Supporting Information

Selective hydrogenation of HMF to DHMF with Ru-PNP complexes in ionic liquids

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1. Experimental Section

General Information. Most chemicals were purchased from commercial suppliers and used without further purification unless otherwise stated. HMF, **Ru-1**, **Ru-2, Ru-3** and **Ru-4** are commercially available and used without further purification.

The ionic liquids: EMIM OAc (purity >98%, water (KF) <1%), BMIM OAc (purity >98%, water (KF) <1%), EMIM $MeCO_3$ (purity >97%, 30% in MeOH, water content <7%), EMIM $(EtO)_2PO_2$ (purity >98%, water (KF) <2500 ppm), BMIM BF_4 (purity >99%, water (KF) <250 ppm), EMIM HSO_4 (purity >98%, water (KF) <250 ppm), DMIM MeSO4 (purity >98%, water (KF) <500 ppm) were purchased from Iolitec and used without further purification. H_2 gas ($H_2O \leq 3$ ppm; $O_2 \leq 2$ ppm) was purchased from Air Liquid. EDMIM OAc[1], **Ru-5**[2] and **Ru-6**[3] were synthesised according to the literature. All catalyst syntheses were performed under inert conditions (Schlenk techniques or inert gas glovebox) unless otherwise stated. Deuterated dimethyl sulfoxide (DMSO-d6) for NMR experiments was purchased from Merck.

Nuclear Magnetic Resonance spectroscopy (NMR). NMR spectra were obtained using a Bruker Ascend 400, or 800 MHz spectrometer equipped with BBFO and TCI CryoProbe probes. Chemical shifts are expressed in ppm relative to tetramethylsilane (TMS) for ^1H and ^{13}C spectra using residual solvent signal peaks or TMS as internal reference. For ^{31}P spectra, values are expressed in ppm relative to H_3PO_4. Residual solvent chemical shifts are explained according to literature.[4] Coupling constants, if available, are given in Hz as absolute values. Multiplicities are given as singlets (s), doublets (d), triplets (t), heptets (hept), doublets of a doublet of a doublet (ddd) and multiplets (m). Literature-known compounds were analysed only using ^1H-NMR spectroscopy to confirm purity. NMR spectra were analysed using MestReNova software.

Reactor specifications. The reactor used in this study is a 7-well reactor (Alloy 600, reactor capacity: 483 mL). The pressure gauge is non-electronic and subject to error.

Figure S1. Custom high-pressure reactor used in this study.

General Procedure for Hydrogenation of HMF to DHMF in Ionic Liquids. For a typical hydrogenation screening experiment, the high-pressure reactor was loaded with the Ru-PNP complex (0.1-0-5 mol%), substrate (0.79 mmol) and 2 mL of Ionic Liquids. Subsequently, the reactor was equipped with a magnetic stirring bar and sealed. The system was flushed with argon/hydrogen (three times). Next, a H_2 pressure of 10-30 bar was applied. The reaction mixture was stirred for 1 to 48 hours

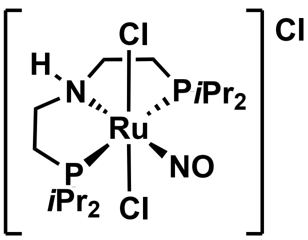
(450 rpm) at the desired temperature. After this time, the reactor was cooled down to room temperature and the gas was released. The crude reaction mixture was then analysed using ^1H-NMR spectroscopy in DMSO to check both the conversion and the NMR yield of the desired product. For NMR analysis, an internal standard, dimethyl sulfone (DMS) (10.0 mg, 0.106 mmol), was added to the reaction mixture. The solution was stirred for 5 min to ensure thorough mixing. A sample was then taken from the mixture for NMR analysis in DMSO. All the experiments were replicated to corroborate the results.

All the experiments were performed twice to corroborate the results.

NMR measurements. Conversions in all reactions were measured by ^1H-NMR spectroscopy at 400 MHz in DMSO at 25 °C. Then, 128 scans were applied for each sample, with a delay between scans of 30 seconds to ensure complete relaxation of the hydrogens. The conversion was calculated using the signals from the CH (6.67 ppm, d) hydrogens of the unreacted substrate HMF and the CH_2 (6.36 ppm, s) hydrogens of DHMF. Errors in the conversion measurements were estimated by comparing the results of at least three integrations of each spectrum.

2. Complexes characterization data

Synthesis and characterization of the complex Ru-5



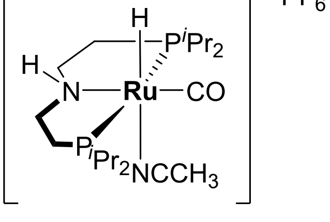
Procedure: Inside the glovebox, a 10 mL vial equipped with a stirring bar was charged with a 10% solution of bis(2-diisopropylphosphinoethyl) amine in THF (251 mg, 0,822 mmol) and an additional amount of THF (aprox. 5 mL). To this solution, $Ru(NO)Cl_3$. H_2O (200 mg, 0,783 mmol) was added in one portion, and the resulting dark violet suspension was stirred overnight, turning into a pinkish suspension. The pink powdery product was filtered off under ambient conditions, washed with acetonitrile until colourless filtrate appeared, followed by washing with Et_2O and dried in air. High quality single crystals were obtained by vapor diffusion of Et_2O into a concentrated ethanolic solution of the compound at room temperature. Pinkish crystals were obtained with 87% yield.

^{1}H NMR (298 K, CD_3OD, 400 MHz, ppm): δ 3.25 (m, NCH_2, 2H), 3.18 (m, NCH_2, 2H), 3.20 (m, iPr-CH, 2H), 3.19 (m, iPr-CH, 2H), 2.74 (m, P-CH_2, 2H), 2.18 (m, P-CH_2, 2H), 1.54 (m, iPr-CH_3, 6H), 1.53 (m, iPr-CH_3, 6H), 1.50 (m, iPr-CH_3, 6H), 1.48 (m, iPr-CH_3, 6H).

^{13}C NMR (298 K, CD_3OD, 101 MHz, ppm): δ 51.5 (t, $^2J(^{13}C\text{-}^{31}P)$ = 2.3 Hz, NCH_2), 25.4 (t, $^1J(^{13}C\text{-}^{31}P)$ = 12.5 Hz, iPr-CH), 24.8 (t, $^1J(^{13}C\text{-}^{31}P)$ = 12.0 Hz, PCH_2), 22.9 (t, $^1J(^{13}C\text{-}^{31}P)$ = 11.4 Hz, iPr-CH), 18.7 (s, iPr-CH_3), 18.2 (s, iPr-CH_3), 17.6 (s, iPr-CH_3), 17.4 (s, iPr-CH_3).

^{31}P NMR (298 K, CD_3OD, 162.01 MHz, ppm): δ 68.0.

Synthesis and characterization of the complex Ru-6.



Procedure: To a suspension of ^{ipr}[Ru-MACHO] **Ru-2** (94 mg, 0.20 mmol, 1 equiv.) in dry and degassed MeCN (3 mL) was added $AgPF_6$ (56 mg, 0.22 mmol, 1.1 equiv.) at room temperature. The reaction was covered from the light and stirred at room temperature for 3 hours. After this time, the silver salts were precipitated in the bottom of the vial. The resulting colourless solution was filtered through a pad of celite and evaporated to dryness under reduced pressure. An off-white powder was isolated in 83% yield.

^{1}H NMR (298 K, C_6D_6, 400 MHz, ppm): δ - 14.61 ppm (*t*, $^3J_{HP}$ = 20 Hz, 1H, Ru-H), -14.88 (*t*, $^3J_{HP}$ = 20 Hz, 1H, Ru-H), 0.80 (m, 3H, $^3J_{HP}$= 16 Hz, $^3J_{HH}$=8.0 Hz, $PCH(CH_3)_2$)), 0.96 (m, 6H, $^3J_{HP}$= 16 Hz, $^3J_{HH}$=8.0 Hz, $PCH(CH_3)_2$), 0.95 (m, 6H,$^3J_{HP}$= 16 Hz, $^3J_{HH}$=8.0 Hz, $PCH(CH_3)_2$), 1.01 (m, 6H, $^3J_{HP}$= 16 Hz, $^3J_{HH}$=8.0

Hz, PCH(CH_3)$_2$), 1.20-1.11 (m, 6H, $^3J_{HP}$= 16 Hz, $^3J_{HH}$=8.0 Hz, PCH(CH_3)$_2$), 1.61 (s, 3H, $CNCH_3$), 2.11 (m, 2H, CH_2P), 2.24 (m, 2H, CH2P), 2.57 (m, 2H,CH_2N), 4.05 (m, 1H, NH).

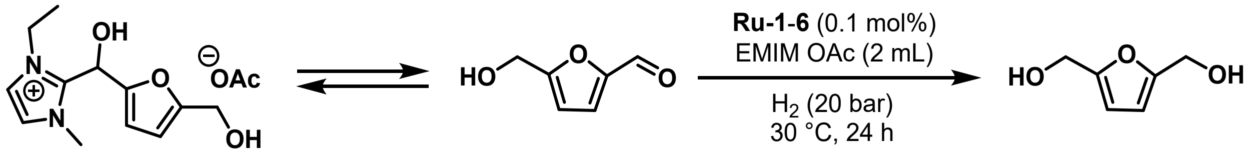
^{13}C NMR (298 K, C_6D_6, 101 MHz, ppm): δ 212.23, 116.01, 54.82, 29.40, 28.67, 25.13, 20.25, 19.94, 18.79, 18.15, 17.78, 2.40.

^{19}F NMR (298 K, C_6D_6, 376.55 MHz, ppm): δ -72.98 (d, J= 706.4 Hz).

^{31}P NMR (298 K, C_6D_6, 162.01 MHz, ppm): δ 73.99 (s), -143.79 (sep).

3. Catalysis results for the hydrogenation of HMF to DHMF

Table S1. Catalyst screening and identification of suitable conditions for the formation of DHMF from HMF in EMIM OAc at 30 °C for 24 h.

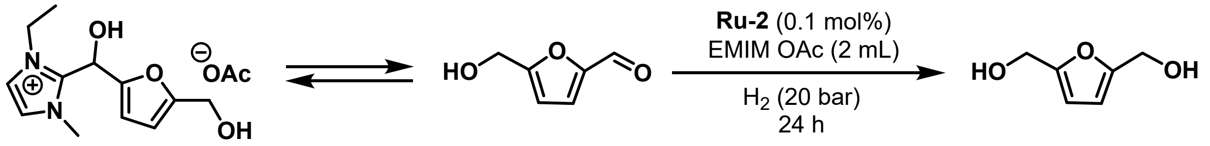


A **HMF** **DHMF**

Entry[a]	Catalyst	Conversion [%][b]	Yield [%][b]
1	**Ru-1**	<5	<5
2	**Ru-2**	69	69
3	**Ru-3**	8	8
4	**Ru-4**	<5	<5
5	**Ru-5**	73	73
6	**Ru-6**	<5	<4

[a] Standard reaction conditions: 0.79 mmol of HMF (100 mg), **Ru 1-6** (0.1 mol%), EMIM OAc (2.0 mL), H_2 (20 bar), 24 h at 30 °C. [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

Table S2. Temperature screening for the formation of DHMF from HMF in EMIM OAc employing **Ru-2** as catalyst.

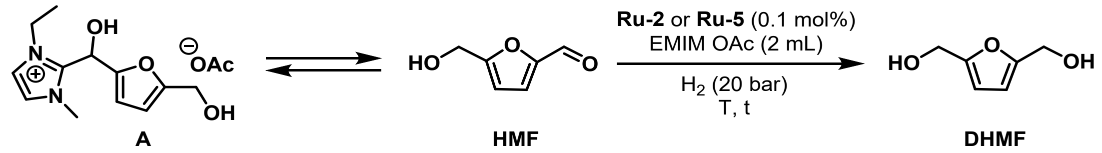


A **HMF** **DHMF**

Entry[a]	Temperature	Conversion [%][b]	Yield [%][b]
1	**100**	92	92
2	**80**	98	98
3	**60**	98	98
4	**40**	60	60
5	**30**	69	69

[a] Standard reaction conditions: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), EMIM OAc (2.0 mL), H_2 (20 bar), 24 h. [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

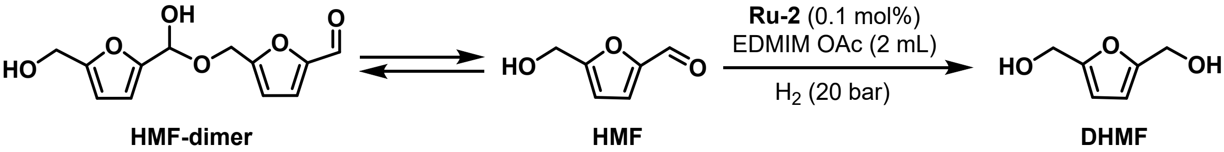
Table S3. Time and temperature screening for the formation of DHMF from HMF in EMIM OAc.



Entry	Catalyst	T (°C)	t (h)	Conversion of HMF (%)[a]	Yield of DHMF (%)[a]
1	**Ru-2**	30	72	93	93
2	**Ru-5**	30	72	74	74
3	**Ru-2**	60	24	98	98
4	**Ru-5**	60	24	98	98
5	**Ru-2**	100	24	92	92
6	**Ru-5**	100	24	98	98
7	**Ru-1**	60	24	77	77
8	**Ru-3**	60	24	72	72
9	**Ru-4**	60	24	<5	<5

Standard reaction conditions: 0.79 mmol of HMF (100 mg), **Ru-2** and **Ru-5** (0.1 mol%), EMIM OAc (2.0 mL), H_2 (20 bar). [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

Table S4. Optimization of the reaction conditions employing EDMIM OAc as IL.



Entry	T (°C)	t (h)	Conversion of HMF (%)[a]	Yield of DHMF (%)[a]
1	60	24	98	98
2	60	3	51	51
3	30	24	28	28

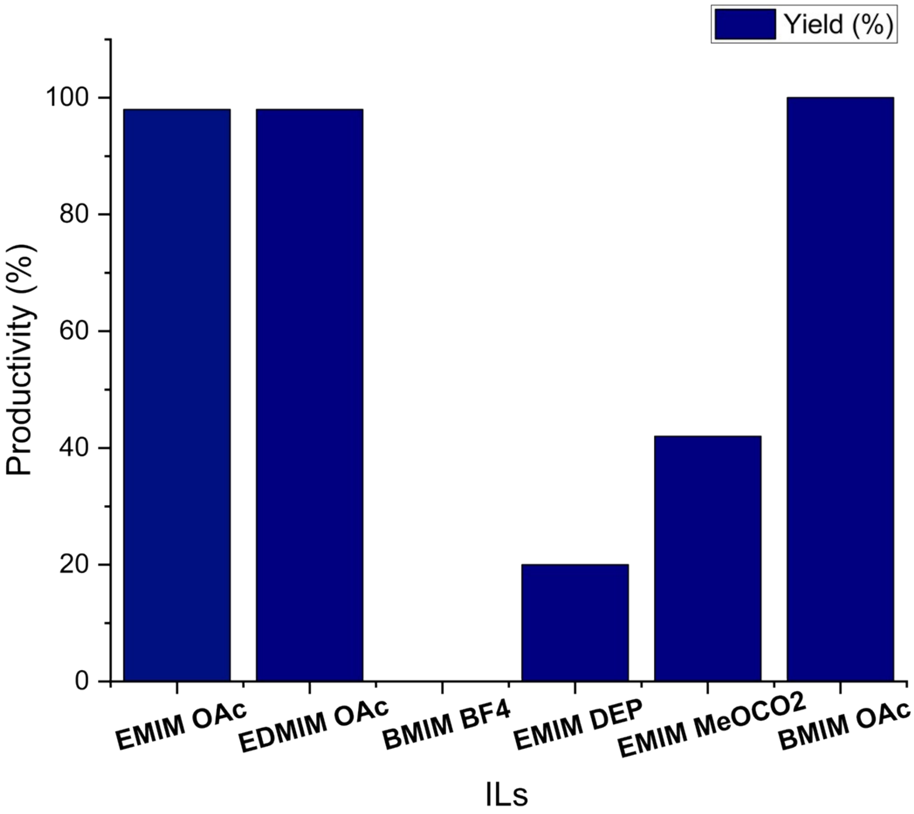
4	30	18	26	26

Standard reaction conditions: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), EDMIM OAc (2.0 mL), H_2 (20 bar). [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

Table S5. Solvents screening for the hydrogenation of HMF to DHMF in ILs.

Entry[a]	Catalyst	IL	Conversion of HMF (%)[b]	Yield of DHMF (%)[b]
1	**Ru-2**	EMIM OAc	98	98
2	**Ru-2**	EDMIM OAc	98	98
3	**Ru-2**	BMIM BF_4	<5	<5
4	**Ru-2**	EMIM DEP	20	20
5	**Ru-2**	EMIM $MeOCO_2$	42	42
6	**Ru-2**	BMIM OAc	>99	>99
7	**Ru-2**	EMIM HSO_4	-	-
8	**Ru-2**	DMIM $MeSO_4$	-	-

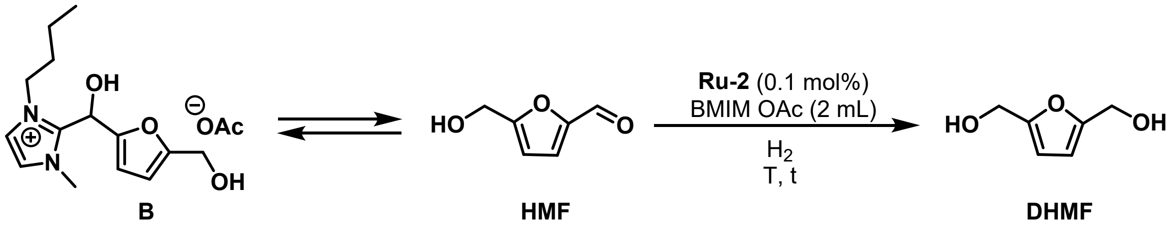
[a] Standard reaction conditions: 0.79 mmol of the HMF (100 mg), **Ru-2** (0.1 mol%), ILs (2.0 mL), H_2 (20 bar), 60 °C, 24h. [a] Conversion and NMR Yield were both determined by crude ^{1}H-NMR. Dimethyl Sulfone was used as internal standard.



[a] Standard reaction conditions: 0.79 mmol of the HMF (100 mg), **Ru-2** (0.1 mol%), ILs (2.0 mL), H_2 (20 bar), 60 °C, 24h. [b] Conversion and NMR Yield were both determined by crude ^{1}H-NMR. Dimethyl Sulfone was used as internal standard.

Figure S2. Solvents screening for the hydrogenation of HMF to DHMF in ILs.

Table S6. Optimization of the reaction conditions employing BMIM OAc as solvent.



Entry	BMIM OAc (mL)	H_2 (bar)	T (°C)	t (h)	Conversion of HMF (%)[a]	Yield of DHMF (%)[a]
1	2.0	20	60	24	>99	>99
2	2.0	20	60	3	>99	>99
3	2.0	20	60	2	65	65
4	2.0	20	60	1	56	56
5	2.0	20	30	24	45	45
6	1.0	20	60	3	>99	>99
7	1.0	20	60	1	45	45
8	0.5	20	60	3	30	30
9	1.0	10	60	3	67	67

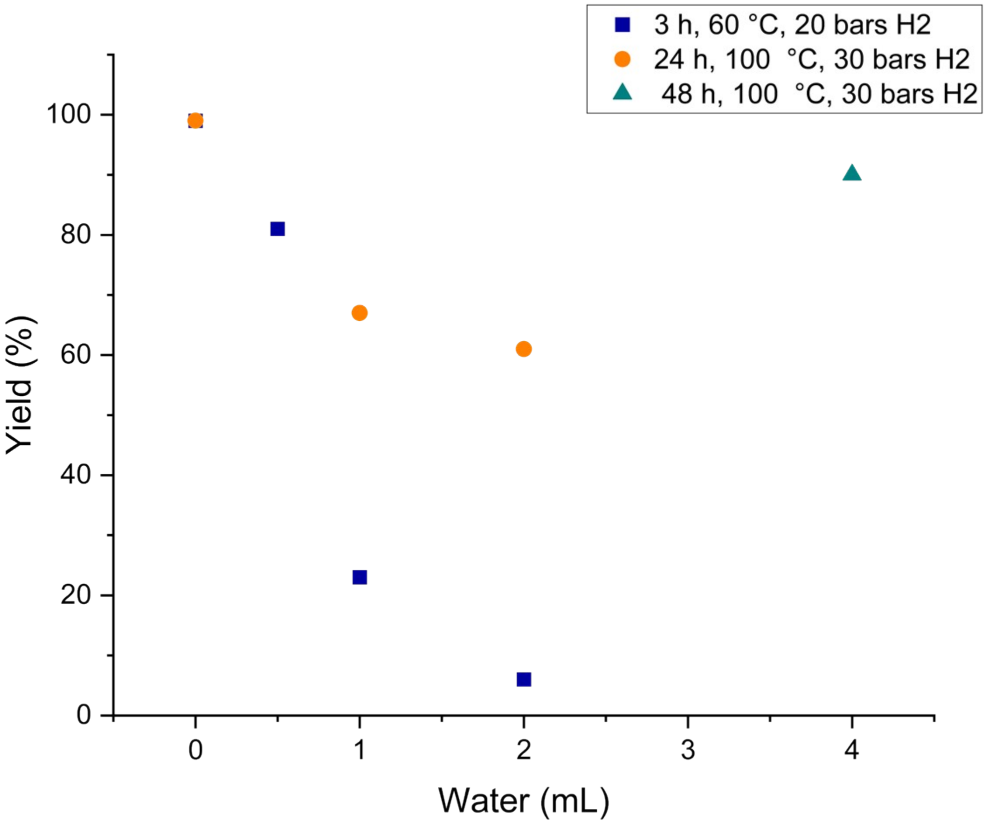
Standard reaction conditions: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc. [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

Table S7. Water amount screening for the hydrogenation of HMF to DHMF in BMIM OAc.

Entry	Water Volume (mL)	T (°C)	t (h)	Conversion of HMF (%)[a]	Yield of DHMF (%)[a]
1[1]	0	60	3	99	99
2[2]	0	100	24	99	99
3[1]	0.5	60	3	81	81
4[1]	2	60	3	14	6
5[1]	1	60	3	23	23
6[2]	1	100	24	67	67

7[2]	2	100	24	61	61
8[3]	4	100	48	90	90

Standard reaction conditions. [1] 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (20 bar), 60 °C, 3 h. [2] 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (30 bar), 100 °C, 24 h. [3] 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (30 bar), 100 °C, 48 h. [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.



Standard reaction conditions. Blue squares: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (20 bar), 60 °C, 3 h. Orange circles: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (30 bar), 100 °C, 24 h. Green triangle: black squares: 0.79 mmol of HMF (100 mg), **Ru-2** (0.1 mol%), BMIM OAc (2.0 mL), H_2 (30 bar), 100 °C, 48 h. [a] Conversion and yield were both determined by crude ^{1}H-NMR. Dimethyl sulfone was used as internal standard.

Figure S3. Water amount screening for the hydrogenation of HMF to DHMF in BMIM OAc.

4. Isolation of DHMF from ILs

Three methods were used to isolate the product from the reaction crude.

Liquid-Liquid Extraction. A 1:4 H_2O:Organic solvent *v:v* mixture was used to extract the product from 2 mL of the reaction mixture in a 50 mL separation funnel. We tested several organic solvents (EtOAc, Et_2O, toluene, *1*-butanol, *1*-heptanol, *tert*-butyl acetate and *i*-propyl acetate). Ethyl acetate as the organic extracting solvent and an additional 4.0 mL of water to the system can extract >99% DHMF from the BMIM OAc.

Direct extraction. In this method, a 1:4 reaction mixture:EtOAc ratio was used directly from the reaction vial. The vial containing the mixture was shaken and the cap was removed and allowed to settle. The organic phase was separated from the ionic liquid using a syringe and the solvent was evaporated on RotaVapor (BÜCHI R-300, Switzerland).

Centrifugation. In this method, a 1:4 reaction mixture:EtOAc *v:v* was used to extract the product. The mixture was shaken and taken into Sigma-2-6E (Germany) centrifuge machine and spun at 3900 rpm for 8 minutes. The organic phase was separated from the ionic liquid using a syringe and the solvent was evaporated on RotaVapor (BÜCHI R-300, Switzerland).

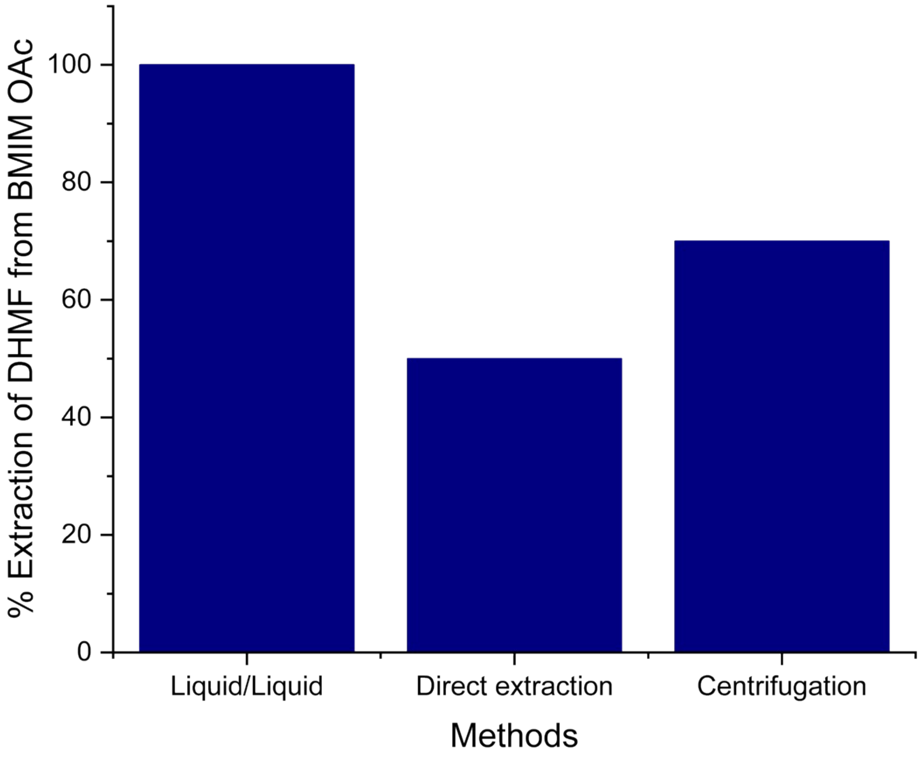


Figure S4. Percentage extraction of DHMF from IL using EtOAc as extracting organic solvent. Comparison between the three different isolation methods.

5. Representative NMR spectra

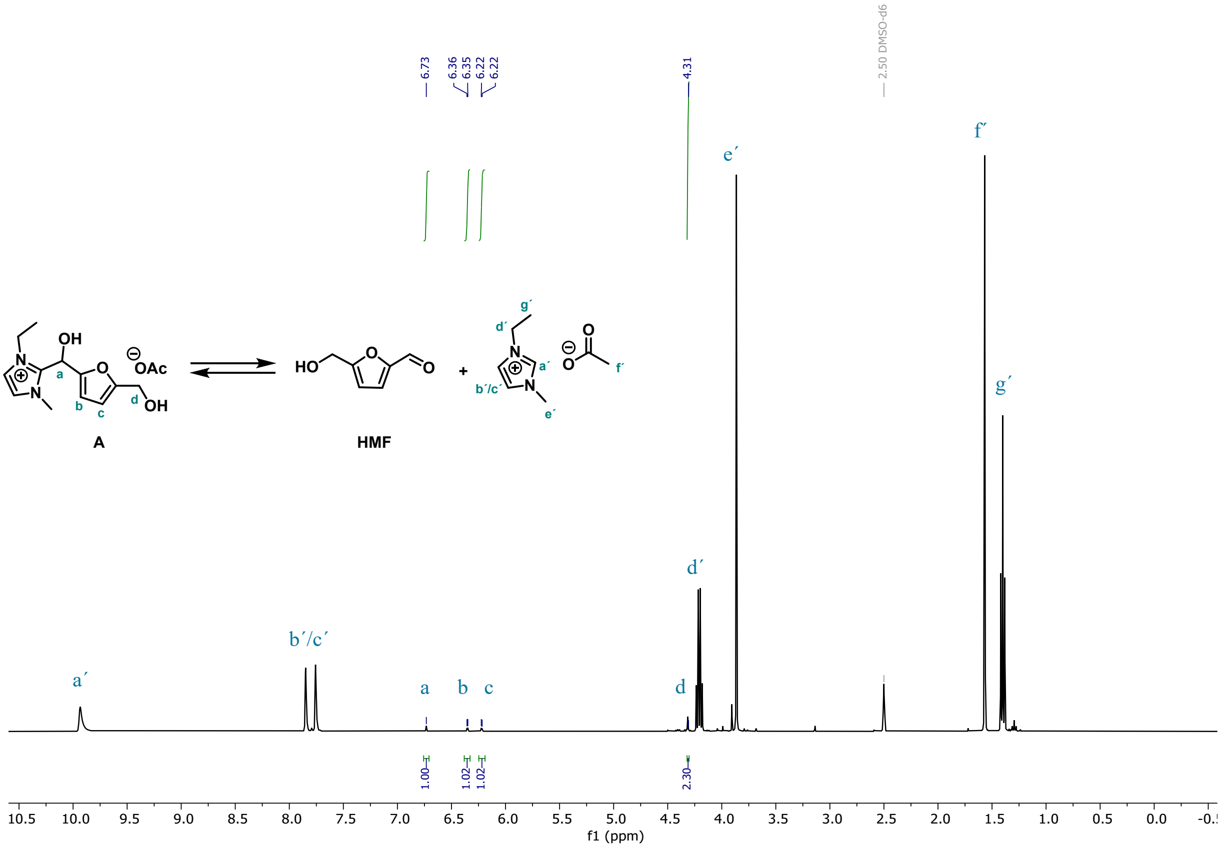


Figure S5. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the mixture of HMF in EMIM OAc at 30 °C after 1 h.

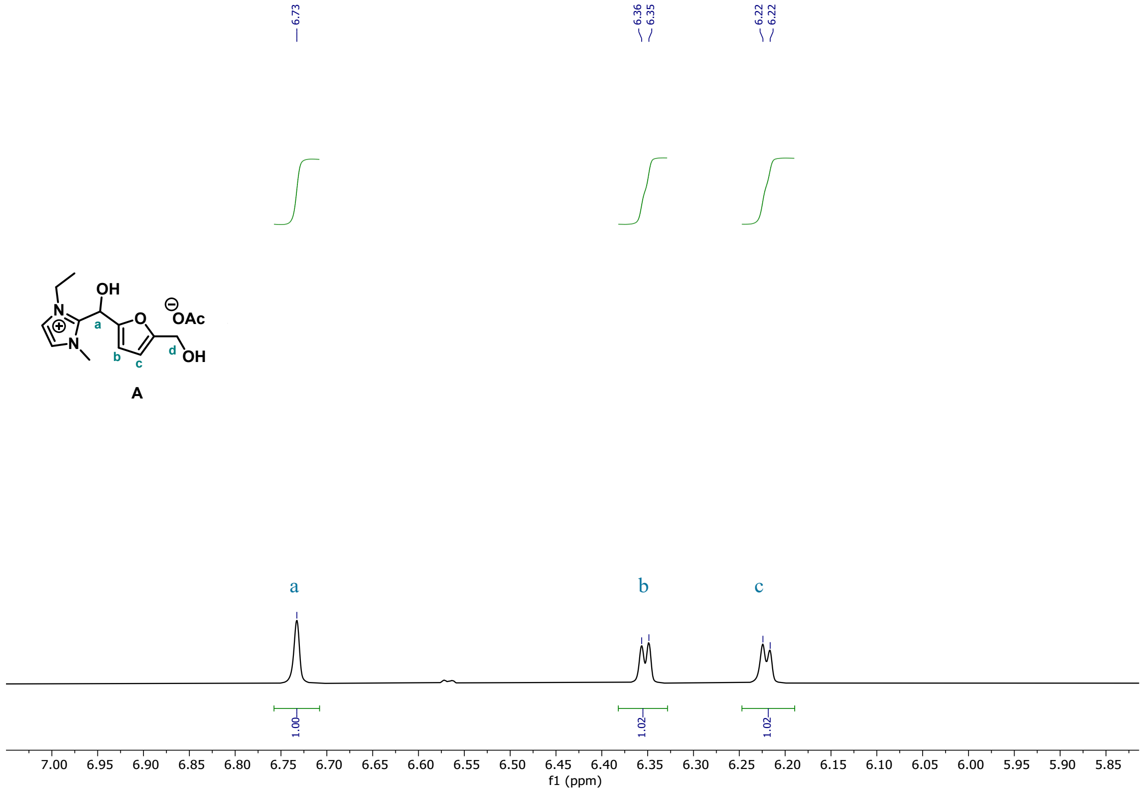


Figure S6. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the mixture of HMF in EMIM OAc at 30 °C after 1 h. Zoom in of the diagnostic peaks.

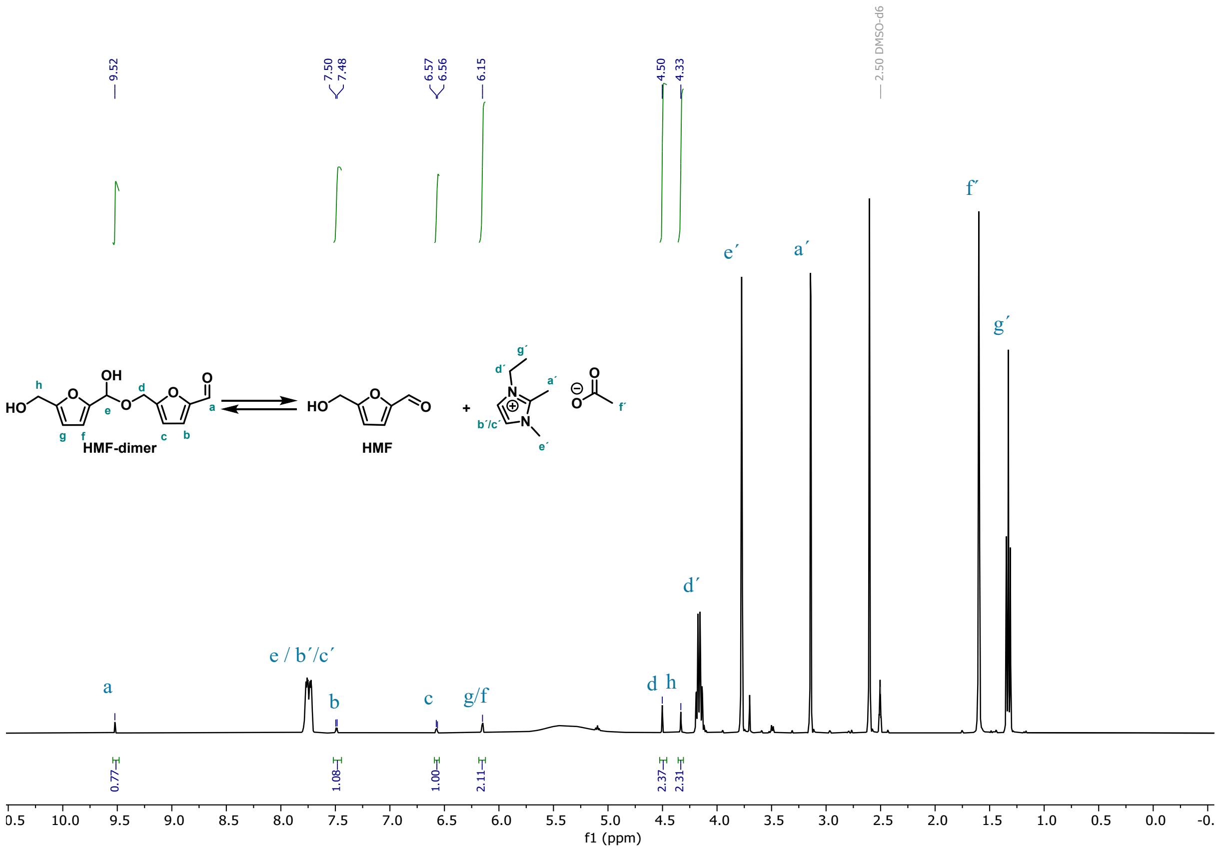


Figure S7. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the mixture of HMF in EDMIM OAc at 30 °C after 1 h.

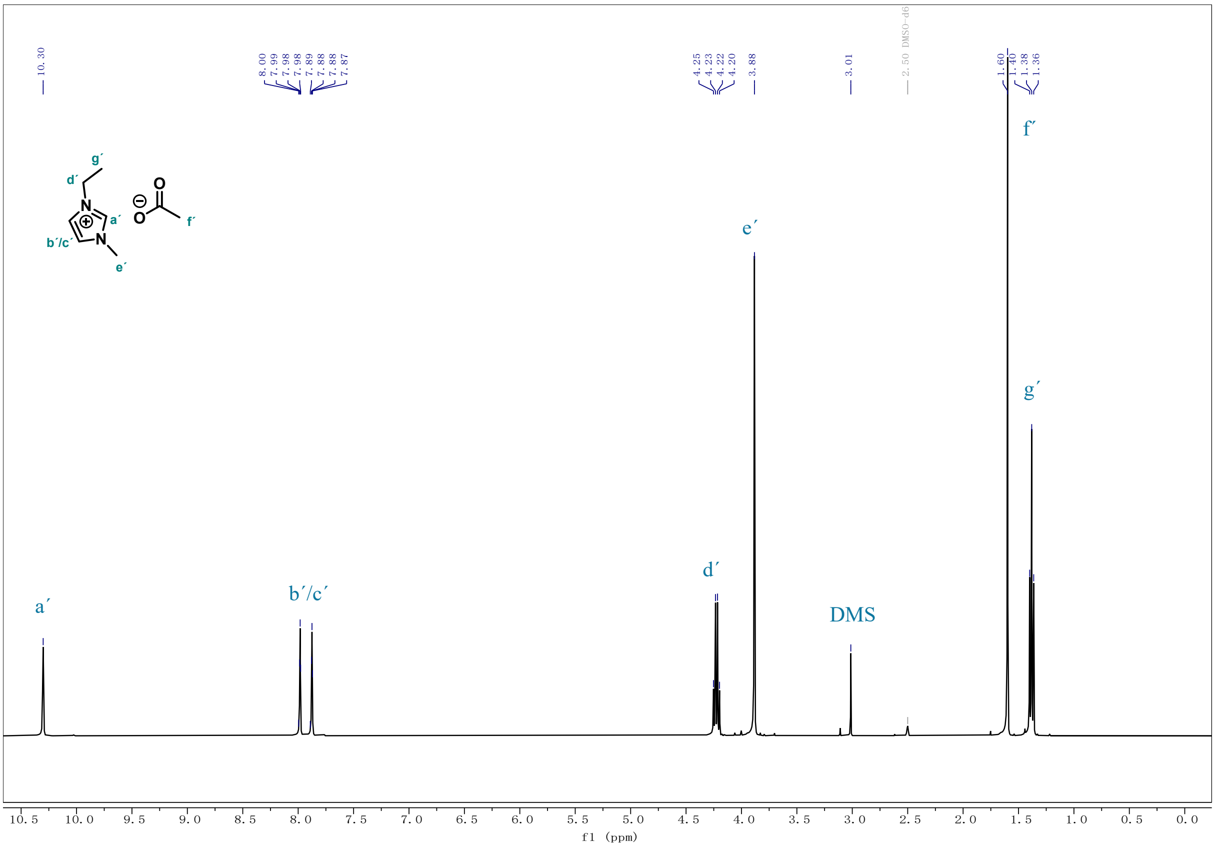


Figure S8. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the mixture of the internal standard (dimethyl sulphone, DMS) in EMIM OAc at 30 °C.

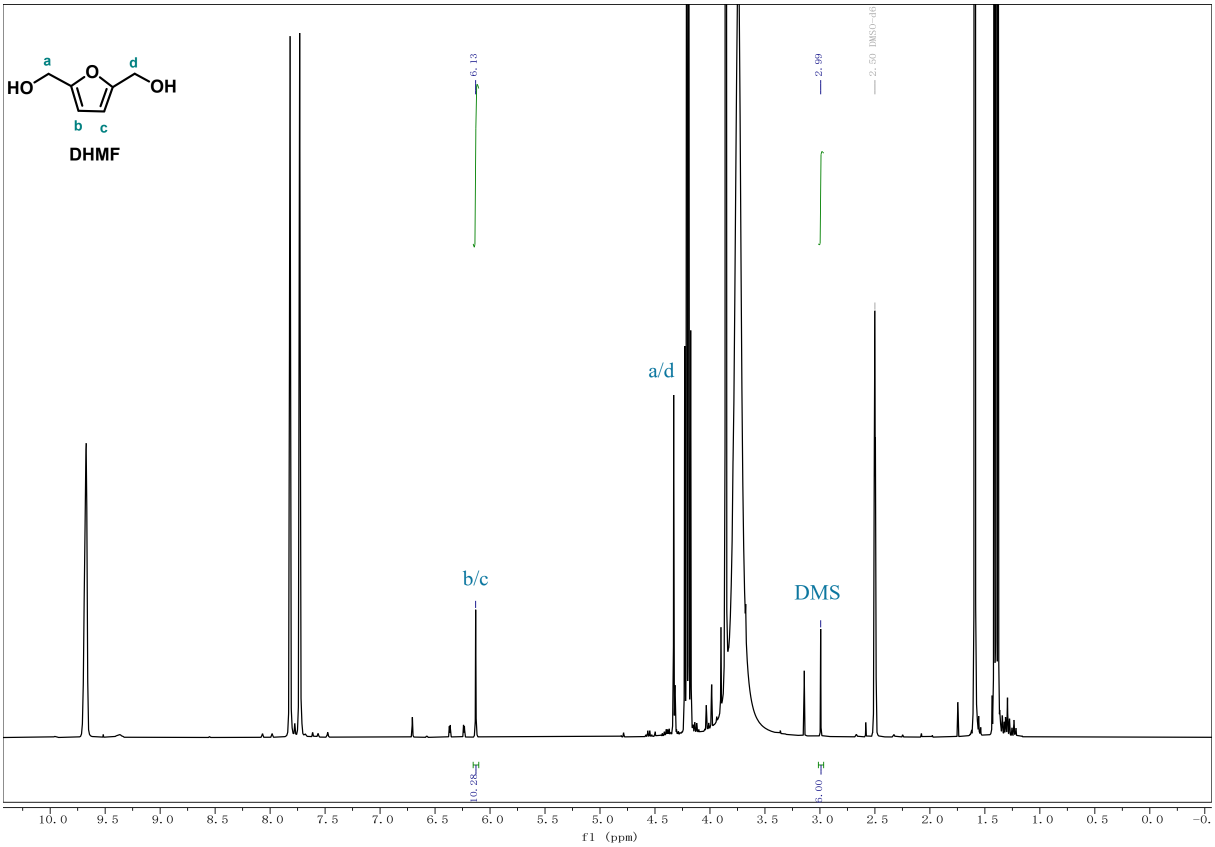


Figure S9. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with **Ru-2** (0.1 mol%), H_2 (20 bar), EMIM OAc (2 mL) at 30 °C after 24 h (conversion= 69 %, yield= 69 % Table S1, entry 2).

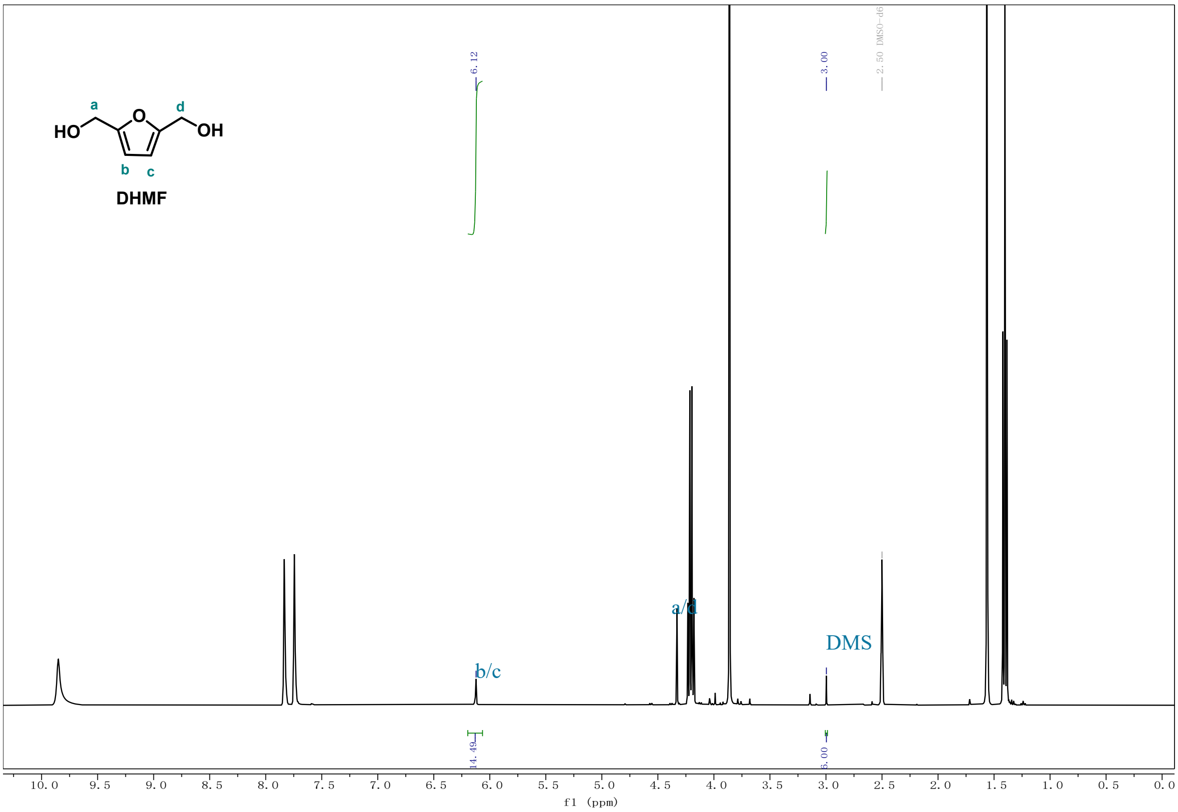


Figure S10. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with **Ru-2** (0.1 mol%), H_2 (20 bar), EMIM OAc (2 mL) at 60 °C after 24 h (conversion= 98 %, yield= 98 % Table S2, entry 3).

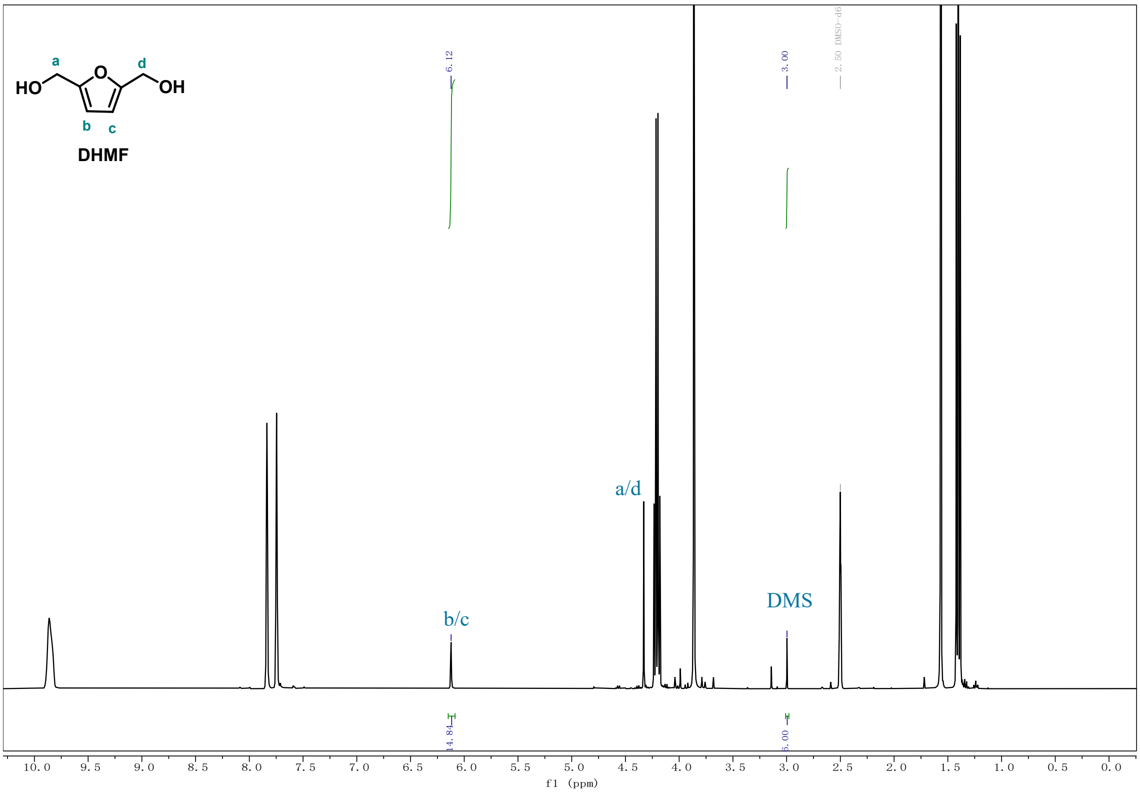


Figure S11. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with **Ru-5** (0.1 mol%), H_2 (20 bar), EMIM OAc (2 mL) at 60 °C after 24 h (conversion= 98 %, yield= 98 % Table S2, entry 4).

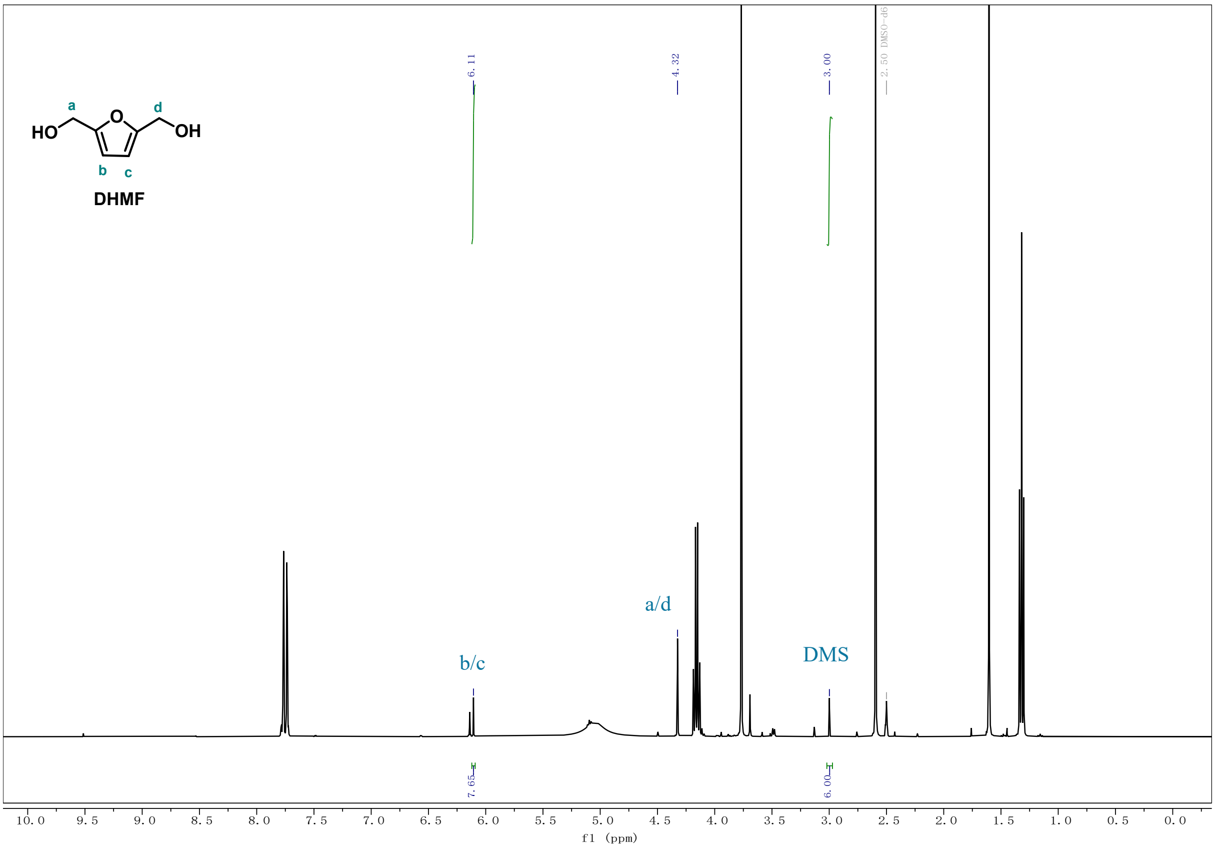


Figure S12. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with Ru-2 (0.1 mol%), H_2 (20 bar), EDMIM OAc (2 mL) at 60 °C after 3 h (conversion= 51 %, yield= 51 % Table S3, entry 2).

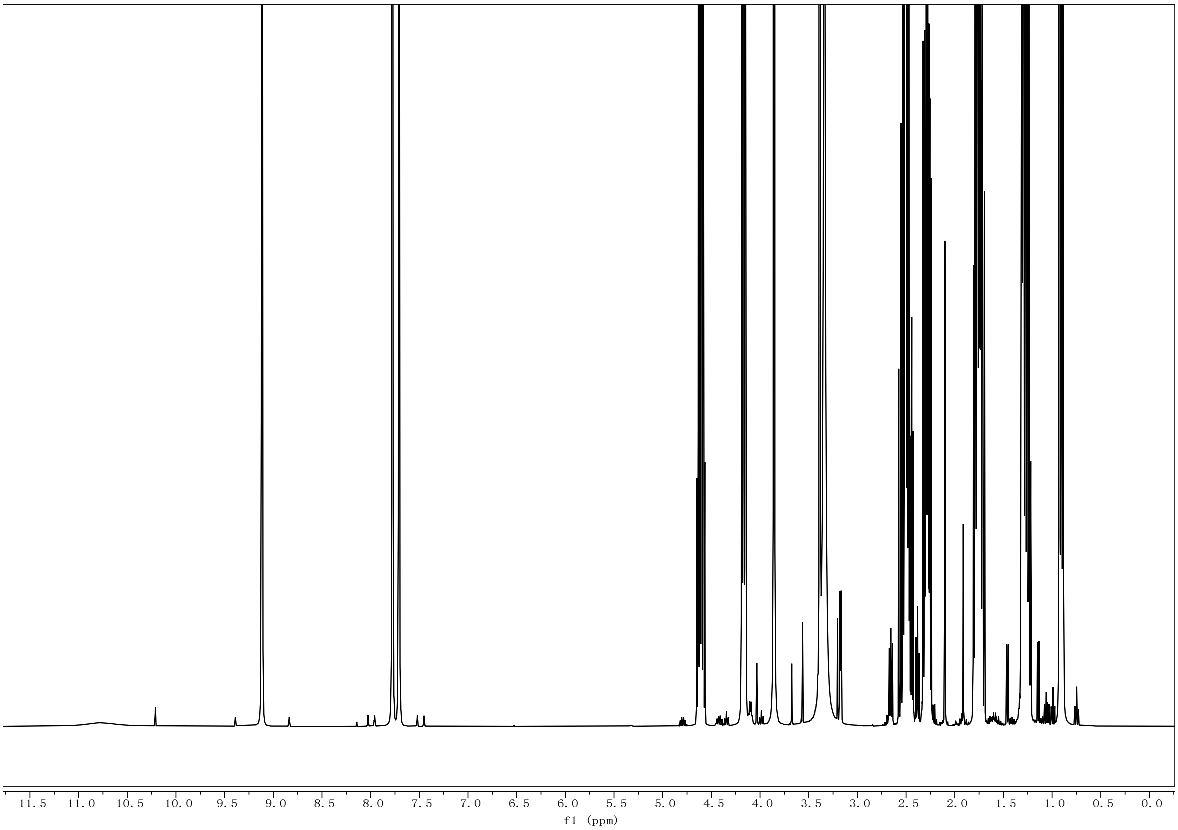


Figure S13. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with Ru-2 (0.1 mol%), H_2 (20 bar), EMIM HSO_4 (2 mL) at 60 °C after 24 h (Table S4, entry 7).

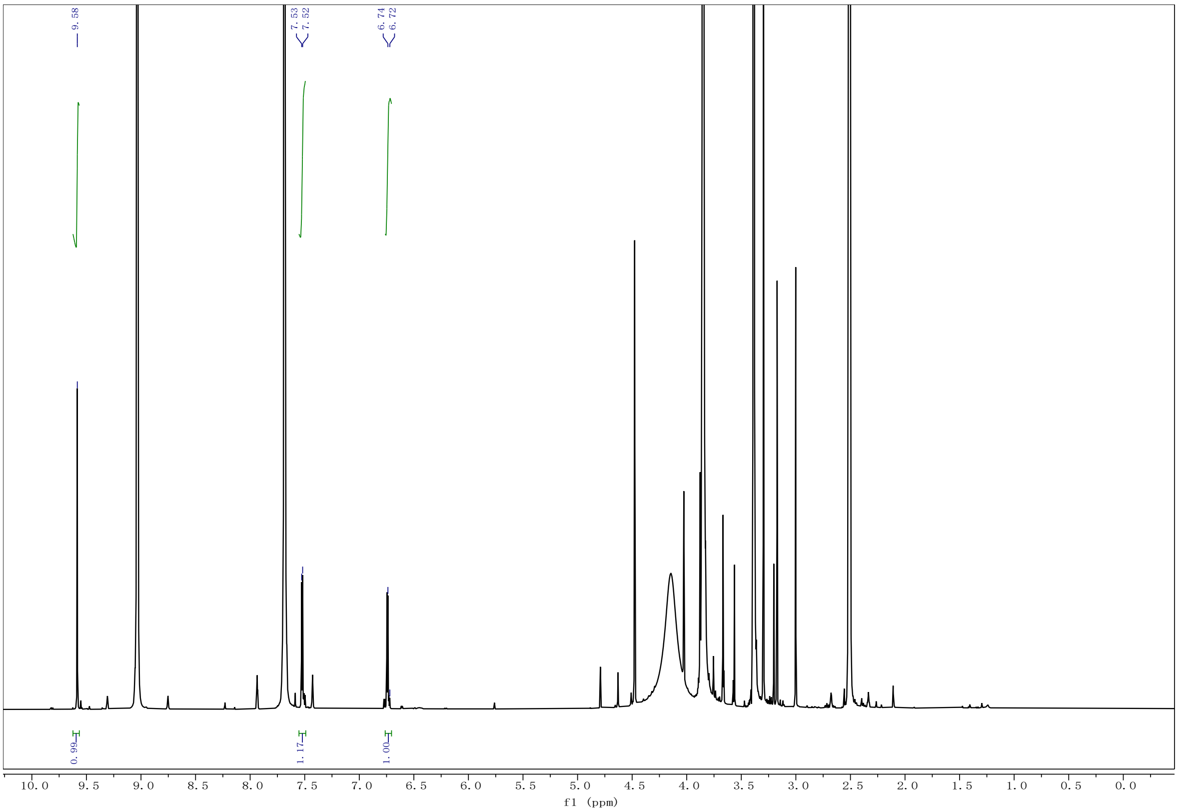


Figure S14. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with Ru-2 (0.1 mol%), H_2 (20 bar), DMIM $MeSO_4$ (2 mL) at 60 °C after 24 h (Table S4, entry 8).

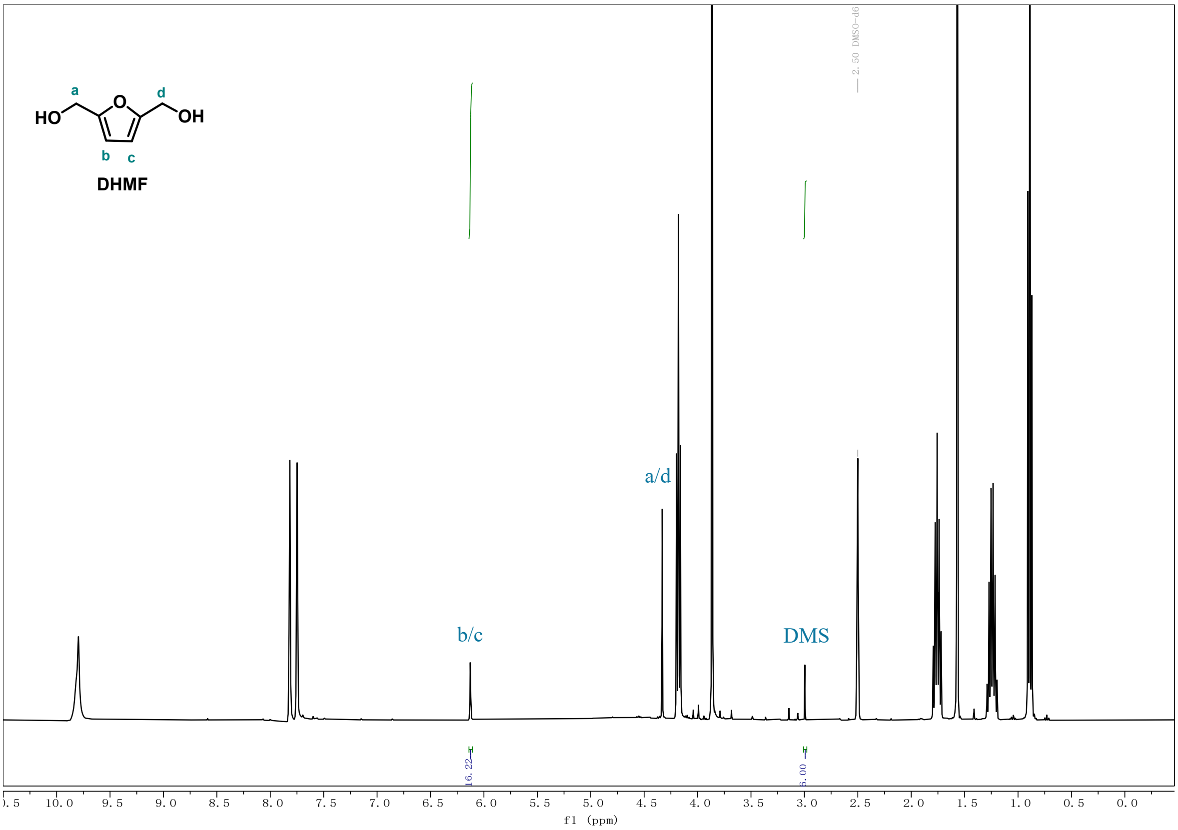


Figure S15. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with Ru-2 (0.1 mol%), H_2 (20 bar), BMIM (1 mL) at 60 °C after 3 h (conversion= >99 %, yield= >99 % Table S5, entry 6).

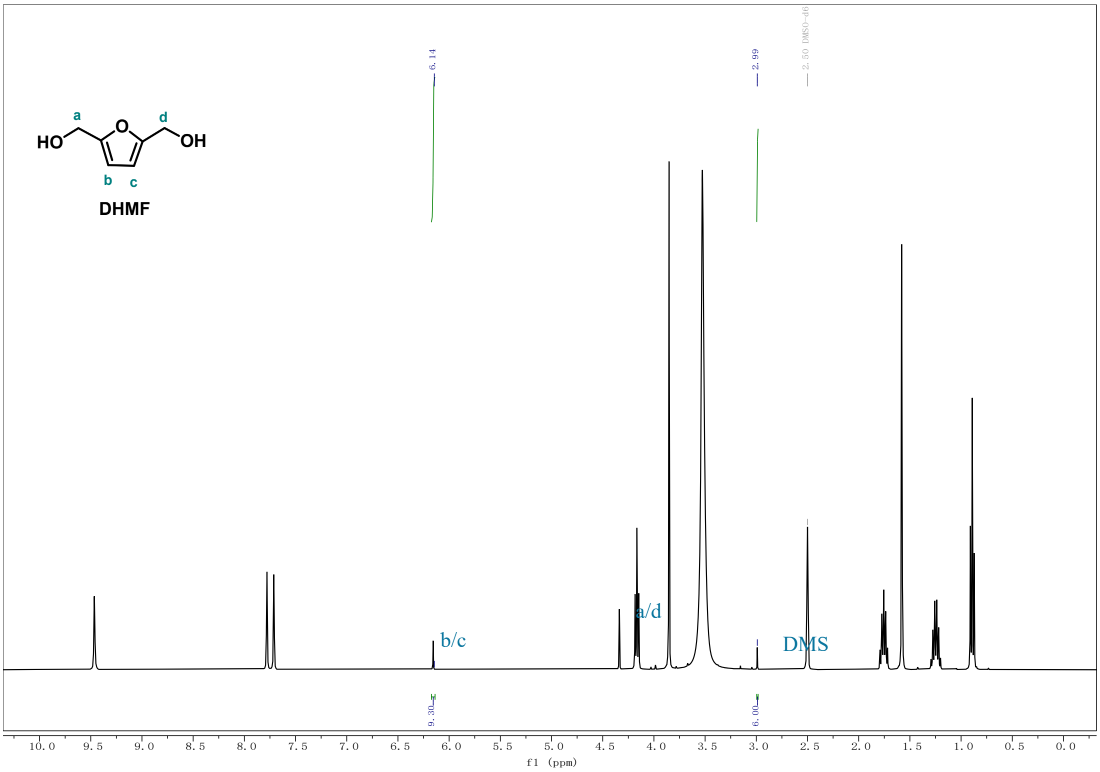


Figure S16. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the crude reaction of HMF with Ru-2 (0.1 mol%), H_2 (20 bar), BMIM (1 mL), H2O (2 mL) at 100 °C after 24 h (conversion= >99 %, yield= 61 % Table S6, entry 7).

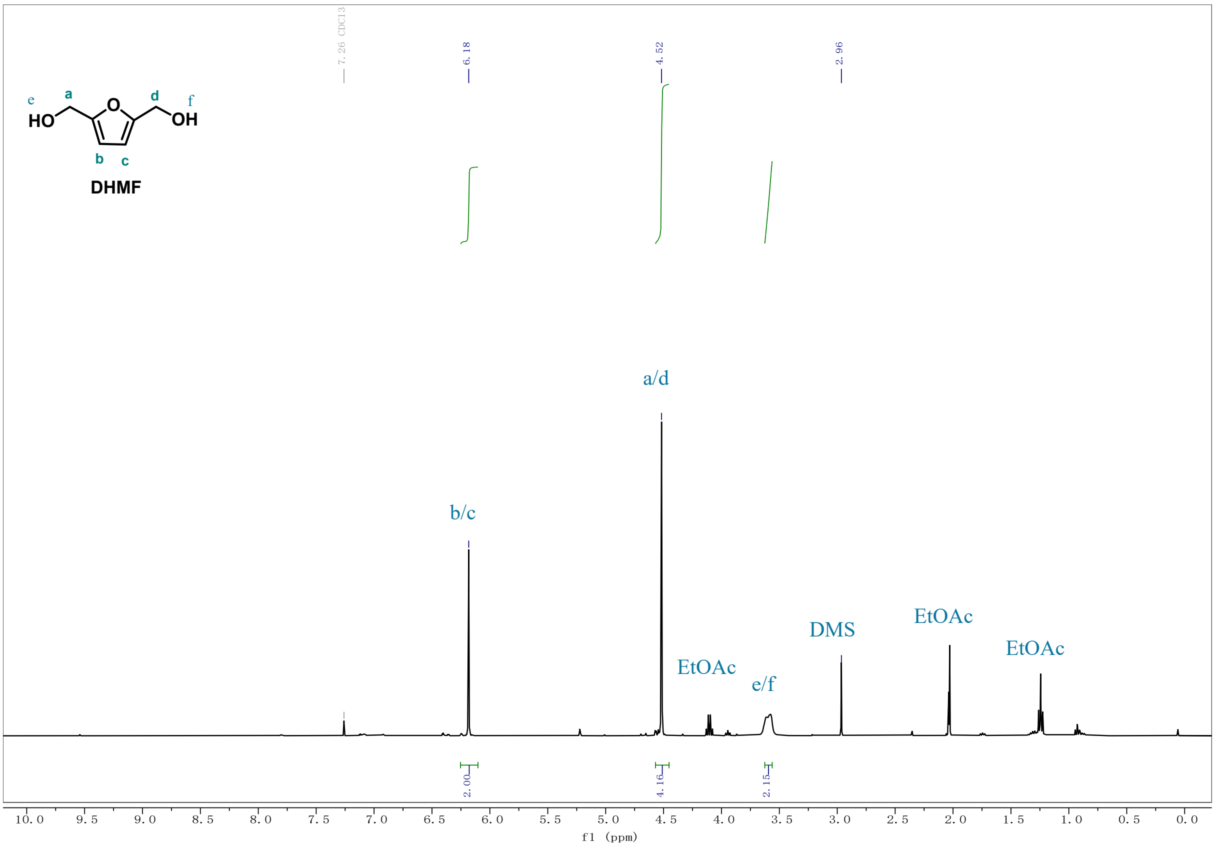


Figure S17. ^{1}H-NMR (DMSO, 400 MHz, 25 °C) of the isolated DHMF from BMIM OAc after liquid/liquid extraction with EtOAc as extracting organic solvent.

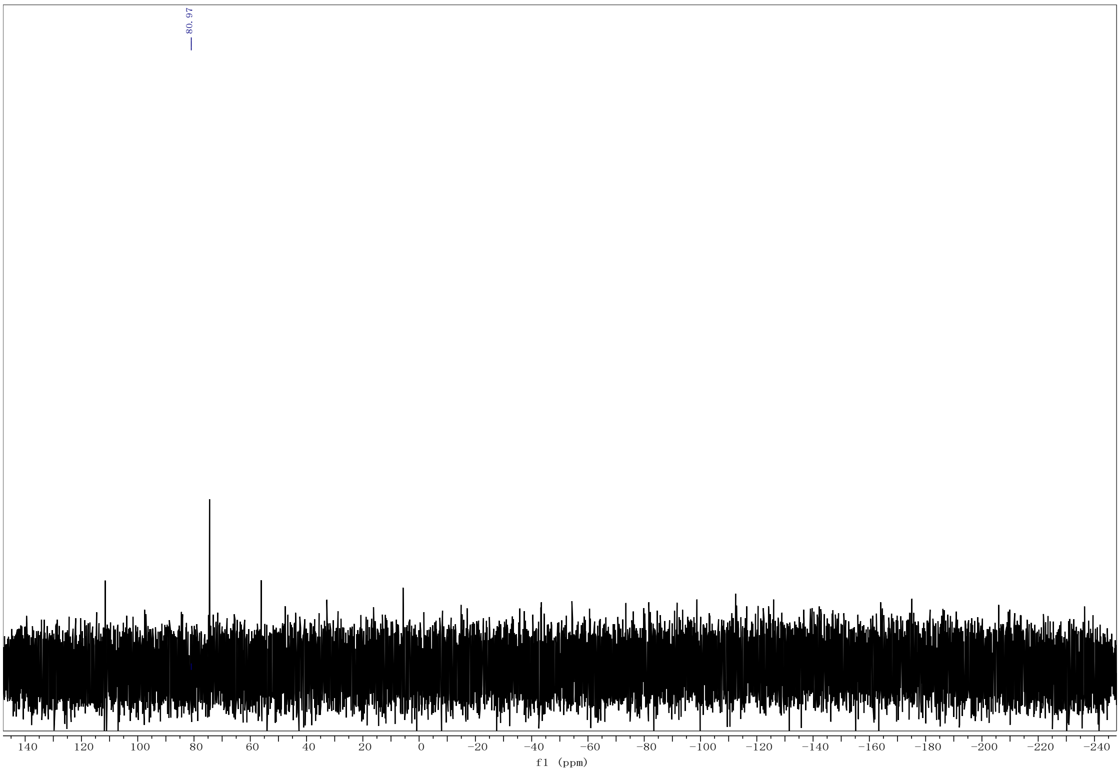


Figure S18. ^{31}P-NMR (DMSO, 400 MHz, 25 °C) of the organic phase after liquid/liquid extraction with EtOAc as extracting organic solvent.

6. References

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