was obtained in [EMim]BF<sub>4</sub> which was also higher than that obtained in DMSO. In the following, [EMim]BF<sub>4</sub> was selected as the solvent.

The reaction was conducted at different reaction conditions using SnCl<sub>4</sub> as the catalyst and [EMim]BF<sub>4</sub> as the solvent, and the optimum condition was at 100 °C with a reaction time of 3 h (see ESI, Table S2).† The yields at different glucose concentrations are presented in Fig. 1b. It can be seen that the yield of HMF could reach 61% when the concentration of glucose in the IL was as high as 23 wt%, indicating that the catalytic system was very effective for the reaction. Moreover, we tested the reusability of the SnCl<sub>4</sub>/[EMim]BF<sub>4</sub> catalytic system. After extraction of the product using ethyl acetate (see ESI),† the catalyst in IL was reused directly. The results showed that reduction in the yields of HMF was not obvious after being reused 4 times (Fig. 1c). One of the advantages of using the IL as the reaction medium and ethyl acetate as the extracting solvent is that the product HMF is soluble in ethyl acetate, while the IL is insoluble in it, which can avoid cross-contamination.

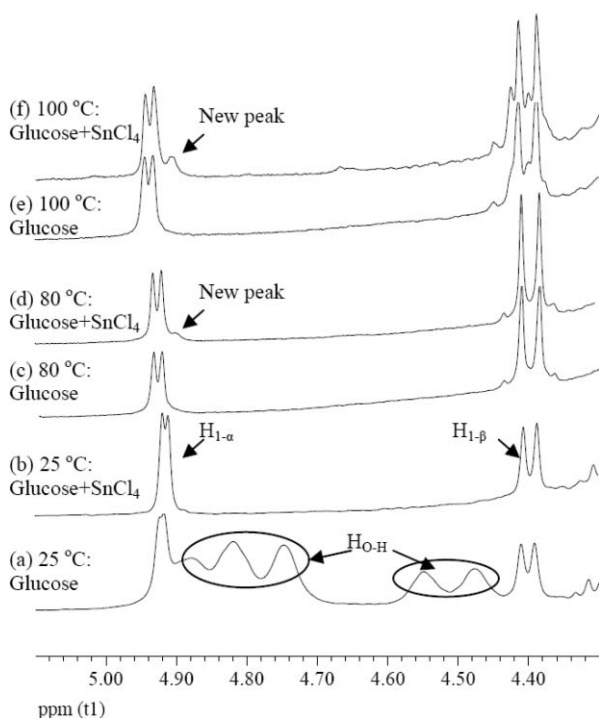
It is known that separation of the product and solvent requires energy. Using ethyl acetate as the extracting solvent, the energy cost of separation can be relatively low because of its low boiling point.

It is very interesting and challenging to study the mechanism of the reaction. The catalytic mechanism of the reaction was studied and is discussed in the following. When the glucose interacts with the Sn atom, there are opportunities for the formation of complexes with the acyclic and five- or six-membered-ring chelate structures. We added three alcohols, including ethanol, ethylene glycol and 1,3-propanediol (molar ratio to glucose was 1:1), respectively, into the reaction mixture. After reaction, the conversion of glucose was less than 5% in the presence of ethylene glycol; but ethanol and 1,3-propanediol did not reduce glucose conversion and HMF yield. This indicates that ethylene glycol, that can form a five-membered-ring chelate complex with Sn, inhibited the conversion of glucose significantly, while ethanol or 1,3-propanediol, which can form acyclic or six-membered-ring chelate complex with Sn (Fig. 2), did not affect the reaction. This suggests that the five-membered-ring chelate structure may be more stable than the acyclic and six-membered-ring chelate structures. We thought that formation of a five-membered-ring chelate structure with the Sn atom with the two neighbouring hydroxyl groups in glucose may play an important role in the catalytic reaction.



**Fig. 2** Proposed processes of glucose conversion to produce HMF catalyzed by SnCl<sub>4</sub> in [EMim]BF<sub>4</sub>.

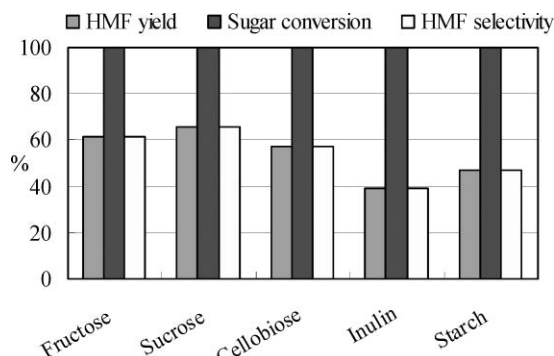
Glucose is usually in the pyranose form, and its conversion to HMF must be through a straight-chain form and an enediol intermediate. It can be shown from <sup>1</sup>H NMR spectra that both  $\alpha$ -glucose and  $\beta$ -glucose are in pyranose form in [EMim]BF<sub>4</sub> (Fig. 3a). When SnCl<sub>4</sub> interacts with glucose at room



**Fig. 3**  $^1\text{H}$  NMR spectra of glucose at different temperatures: 5 wt% glucose and 1 wt%  $\text{SnCl}_4$  dissolved in the mixture of  $[\text{EMim}]\text{BF}_4$  and  $d^6$ -DMSO with weight ratio of 9 : 1.

temperature, the peaks of the hydrogen atoms in hydroxyl groups of glucose ( $\text{H}_{\text{O-H}}$ ) disappeared (Fig. 3b), indicating that Cl atoms interacted with these hydrogen atoms and the intermediate **2** was formed (Fig. 2). Then,  $^1\text{H}$  NMR spectra of glucose mixed with  $\text{SnCl}_4$  were collected at 80 °C or 100 °C for 2 min, and a new peak at 4.90 ppm was observed and its height increased with the increase of temperature (Fig. 3d and 3f), indicating a new interaction between glucose and  $\text{SnCl}_4$  at the higher temperature. It is speculated that the new peak can be assigned to intermediate **3**. This suggests that heating would enhance the interaction between the Sn atom and O atoms to convert **2** into **3**. **3** could induce the formation of the intermediate complex **4**, which consisted of glucose in straight-chain form and  $\text{SnCl}_4$ . **4** was further converted into  $\beta$ -glucose and enediol intermediate **5** (Fig. 2). The important intermediate **5** was able to yield HMF directly and to be isomerized into fructose.<sup>17</sup> This was supported by the fact that fructose was indeed observed by HPLC when the reaction was processed at 80 °C for 3 h (see ESI, Fig. S1).<sup>†</sup> We believe that Cl atoms in  $\text{SnCl}_4$  interacted with hydrogen atoms and transferred the hydrogen atoms. The Sn atom in  $\text{SnCl}_4$  interacted with O atoms and promoted the formation of straight-chain glucose and the enediol intermediate. The latter intermediate was further transformed into fructose which could be dehydrated to form HMF in the presence of  $\text{SnCl}_4$  (Fig. 2). This was proved by the fact that 62% HMF yield was achieved when fructose was the reactant instead of glucose.

We also tested  $\text{SnCl}_4$  for catalyzing other sugars to form HMF (Fig. 4). When disaccharides and polysaccharides were converted, HMF yield was equal to  $\text{mol}_{(\text{HMF})}/\text{mol}_{(\text{total monomer})}$ . A wonderful result was obtained when 17 wt% sucrose in  $[\text{EMim}]\text{BF}_4$  was used as the resource, with 65% HMF yield.



**Fig. 4** Yielding HMF from various sugars in  $[\text{EMim}]\text{BF}_4$ : fructose/sucrose/cellobiose/inulin (200.0 mg),  $\text{SnCl}_4$  (10 mol% based on sugar monomer), IL (1.0 g), 100 °C, 3 h; starch (100.0 mg, 0.62 mmol of glucose unit),  $\text{SnCl}_4$  (21.6 mg, 0.062 mmol), IL (1.0 g), 100 °C, 24 h.

Sucrose is a disaccharide consisting of glucose and fructose. In reported works, HMF was produced only from the fructose moiety and the glucose moiety was wasted.<sup>12a,18</sup> Here, both the glucose and fructose moiety could be converted into HMF and most of the carbon in sucrose was utilized. When cellobiose was used as a resource, a good result was also obtained, with 57% HMF yield. It is worth mentioning that 47% HMF yield was obtained when starch was used as the feedstock.

In summary, we demonstrated that  $\text{SnCl}_4$  and  $[\text{EMim}]\text{BF}_4$  was an excellent combination for the conversion of glucose into HMF. High HMF yield was obtained even when the glucose concentration in the IL was as high as 26 wt%. Formation of the five-membered-ring chelate complex of Sn and glucose may play a key role for the formation of HMF. Satisfactory results were also obtained when fructose, sucrose, cellobiose, inulin and starch were as the feedstocks. The efficient, cheaper, low toxicity, and reusable catalytic system has great potential for application.

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