Green Chemistry



View Article Online

PAPER

() Check for updates

Cite this: *Green Chem.*, 2019, **21**, 6146

Received 26th July 2019, Accepted 18th October 2019 DOI: 10.1039/c9gc02600b

rsc.li/greenchem

Introduction

Lignocellulosic biomass, a renewable carbon resource, is primarily composed of carbohydrates such as cellulose and hemicellulose.^{1–3} Conversion of these carbohydrates to furanic compounds is an important step in producing value added chemicals such as polymers, fuels, resins, and solvents.^{4–8} In this step, monomeric pentoses are converted to furfural and hexoses are converted to 5-hydroxymethylfurfural (5-HMF), by a combination of isomerization and dehydration reactions (Fig. 1).^{9,10} Furfural is currently produced industrially by dehydration of pentose (mainly xylose), obtained from hemicellulose, in the presence of a homogeneous acid catalyst.¹¹ Heterogeneous catalysts such as SO_4^{2-}/SNO_2 ,¹² Nafion,¹³ Nb₂O₅,^{14,15} SAPO-44,¹⁶ and beta-zeolite,¹⁷ have been reported to be active for conversion of xylose to furfural. However, commercial application of these catalysts is not yet viable.

One of the drawbacks of furfural synthesis is the low abundance of xylose in biomass leading to low yield of furfural (4–12%) per unit weight of biomass processed.¹⁸ Synthesis of

Solvent basicity controlled deformylation for the formation of furfural from glucose and fructose[†]

Miyuki Asakawa,^{a,b} Abhijit Shrotri, 🕩 *ª Hirokazu Kobayashi ២ ª and Atsushi Fukuoka ២ *ª

The conversion of glucose and fructose to furfural can improve the productivity of furfural synthesis from biomass. We report that sulfolane, a weakly basic polar aprotic solvent, promoted the formation of furfural from hexoses with a maximum yield of 50% obtained from fructose. Addition of Sn/SBA-15 that acted as a Lewis acid catalyst enabled the conversion of glucose to furfural with 36% yield. Analysis of products obtained from isotopically labelled glucose showed that furfural is produced by elimination of the C6 carbon atom as a formaldehyde molecule. DFT calculations revealed that this elimination reaction is plausible in the presence of weakly basic solvents that are unable to abstract the proton from the C–H bond in the last step of the reaction, which would otherwise lead to formation of 5-HMF. The furfural yield was correlated with the basicity of solvents, calculated as proton affinity (E_{pa}), confirming the hypothesis that the basicity of solvent determines the selectivity for the formation of furfural or 5-HMF. Hence furfural formation from hexoses can be achieved by acid catalysed reaction of hexoses in the presence of low basicity polar aprotic solvents.

furfural from hexoses can overcome this problem by providing a single product stream from the total carbohydrate content of biomass, which accounts for 50–80% of biomass by weight. This approach is attractive as it would maximize the yield of furfural and simplify downstream processes. Furthermore, hexoses are abundantly available in the form of starch and molasses, which can be utilized for furfural synthesis without relying on the hemicellulose fraction.

The acid catalysed reaction of glucose and fructose to 5-HMF in water and organic solvents frequently produces furfural as a minor by-product.^{19,20} Pyrolysis of glucose and fructose in the absence of any solvent also yields furfural in appreciable amounts.^{21,22} Furfural is obtained in very small amounts even during the hydrolysis of cellulose to glucose.²³ These results suggest that formation of furfural from hexoses and its polymers is an inevitable side reaction, which can be promoted to obtain furfural as the primary product.

Higher yields of furfural have been achieved in the presence of polar aprotic solvents.^{24,25} The presence of an acid catalyst such as zeolite was essential for the furfural formation from hexoses during these reactions.²⁶ Catalysts with Lewis acid sites (for example Sn-beta zeolite) were required to catalyse the isomerization of glucose to fructose.²⁵ Sn-Beta zeolite is a wellknown catalyst for the isomerization of glucose to fructose and its subsequent dehydration to 5-HMF.²⁷ However, its contribution towards formation of furfural beyond isomerization is not clearly understood. The choice of solvent was also crucial in all previous studies. Polar aprotic solvents such as

^aInstitute for Catalysis, Hokkaido University, Kita 21 Nishi 10, Kita-ku, Sapporo, Hokkaido 001-0021, Japan. E-mail: ashrotri@cat.hokudai.ac.jp,

fukuoka@cat.hokudai.ac.jp

^bGraduate School of Chemical Sciences and Engineering, Hokkaido University,

Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan

[†]Electronic supplementary information (ESI) available. See DOI: 10.1039/ c9gc02600b



Fig. 1 Established reactions of glucose and xylose to 5-HMF and furfural, respectively (solid arrows) and the proposed reaction for producing furfural from hexoses to increase overall furfural productivity from biomass (dashed arrow).

 γ -valerolactone and γ -butyrolactone were especially active for furfural synthesis.²⁸ These solvents were predicted to enhance the formation of acyclic fructose that would easily diffuse through the pores of zeolite.²⁹ However, the formation of furfural in the presence of catalysts other than zeolites does not fit this hypothesis.²⁴

The reaction pathway for furfural formation from hexoses and the associated mechanism is not yet understood. Earlier studies focusing on 5-HMF synthesis from fructose have concluded that furfural is not formed via 5-HMF and it was the result of a separate pathway.^{30,31} Recently, it was predicted that pentose sugars such as xylose or arabinose are formed via retro-aldol cleavage of the C-C bonds of an acyclic fructose molecule.^{26,29} Subsequent dehydration of pentoses on the zeolitic acid sites was proposed as the pathway for furfural formation. However, retro-aldol reaction of fructose yields glyceraldehyde and dihydroxyacetone,³² and the formation of xylose is not viable through this pathway. Another study experimentally deduced that the C6 carbon atom on the fructose molecule was eliminated when furfural was formed as a byproduct.³³ However, no attempts were made to deduce the C-C cleavage mechanism. Consequently, the mechanism of furfural formation from fructose remains unclear. The elucidation of mechanism for this reaction is necessary to design catalysts and processes for furfural synthesis from hexoses.

In this study, we explore the mechanism of furfural formation from glucose and fructose in detail and examine the role of solvents and catalytically active species. An Sn/SBA-15 catalyst was used as a Lewis acid catalyst in the presence of polar aprotic solvents. We establish the reaction pathway for formation of furfural by using ¹³C labelled sugar molecules and evaluating the products by ¹³C NMR and mass spectrometry. Density functional theory (DFT) calculations were used to determine the influence of solvent in the reaction mechanism. Based on these experimental and theoretical data we propose a mechanism for furfural formation.

Materials and methods

Catalyst preparation

SBA-15 was prepared according to method reported by Stucky *et al.*³⁴ During synthesis, 450 mL of 1.6 M hydrochloric acid was added to 12 g of poly(ethylene glycol)-*block*-poly(propylene glycol)-*block*-poly(ethylene glycol) (P123) and stirred at room temperature until the P123 was hydrolysed. The solution was stirred rapidly at 35 °C and 25.5 g of tetraethyl orthosilicate was added dropwise over a span of 30 minutes. The solution was kept standing at 35 °C for 24 h and then kept standing at 100 °C for another 24 h. The obtained solid was filtered and washed with water and ethanol until the presence of chloride ions was not detected in the filtrate. The solid was dried at 110 °C overnight and then calcined at 560 °C for 16 h to obtain SBA-15.

Sn/SBA-15 catalyst was prepared by impregnation method. Desired amount of $SnCl_4 \cdot 5H_2O$, corresponding to 1 wt% Sn in the catalyst, was dissolved in 5 mL of distilled water and then 500 mg of SBA-15 was added to the solution. The mixture was sonicated for 5 minutes and then stirred continuously over a hot plate maintained at 105 °C until a powder was obtained. After further drying at 110 °C for 2 h, the powder was calcined at 500 °C for 2 h.

Bulk SnO_2 catalyst for comparison was prepared by dissolving 3.5 g $SnCl_4$ ·5H₂O in 100 mL water and then adding 28% aqueous NH₃ solution until the pH was neutral. The precipitated solid was washed with water and then ethanol. The washed solid was dried at 110 °C and then calcined at 500 °C for 2 h.

Catalyst characterization

X-ray diffraction (XRD) was measured with Rigaku MiniFlex using CuK α X-ray ($\lambda = 1.54$ Å). UV visible diffuse reflectance spectroscopy (UV-vis) measurement was done using Jasco V-650 spectrophotometer. Transmission electron microscope (TEM) images were taken with a JEM-2100F field emission

Paper

transmission electron microscope at an accelerating voltage of 200 kV. The sample was prepared by dispersing a small amount of catalyst in ethanol and then dropping it on a carbon-coated copper grid. N₂ adsorption isotherms were measured at -196 °C using a Belsorp mini analyser. NH₃ temperature experiments were performed in at BELCAT-A instrument.

Catalytic reaction

Catalytic reactions were performed in a pressure resistant glass reaction vessel (Ace Glass). In a typical reaction, 0.22 mmol of substrate (glucose or fructose), 5 mL of solvent and catalyst were added to the reaction vessel and stirred in oil bath at 160 °C for 2 h. After the reaction, the solution was cooled to room temperature and 5 mL of distilled water was added. The mixture was then analysed using high performance liquid chromatography (HPLC) (Shodex SH-1011 column and Rezex RPM monosaccharide Pb++ column) equipped with a refractive index detector. Product yields were calculated by using the following equation.

$$\text{Yield of products} = \frac{\text{moles of product obtained}}{\text{moles of substrate added}} \times 100$$

Gram scale experiment was performed using 8 g of fructose in 50 mL of sulfolane containing 1.5 mM H_3PO_4 . The reaction was performed at 160 °C for 45 minutes. After the reaction, 200 mL of water was added to the solution and the mixture was distilled at 100 °C and 500 hPa. The resulting aqueous solution was extracted twice using dichloromethane, which was subsequently evaporated to obtain the product.

Isotopic tracer study

Glucose and fructose labelled with ¹³C at different position were used for the isotopic tracer study. After reaction with the isotopically labelled samples, products were analysed using ¹³C NMR and gas chromatography-mass spectrometry (GC-MS). NMR analysis was performed using a JNM-ECX600, JEOL instrument operating at magnetic strength of 600 MHz. Prior to NMR analysis, 0.5 mL of product solution was added to equal amount of D₂O containing 4,4-dimethyl-4-silapentane-1-sulfonic acid (DSS) as reference and the resulting mixture was filtered. GC-MS analysis was done using a SHIMADZU GCMS-QP2010 equipped with an ULBON HR-20M column, 0.25 mm × 25 m.

DFT calculation

All the DFT calculations were performed with the Gaussian 09 program or Gaussian 16 with the G09Defaults option. Chemical structure of molecules (M) and their protonated forms (M – H⁺) were optimized using the hybrid functional B3LYP³⁵ with the split-valence triple- ζ basis set 6-311G(d,p).³⁶ In the reaction analysis, solvent effect was included by self-consistent reaction field (SCRF) method with a polarized continuum model (PCM) and dielectric constant (32.74), radius (3.35 Å), and density (1.179 g cm⁻¹) for sulfolane at a temperature similar to that in our reaction (125 °C).³⁷ Proton affinity is

defined as $E_{\text{pa}} = -\Delta H^{\circ} = [H^{\circ}(M - H^{+}) - H^{\circ}(M) - H^{\circ}(H^{+})]$. Standard enthalpy, $H^{\circ} = E_{\text{electronic}} + E_{\text{vib}} + E_{\text{trans}} + E_{\text{rot}} + p^{\circ}V$, of each structure was determined with the harmonic vibration calculations except for proton. $H^{\circ}(H^{+})$ at 298 K was approximated to $5/2RT = 6.19 \text{ kJ mol}^{-1}$.

Results and discussion

Several polar aprotic solvents were first tested for conversion of fructose to furfural at 160 °C. The formation of furfural or 5-HMF from fructose was highly dependent on the solvent used. A reaction of fructose in the presence of sulfolane without the addition of any catalyst produced 50% yield of furfural and 7.2% of 5-HMF (Table 1). In contrast, when dimethyl sulfoxide (DMSO) was used as the solvent, 5-HMF was the primary product with a yield of 69% under the same reaction conditions. Moreover, furfural yield was only 2.9% in the presence of DMSO. Tetramethylene-sulfoxide, also produced 5-HMF as the major product (56%) with low yield of furfural (0.4%). These results indicated that the nature of solvent altered the selectivity of products formed during the reaction. Other solvents such as γ -valerolactone, and γ -butyrolactone, previously reported to be good for furfural synthesis, produced furfural but with low yields of 3.2% and 8.7%, respectively.

Addition of a small amount of phosphoric acid (1.5 mM in the reaction mixture) as a Brønsted acid catalyst enhanced the rate of furfural formation in sulfolane (Fig. S1[†]). Final furfural yield of 50% was obtained in the presence of acid catalyst in about 30 minutes (Table 1, entry 6). The addition of acid catalyst also led to increased amount of furfural formation in γ -valerolactone (7.6%) and γ -butyrolactone (18%). It was evident that these solvents can also produce furfural as demonstrated in previous reports when a suitable acid catalyst is present. The formation of both furfural and 5-HMF requires removal of hydroxyl groups via the dehydration reaction, which will be accelerated by the addition of a Brønsted acid catalyst. The acceleration of furfural formation suggests that a common intermediate may be present for both the reactions, which is formed by the dehydration of fructose. The possibility of furfural formation from 5-HMF³⁸ was discarded because a reaction with 5-HMF as the substrate did not produce any detectable amount of furfural in sulfolane (Table 1, entry 14).

The conversion of glucose to furfural and 5-HMF required the presence of a Lewis acid catalyst. We synthesized SBA-15 supported Sn catalyst for this reaction. The impregnation of Sn on the SBA-15 did not alter the structure of support as measured by N₂ adsorption isotherm (Fig. S2-a†) and the surface area reduced only slightly from 876 m² g⁻¹ to 851 m² g⁻¹. XRD pattern of the prepared catalyst showed only one broad peak centred at 25 degree 2θ corresponding to amorphous silica in SBA-15 (Fig. 2a). Diffraction for SnO₂ crystals were not observed suggesting high dispersion of Sn species. The high resolution TEM image of the catalyst did not show any Sn particles further confirming high dispersion of the tin species (Fig. S3†). The absorption edge for the Sn/SBA-15 cata-

Paper

Table 1 Yields of furfural and 5-HMF from hexoses in the presence of various polar aprotic solvents^a

Entry	Substrate	Solvent	Catalyst	Time (min)	Product yield (%)	
					Furfural	5-HMF
1	Fructose	Sulfolane	_	120	50	7.2
2		DMSO	_	120	2.9	69
3		Tetramethylene-sulfoxide	_	120	0.4	56
4		γ-Valerolactone	_	120	3.2	c
5		γ-Butyrolactone	_	120	8.7	0.5
5		Sulfolane	$H_3PO_4^{b}$	30	50	16
7		Diethyl sulfone	$H_3PO_4^{b}$	30	11	14
8		3-Methyl sulfolane	$H_3PO_4^{b}$	30	23	11
9		γ-Valerolactone	$H_3PO_4^{b}$	30	7.6	
10		γ-Butyrolactone	$H_3PO_4^{b}$	30	18	15
11		DMSO	$H_3PO_4^{b}$	30	2.1	77
12		Tetramethylene-sulfoxide	$H_3PO_4^{b}$	30	0.4	73
13		Sulfolane ^d	$H_3PO_4^{b}$	45	22	21
14	5-HMF	Sulfolane	_	120	0	
15	Glucose	Sulfolane	Sn/SBA-15 ^e	120	36	8.2
16		DMSO	Sn/SBA-15 ^e	120	1.2	11

^{*a*} Reaction conditions: 0.22 mmol substrate in 5 mL of solvent, 160 °C, atmospheric pressure. ^{*b*} 1.5 mM H₃PO₄ in solvent. ^{*c*} 5-HMF yield could not be determined due to overlapping peak of γ -valerolactone in the HPLC chromatograms. ^{*d*} Large-scale experiment with high fructose concentration: 8 g fructose in 50 mL of sulfolane. ^{*e*} 20 mg of 1 wt% Sn/SBA-15 was added during the reaction.



Fig. 2 (a) XRD spectra of SBA-15 support, Sn/SBA-15 catalyst and bulk SnO₂. (b) UV-Vis diffuse reflectance spectra for Sn/SBA-15 catalyst and bulk SnO₂.

lyst in the UV-Vis diffuse reflectance spectra was at 210 and 233 nm indicating the presence of tetrahedrally coordinated Sn species and its hydrated analogue (Fig. 2b). These Sn species are known to exhibit Lewis acidity that is capable of catalysing the isomerization of glucose. Bulk SnO_2 showed absorbance band at 280 nm which corresponds to octahedrally coordinated Sn species that are not active as Lewis acid sites. NH_3 TPD experiment was performed to measure the acidity of the catalyst. SBA-15 support had very low acid density as shown by the absence of NH_3 desorption peaks (Fig. S2-b†). Presence of Sn on the catalyst surface resulted in incorporation of 0.141 mmol g⁻¹ of acid sites. These acid sites were associated with both Brønsted and Lewis acidic species formed on the catalyst.

Reaction of glucose in sulfolane without any catalyst did not yield furfural or 5-HMF and produced levoglucosan and anhydroglucofuranose, resulting from dehydration of glucose, as the main products. Addition of Sn/SBA-15 catalyst under the same conditions produced 36% furfural from glucose in sulfolane (Table 1, entry 15). However, fructose was not directly observed as an intermediate in the HPLC chromatogram owing to its low concentration and multiple overlapping peaks. In our study, the formation of fructose as an intermediate for furfural synthesis from glucose was confirmed by using ¹³C-1 and ¹³C-6 labelled glucose and analysing the product solution by ¹³C NMR analysis (Fig. S4 and S5[†]). The NMR spectrum after 5 min of reaction showed peaks that were assigned to the furanic form of fructose at 68.2 ppm in ¹³C-1 NMR spectrum and at 66.9–67.3 ppm in the ¹³C-6 NMR spectrum. The activity of Sn/SBA-15 catalyst for isomerization of glucose to fructose in sulfolane was further confirmed by performing the reaction at lower temperature (120 °C) at which detectable amount of fructose was present (8.8%, 5 min). Furthermore, the Sn/SBA-15 catalyst showed excellent activity for the isomerization of glucose to fructose in ethanol with 85% selectivity and 66% yield (90 °C 2 h) attesting its activity as an isomerization catalyst.

To understand the mechanism of furfural formation from fructose, or from glucose *via* fructose, it is essential to first elucidate the pathway responsible for the elimination of one carbon atom. We used isotopically labelled ¹³C-1-glucose and ¹³C-6-glucose as substrate for furfural synthesis to track the fate of carbon atoms. The product solution obtained after reaction was analysed using GC-MS and the mass spectra of furfural were compared (Fig. 3). Furfural with an additional atomic mass (m/z = 97) was observed when ¹³C-1 labelled glucose was used. The furan fragment appeared in the mass spectrum at an m/z = 67 indicating that the ¹³C carbon atom was not present within the furan ring. This result confirmed that the ¹³C carbon atom was present at the C1 position of the furfural molecule. Normal furfural with an m/z = 96 was obtained when ¹³C-6-glucose was used as the substrate



Fig. 3 GC-MS spectra of furfural obtained after reaction using (a) 13 C-1-glucose and (b) 13 C-6-glucose as substrate. Reaction conditions: Substrate 0.22 mmol, Sn/SBA-15 catalyst 20 mg, 5 mL sulfolane, 160 °C, 2 h.

(Fig. 3b). Therefore, the C6 carbon atom was eliminated in the synthesis of furfural from glucose/fructose. This observation contradicts the mechanism proposed in previous studies that claim the elimination of C1 carbon atom by retro-aldol elimination reaction of acyclic fructose to produce xylose.^{25,29}

Based on the stoichiometry of the reaction the elimination of C6 carbon atom from fructose is expected to produce a formaldehyde molecule. Detection of formaldehyde by chromatography was difficult due to its tendency to react at high temperatures. However, when the product of reaction with ¹³C-6 glucose was analysed by ¹³C NMR, a small distinct peak appeared at 84.1 ppm for methylene glycol, the hydrated form of formaldehyde, confirming its formation (Fig. S5,† Inset of 30 min NMR spectrum).³⁹

To elucidate the mechanism of furfural formation we need to first examine the formation of 5-HMF from hexose, which is a well-studied reaction. The mechanism of its formation has been described in detail using experimental and computational methods.^{40,41} In DMSO, 5-HMF is formed by sequential dehydration of fructose catalysed by an acid catalyst starting from the C2 carbon atom of fructose. After removal of –OH groups from the C2 and C3 positions the intermediate compound 2 is formed (Fig. 4). The penultimate step in 5-HMF formation is the removal of the water molecule to produce compound 3 by protonation of hydroxyl group at the C4 position. Finally, the compound 3 loses the proton attached to the C5 carbon atom to DMSO and the formation of furan ring is completed. The formation of the five membered π conjugated furan ring drives the last step of the reaction.

Furfural formation is also expected to follow the same path initially as the addition of a small amount of acid accelerated the furfural formation. Furthermore, addition of a small amount of base (20 mM NaHCO₃) completely blocked the forward reaction of fructose in both sulfolane and DMSO. Therefore, we predict that the furfural formation would also proceed via compound 3. Based on the isotope tracer experiments, we expect that the removal of hydroxymethyl group at C6 position from the compound 3 would produce furfural and formaldehyde. Thus, the selectivity of furfural/5-HMF is determined by competition of the deformylation at C6 position and the proton abstraction from C-H at C5 position. Here, unlike DMSO, sulfolane lacks the basicity required to dissociate C-H group at the C5 position. Consequently, the deformylation reaction is dominant (Fig. 4). Elimination of the hydroxymethyl group leads to the formation of a stable furan ring that promotes the forward reaction.

To theoretically confirm if the reaction can take place by this mechanism, we evaluated the energy profile for the defor-



Fig. 4 Proposed mechanism for furfural formation in comparison with mechanism for formation of 5-HMF.



Fig. 5 DFT calculations for the deformylation of the compound 3 at the B3LYP/6-311G(d,p) level. *E* indicates sum of electronic and zero-point vibration energy.

mylation by the DFT calculations at the B3LYP/6-311G(d,p) level of theory (Fig. 5). Compound 3 hydrogen bonded with a sulfolane molecule was set as the initial structure for the calculation. In the transition state, the C5–C6 bond was elongated owing to the charge transfer from oxygen atom in the hydroxymethyl group to the oxocarbenium in the five-membered ring. The activation energy for this step was calculated to be a low value of 21 kJ mol⁻¹. An imaginary vibration frequency (304i cm⁻¹) and smooth connection between substrate and product in intrinsic reaction coordinate (IRC) were confirmed. This reaction produced formaldehyde in a protonated form, and finally the proton was subtracted by sulfolane due to very weak basicity of the solvent molecule. Accordingly, the DFT calculations indicated that this reaction is plausible.

This mechanism suggests that polar aprotic solvents with very low basicity can promote the formation of furfural and moderately basic solvents will promote the formation of 5-HMF. To validate this assumption, we compared the gas phase proton affinity of the solvent molecules determined by the DFT calculations and the experimental furfural yield obtained from fructose in the presence of small amount of H_3PO_4 (Fig. 6). Prior to this, we verified that the calculations for proton affinity are accurate using several molecules for which experimental values are available, e.g., $(E_{pa}/kJ \text{ mol}^{-1})$ DMSO calc. 888, exp. 884; γ-butyrolactone calc. 839, exp. 840.⁴² Consequently we found that the yield of furfural was inversely correlated to the proton affinity of the solvents. Sulfolane showed the lowest proton affinity among all solvents used in this study ($E_{pa} = 835 \text{ kJ mol}^{-1}$), which corresponds to its highest furfural yield. The highest proton affinity for which furfural was the main product was that of γ -valerolactone $(E_{pa} = 853 \text{ kJ mol}^{-1})$. DMSO $(E_{pa} = 888 \text{ kJ mol}^{-1})$ was more basic and produced only a small amount of furfural with high 5-HMF yield, indicating a transition in the reaction selectivity.



Fig. 6 Yield of furfural from fructose compared with the basicity of solvents calculated as the proton affinity (E_{pa}). Reaction condition: Fructose 0.22 mg, solvent 5 mL containing 1.5 mM H₃PO₄, 160 °C, 30 min.

Tetrahydrothiophene-1-oxide, which has a similar structure to sulfolane albite with a sulfoxide group instead of the sulfonyl group, was even more basic ($E_{pa} = 924 \text{ kJ mol}^{-1}$) than DMSO and produced almost no furfural as expected.

Based on the above mechanism sulfolane acts just as a solvent without any catalytic influence. To test this phenomenon, we performed experiment with solvent mixture containing different concentration of DMSO in sulfolane. Furfural was obtained in high yield (50%) only in the absence of DMSO (Fig. 7). 5-HMF was obtained in 66% yield with 12% yield of furfural even when the amount of DMSO was 5 vol%. Further increase in DMSO concentration reduced furfural yield. These results show that the formation of 5-HMF was catalysed by the



Fig. 7 Yield of products after reaction of fructose in a solvent mixture with varying concentration of DMSO in sulfolane. Reaction condition: Fructose 0.22 mg, solvent 5 mL, 160 °C, 2 h.

presence of small amount of DMSO in sulfolane and furfural was formed only in the presence of a low basicity polar aprotic solvent.

To establish the industrial viability of this process we performed a large-scale reaction with high concentration of fructose (8 g in 50 mL sulfolane). The furfural yield reduced to 22% and the 5-HMF yield increased to 21% (Table 1, entry 13). The reduction in furfural yield was caused by accumulation of water released during the dehydration step of the reaction, which favoured the formation of 5-HMF over furfural. Work up of the reaction mixture gave 0.83 g of product which was analysed by ¹H and ¹³C NMR (Fig. S6[†]). The resulting product contained 92% furfural along with sulfolane (6.9%). Therefore, we established that furfural can be produced and separated from hexose sugars in sulfolane with relatively good purity by simple distillation and extraction. Furthermore, separation of product by simple steps along with use of heterogeneous catalyst will enable the design of continuous process for commercial application.

Conclusion

Furfural and 5-HMF yields were found to be influenced by the type of polar aprotic solvent used. The highest yield of furfural (50%) was achieved from fructose in the presence of sulfolane. In contrast, reaction in DMSO produced 5-HMF as the primary product with low furfural yield. Sn/SBA-15, a Lewis acid catalyst, was necessary to produce furfural from glucose with a maximum yield of 36%. Mechanistic study revealed that the formation of furfural is similar to that of 5-HMF until the final step leading to furan ring formation. Furfural was produced by the elimination of the hydroxymethyl groups as formaldehyde. The formation of furfural was preferred in the presence of polar aprotic solvents with very low basicity as determined by calculating the gas phase proton affinity of solvents. Sulfolane, with the lowest proton affinity of 835 kJ mol⁻¹, afforded the highest furfural yield. Our results demonstrate the crucial role of solvent in the formation of furfural from hexose sugars and also indicates the importance of using basic additives during the synthesis of 5-HMF.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors would like to thank Dr Sho Yamaguchi and Dr Shinji Inagaki from Toyota Central R&D Laboratories, Japan for fruitful discussion on the mechanistic aspects of this research.

References

- 1 D. L. Klass, *Biomass for renewable energy, fuels, and chemicals*, Academic Press, San Diego, 1998.
- N. Mosier, C. Wyman, B. Dale, R. Elander, Y. Y. Lee, M. Holtzapple and M. Ladisch, *Bioresour. Technol.*, 2005, 96, 673–686.
- 3 G. W. Huber, S. Iborra and A. Corma, *Chem. Rev.*, 2006, **106**, 4044–4098.
- 4 A. Corma, S. Iborra and A. Velty, *Chem. Rev.*, 2007, **107**, 2411–2502.
- 5 J. B. Binder and R. T. Raines, *J. Am. Chem. Soc.*, 2009, **131**, 1979–1985.
- 6 D. M. Alonso, J. Q. Bond and J. A. Dumesic, *Green Chem.*, 2010, **12**, 1493–1513.
- 7 P. Gallezot, Chem. Soc. Rev., 2012, 41, 1538-1558.
- 8 H. Kobayashi, M. Yabushita, T. Komanoya, K. Hara, I. Fujita and A. Fukuoka, *ACS Catal.*, 2013, **3**, 581–587.
- 9 J. P. Lange, E. Van Der Heide, J. Van Buijtenen and R. Price, *ChemSusChem*, 2012, 5, 150–166.
- 10 R. Van Putten, J. C. Van Der Waal, E. De Jong, C. B. Rasrendra, H. J. Heeres and J. G. De Vries, *Chem. Rev.*, 2013, **113**, 1499–1597.
- R. Mariscal, P. Maireles-Torres, M. Ojeda, I. Sádaba and M. López Granados, *Energy Environ. Sci.*, 2016, 9, 1144– 1189.
- 12 T. Suzuki, T. Yokoi, R. Otomo, J. N. Kondo and T. Tatsumi, *Appl. Catal., A*, 2011, **408**, 117–124.
- 13 E. Lam, E. Majid, A. C. W. Leung, J. H. Chong, K. A. Mahmoud and J. H. T. Luong, *ChemSusChem*, 2011, 4, 535–541.
- 14 C. García-Sancho, I. Sádaba, R. Moreno-Tost, J. Mérida-Robles, J. Santamaría-González, M. López-Granados and P. Maireles-Torres, *ChemSusChem*, 2013, 6, 635–642.
- 15 N. K. Gupta, A. Fukuoka and K. Nakajima, *ACS Catal.*, 2017, 7, 2430–2436.
- 16 P. Bhaumik and P. L. Dhepe, *RSC Adv.*, 2014, 4, 26215–26221.
- 17 R. Otomo, T. Tatsumi and T. Yokoi, *Catal. Sci. Technol.*, 2015, 5, 4001–4007.
- 18 D. Tin Win, AU J. Technol., 2005, 8, 185-190.
- 19 G. C. A. Luijkx, F. van Rantwijk, H. van Bekkum and M. J. Antal, *Carbohydr. Res.*, 1995, 272, 191–202.
- 20 F. S. Asghari and H. Yoshida, *Ind. Eng. Chem. Res.*, 2006, **45**, 2163–2173.
- 21 J. B. Paine, Y. B. Pithawalla and J. D. Naworal, *J. Anal. Appl. Pyrolysis*, 2008, **83**, 37–63.
- 22 D. Carnevali, O. Guévremont, M. G. Rigamonti, M. Stucchi,
 F. Cavani and G. S. Patience, ACS Sustainable Chem. Eng.,
 2018, 6, 5580–5587.
- 23 A. Shrotri, H. Kobayashi and A. Fukuoka, *ChemCatChem*, 2016, **8**, 1059–1064.
- 24 E. I. Gürbüz, J. M. R. Gallo, D. M. Alonso, S. G. Wettstein,
 W. Y. Lim and J. A. Dumesic, *Angew. Chem., Int. Ed.*, 2013, 52, 1270–1274.

- 25 L. Zhang, G. Xi, Z. Chen, D. Jiang, H. Yu and X. Wang, *Chem. Eng. J.*, 2017, **307**, 868–876.
- 26 J. Cui, J. Tan, T. Deng, X. Cui, Y. Zhu and Y. Li, *Green Chem.*, 2016, **18**, 1619–1624.
- 27 E. Nikolla, Y. Román-Leshkov, M. Moliner and M. E. Davis, *ACS Catal.*, 2011, **1**, 408–410.
- 28 L. Zhang, G. Xi, Z. Chen, D. Jiang, H. Yu and X. Wang, *Chem. Eng. J.*, 2017, **307**, 868–876.
- 29 L. Wang, H. Guo, Q. Xie, J. Wang, B. Hou, L. Jia, J. Cui and D. Li, *Appl. Catal.*, A, 2018, 572, 51–60.
- 30 R. K. M. R. Kallury, C. Ambidge, T. T. Tidwell, D. G. B. Boocock, F. A. Agblevor and D. J. Stewart, *Carbohydr. Res.*, 1986, 158, 253–261.
- 31 T. M. Aida, Y. Sato, M. Watanabe, K. Tajima, T. Nonaka, H. Hattori and K. Arai, *J. Supercrit. Fluids*, 2007, 40, 381– 388.
- 32 M. Orazov and M. E. Davis, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 11777–11782.

- 33 J. Zhang and E. Weitz, ACS Catal., 2012, 2, 1211-1218.
- 34 D. Zhao, Q. Huo, J. Feng, B. F. Chmelka and G. D. Stucky, J. Am. Chem. Soc., 1998, 120, 6024–6036.
- 35 A. D. Becke, J. Chem. Phys., 1993, 98, 5648-5652.
- 36 W. J. Hehre, R. Ditchfield and J. A. Pople, *J. Chem. Phys.*, 1972, **56**, 2257–2261.
- 37 J. F. Casteel and P. G. Sears, *J. Chem. Eng. Data*, 1974, **19**, 196–200.
- 38 F. Jin and H. Enomoto, *Energy Environ. Sci.*, 2011, 4, 382– 397.
- 39 I. Hahnenstein, H. Hasse, C. G. Kreiter and G. Maurer, *Ind. Eng. Chem. Res.*, 1994, 33, 1022–1029.
- 40 A. S. Amarasekara, L. T. D. Williams and C. C. Ebede, *Carbohydr. Res.*, 2008, **343**, 3021–3024.
- 41 G. Yang, E. A. Pidko and E. J. M. Hensen, *J. Catal.*, 2012, 295, 122–132.
- 42 R. W. Taft, in *Progress in Physical Organic Chemistry*, John Wiley & Sons Ltd., 1983, vol. 14, pp. 247–350.