

Electronic Supplementary Information

Facile Synthesis and Isolation of 5-Hydroxymethylfurfural from Diphenyl Sulfoxide[‡]

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Experimental synthesis and Characterization

Materials

D-Fructose, DPhSO (95%), HMF (99%) and NaOH were purchased from Aladdin Industrial Inc. (Shanghai, China). DMSO and H₂O₂ (30 wt%) were obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). EMImBr, BMImBr, and BMImCl were supplied by Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences. [2-¹³C] fructose was purchased from SHANGHAI ZZBIO CO., LTD. Methanol-d₄ (99.8 atom% D) DMSO-d₆ (99.8 atom% D) and D₂O (99.9 atom% D) were supplied by Ningbo Cuiying Chemical Co.,Ltd.

HMF synthesis and isolation

Dehydration reaction of fructose to HMF in DPhSO was done under various conditions. As a general procedure, fructose and DPhSO were added in a glass bottle (5 mL) with a sealed cap which preheated to the desired temperature (100-160 °C) by means of a temperature regulated oil bath. For the scale-up experiment, an optimal ratio of fructose (1.5 g) and DPhSO (30 g) were added into a 50 mL glass flask equipped with a magnetic stirrer. After reaction, the water (80 °C) with ten times as much as DPhSO was added to extract the HMF, then the solution was oscillated for 30 seconds and cooled down. The extraction solution was filtered and diluted with water and then analyzed by HPLC.

Recycling and regeneration of DPhSO

To test the recyclability of DPhSO in the dehydration reaction, low temperature dried DPhSO was reused directly for the next run under the same procedure mentioned above without removing humins after each run. The refreshing of DPhSO is a simple oxidation in oil bath at 50 °C for 30 min via adding 5 mL of 30 wt% H₂O₂ and 1M NaOH, respectively, then washed with water several times, dried overnight and reused for the dehydration reaction.

Products analysis and characterization

The content of 5-HMF was analyzed on an Agilent 1260 HPLC (UV wavelength: 284 nm; C18 column: 250 mm × 4.6 mm), using 60% methanol in ultrapure water as mobile phase at a flow rate of 1 mL·min⁻¹ at 35 °C. The fructose was analyzed on Bio-Rad Aminex HPX-87H column equipped with refractive index detector (300 mm × 7.8 mm) using a 5 mM H₂SO₄ mobile phase at a flow rate of 0.6 mL·min⁻¹ at 65 °C. For the ESI-MS and NMR experiments, 10 mg of fructose and 200 mg DPhSO were added in bottle and heated at 100 °C for different reaction time. 1 mL of methanol and 0.5 mL of deuterium DMSO were added respectively to dissolve the system for the ESI-MS and NMR

tests. A control experiment for fructose and DPhSO chemicals before reaction were also performed. ESI-MS were recorded on a AB SCIEX TripleTOF 4600 Advantage spectrometer in ESI mode with a spray voltage of 5.5 kV and operated in negative ion mode. The NMR spectra were acquired on a Bruker Avance III 400. NMR spectra were obtained at a base frequency of 150.94 MHz, (rd = 4 s, NS = 2048) for ^{13}C and 600.23 MHz (rd = 2 s, NS = 16) for ^1H . The ^1H NMR of DPhSO were tested with DPhSO dissolved in deuterated methanol.

Computational method

All DFT calculations were performed with the Gaussian 09 program package.¹ All geometries and zero-point energies were calculated at the M062X/6-31g(d) level. The single point energies were calculated at M062X/6-311+g(d,p) and the continuum solvent model (SMD) was also considered. For the reaction step analysis, each transition state structure has a single imaginary frequency. The intrinsic reaction coordinate (IRC) calculations were done to verify the connections between each transition state and corresponding intermediates.^{2, 3} The Gibbs free energy formation (ΔG , Kcal/mol) is relative to the isolated fructose and DPhSO under atmospheric pressure and experimental temperature (1 atm and 120 °C). At the optimized geometry, isotropic shielding constant (σ) of intermediates were calculated at the M062X/cc-pVDZ level and water solvent, and the chemical shift value (δ) was obtained by using tetramethylsilane (TMS) as a computational reference as shown in equation 1⁴:

$$\delta_i = \sigma_{\text{TMS}} - \sigma_i \quad (1)$$

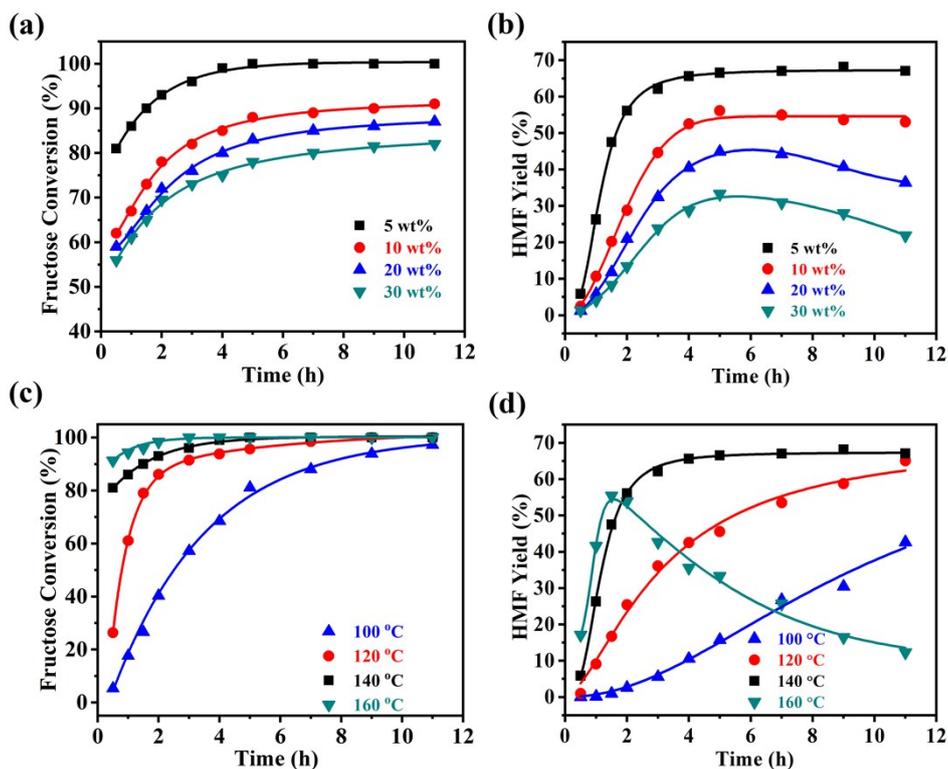


Fig. S1. The effects of fructose concentration on (a) fructose conversion and (b) HMF yield in DPhSO system. Reaction conditions: DPhSO, 1.00 g; reaction temperature, 140 °C. The effects of reaction temperatures on (c) fructose conversion and (d) HMF yield in DPhSO system. Initial conditions: fructose, 0.05 g; DPhSO, 1.0 g.

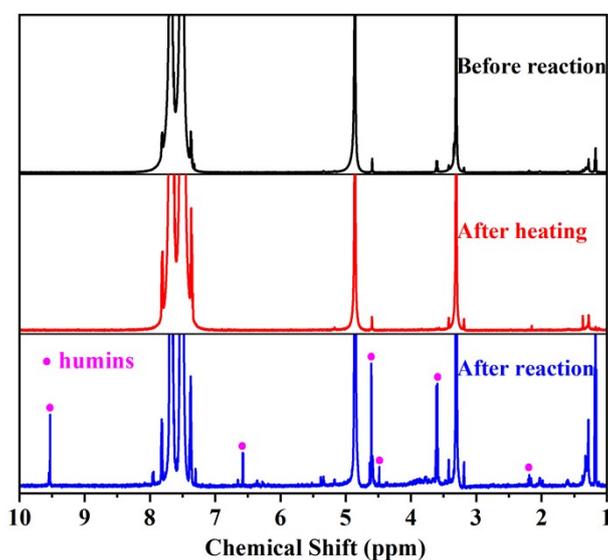


Fig. S2. The magnified ^1H NMR spectra of DPhSO before reaction, after heating (120 °C, 15 h) and after reaction.

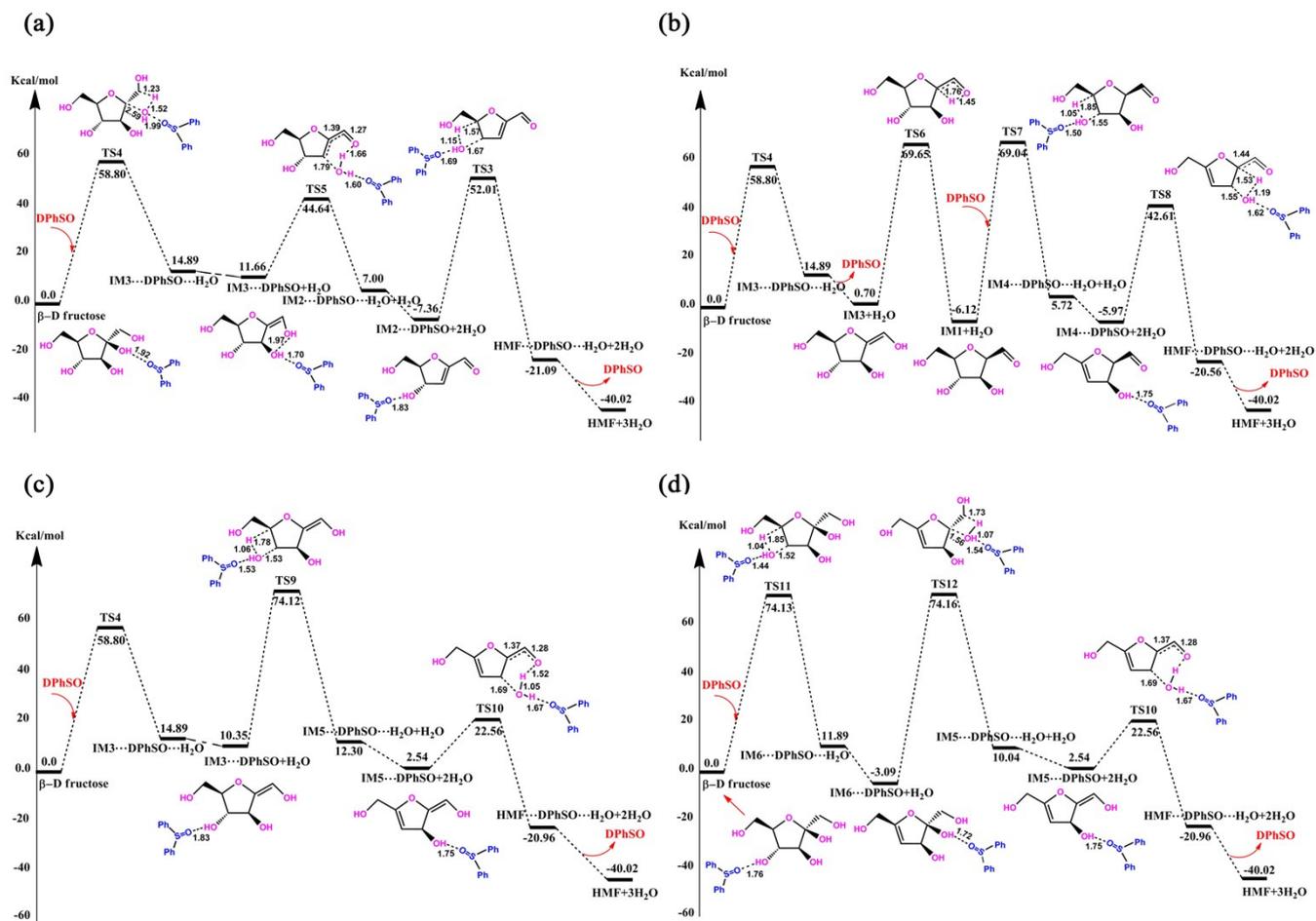


Fig. S3. Geometric structures of the dehydration intermediates and the relative Gibbs free energy changes (Kcal/mol) for the possible pathways of fructose conversion to HMF catalyzed by DPhSO at 120 °C.

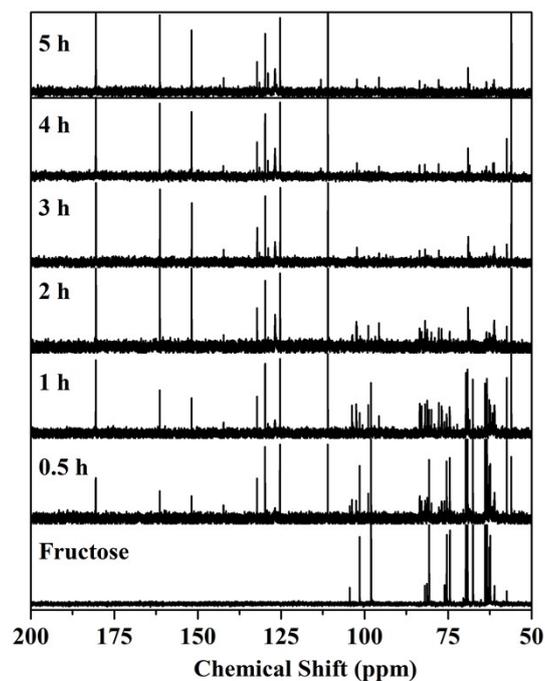


Fig. S4. The unlabeled ^{13}C NMR spectra evolution for reaction of fructose with DPhSO at $120\text{ }^\circ\text{C}$, the solution was extracted by D_2O and the spectra was obtained at room temperature.

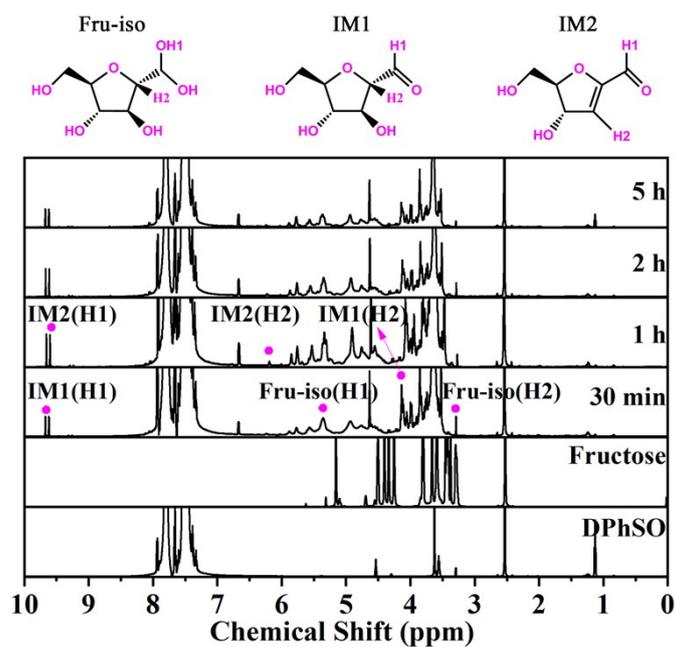


Fig. S5. ^1H NMR spectra for the reaction of fructose with DPhSO at $100\text{ }^\circ\text{C}$, the solution was dissolved in DMSO and the spectra was obtained at room temperature.

Table S1. Conversion of fructose to HMF in various solvents (no catalyst was added).

Solvent	Fructose concentration (wt%)	T (°C)	t (h)	Conversion (%)	Yield (%)
DMSO ⁵	11	120	2	20.0	22.0
DPhSO	10	120	2	65.5	23.5
DMSO ⁶	10	100	1	3.1	1.8
DPhSO	10	100	1	18.7	13.5
BMImCl ⁷	18	100	1	42.0	5.0
BMImI ⁷	18	100	1	96.0	65.0
BMImBr ⁷	18	100	1	99.0	92.0
DPhSO	20	100	1	12.1	6.6
EMImCl ⁸	10	120	3	100	74.0
DPhSO	10	120	3	73.2	26.3

Table S2. Experimental and Calculated Chemical Shifts of ¹H for the Intermediates (Fru-isomer, IM1 and IM2 in Fig. 2a) in DPhSO.

Intermediates	Chemical Shift / ppm	
	DPhSO ^a	DMSO (DFT) ^b
Fru-iso (H1)	5.35	5.27
Fru-iso (H2)	3.28	3.29
IM1(H1)	9.66	9.86
IM1(H2)	4.12	4.15
IM2(H1)	9.61	9.54
IM2(H2)	6.23	6.10

^aThe experimental values of the intermediates from fructose conversion in DPhSO, the cooled solution was dissolved in DMSO and the spectra was determined at room temperature.

^bThe computational values of the intermediates in continuum solvent model (SMD) of DMSO.

Table S3. The comparison of catalytic activity and physical properties for DPhSO and DMSO.

	DPhSO	DMSO
Reaction energy barrier for rate-limiting step (Kcal/mol)	59.37	48.57
Melting point (°C)	69–71	18.5
Boiling point (°C)	206-208	189

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