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Full Paper

One-pot production of 2,5-dimethylfuran from fructose over Ru/C and Lewis-Brönsted acid mixture in N,N-dimethyl-formamide

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An efficient catalysis system composed of Lewis-Brönsted acid mixture and Ru/C by using N,N-dimethylformamide as a solvent was developed for the one-pot conversion of fructose to 2,5-dimethylfuran (2,5-DMF) via the dehydration/hydrogenolysis sequence. The effects of various reaction parameters, such as solvent, catalyst type, catalyst loading, reaction pressure, temperature and time on the single fructose dehydration, 5-hydroxymethylfurfural (5-HMF) hydrogenolysis and the one-pot conversion of fructose to 2,5-DMF were systematically investigated. The results showed that 2,5-DMF could be successfully produced with a yield as high as 66.3 mol% by a one-pot method directly from fructose at the optimized reaction conditions, which is by far the highest yield ever reported for production of 2,5-DMF from fructose through a one-pot strategy. Ru/C catalyst could be reused at least three times with slight decrease in 2,5-DMF yield.

Introduction

2,5-Dimethylfuran (2,5-DMF) is regarded as one of the most promising renewable biofuels.[1-8] Compared with traditional bio-derived ethanol, 2,5-DMF possesses a higher boiling point (92–94 °C vs. 78.4 °C) , higher research octane number (119 vs. 111), higher energy density (31.5 $\mathrm{kJ\cdot cm^{-3}}$ vs. 23 $\mathrm{kJ\cdot cm^{-3}}$) and is easier to blend with gasoline. It also has a lower latent heat of vaporization (0.30 $\mathrm{kJ\cdot cm^{-3}}$ vs. 0.71 $\mathrm{kJ\cdot cm^{-3}}$), which means lower energy consumption during purification through distillation.[1-4, 9-12]

The main strategy for 2,5-DMF production is the hydrogenolysis of biomass based platform chemical 5-hydroxymethylfurfural (5-HMF) in the presence of a metal-based catalyst, which was first developed by Dumesic et al.[13] in 2007, who hydrogenated 5-HMF over CuRu/C catalyst in 1-butanol to obtain 2,5-DMF with 76 mol%–79 mol% yield at 0.68 MPa of H_2 and 220 °C for 10 h. Hu et al.[12] achieved a much higher 2,5-DMF yield of 94.7 mol% by replacing the solvent with tetrahydrofuran (THF) and using commercial Ru/C catalyst. A similar yield (93.4 mol%) was obtained by Zu et al.,[14] who optimized Co_3O_4 as a support for Ru catalyst. Saha et al.[10] recently determined that Pd/C modified with zinc could achieve 2,5-DMF yield as high as 85 mol% under 150 °C and 0.8 MPa of H_2 in THF. Wang et al.[15] fabricated PtCo bimetallic nanoparticles in hollow carbon spheres and obtained the highest 98 mol% yield of 2,5-DMF ever reported. Although ionic liquid, which acts as both a solvent and a catalyst, was very effective for carbohydrates dehydration to 5-HMF,[16-21] it failed to catalyze 5-HMF hydrogenolysis and a 2,5-DMF yield of only less than 20 mol% was obtained.[10, 22] A process called transfer hydrogenation, which uses small organic molecules instead of pressurized H_2 as a hydrogen source, has been developed to avoid pressurized H_2 depletion. For example, Thananatthanachon and Rauchfuss[23] obtained a 2,5-DMF yield of up to 95 mol% at 70 °C for 15 h by using formic acid as both an acid catalyst and hydrogen source over Pd/C catalyst. Jae et al.[7] determined that isopropanol was also an effective hydrogen source for the transfer hydrogenolysis of 5-HMF over Ru/C. However, this method seems neither green nor economical.[7, 23]

Considering the efficiency of biomass resource transformation, scientists have focused more on carbohydrates than on 5-HMF as a starting material for 2,5-DMF production, because the former is more easily available, up-streaming, and inexpensive. In general, carbohydrate conversion to 2,5-DMF requires two steps. In the first step, carbohydrates are dehydrated to 5-HMF in the presence of a Lewis or Brönsted acid;[17, 24-29] in the second step, 5-HMF is converted into 2,5-DMF through hydrogenolysis over a metal catalyst.[30, 31]

Although the aforementioned strategies can achieve 2,5-DMF from 5-HMF with considerably high yields, the difficulty in 5-HMF purification from the dehydration products of carbohydrates[13, 17, 32-34] casts a shadow on these processes. Unfortunately, when carbohydrates are used as starting feedstocks based on the aforementioned hydrogenolysis catalysts, the selectivity toward 2,5-DMF becomes very poor. For example, Dumesic[13] and Binder[1] initially developed a two-

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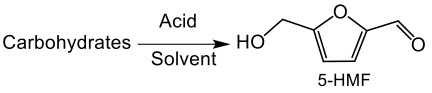
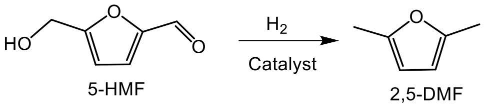
Table 1 Recent progress on the two-step process for the production of 2,5-DMF from carbohydrates.

Step 1 of the two-step process: dehydration



Step 2 of the two-step process: hydrogenolysis



Catalyst	Substrate	Solvent	Con. of carbohydr. (mol%)	5-HMF yield (mol%)	Catalyst	Solvent	T (°C)	P (MPa)	t (h)	Con. of 5-HMF (mol%)	2,5-DMF yield (mol%)	Ref
HCl	Fructose	1-Butanol	88	72	CuRu/C	1-Butanol	220	0.68	-	100	71	13
$CrCl_3$	Corn	DMA+[EMIM]Cl	-	-	CuRu/C	1-Butanol	220	0.68	10	-	49	1
12-MPA	Glucose	[EMIMCl]+CH_3CN	98	97	Pd/C	[EMIM]Cl	120	6.2	1	47	32	22
$HCOOH+H_2SO_4$	Fructose	DMSO	100	93	Pd/C	THF	70	-	15	-	>95	23
HCOOH	Fructose	HCOOH	-	-	Ru/C+H_2SO_4	THF	75	-	1	-	32	2
$[DMA]^+[CH_3SO_3]^-$	Cellulose	DMA/LiCl	-	-	Ru/C+H_2SO_4	THF	150	-	1		16	2
SO_4^{2-}/ZrO_2-TiO_2	Glucose	n-Butanol	96.5	26.0	Ru/C	n-Butanol	260	-	1	99.8	60.3	3
SO_4^{2-}/ZrO_2-TiO_2	Glucose	[BMIM]Cl	-	82.5	Ru/C	THF	200	2	2	-	92.7	35
SO_4^{2-}/ZrO_2-TiO_2	Glucose	[BMIM]Cl	-	47.4	Ru/C	THF	200	2	2	-	88.1	
SO_4^{2-}/ZrO_2-TiO_2	Sucrose	[BMIM]Cl	-	63.2	Ru/C	THF	200	2	2	-	90.4	
SO_4^{2-}/ZrO_2-TiO_2	Maltose	[BMIM]Cl	-	46.8	Ru/C	THF	200	2	2	-	87.3	
SO_4^{2-}/ZrO_2-TiO_2	Cellobiose	[BMIM]Cl	-	45.1	Ru/C	THF	200	2	2	-	86.2	
SO_4^{2-}/ZrO_2-TiO_2	Starch	[BMIM]Cl	-	43.9	Ru/C	THF	200	2	2	-	84.6	
C-SO_3H	Fructose	THF	-	81	Ru/Co_3O_4	THF	150	1	24	-	75.1	14
C-SO_3H		-	-	-	$ZnCl_2$-Pd/C	THF	150	0.8	8		85	10
C-SO_3H	Fructose	-	-	-	$ZnCl_2$-Pd/C	THF	150	0.8	8		22[a]	
Amberlyst-15	Fructose	1-Butanol+H_2O	96	93	Ru–Sn/ZnO	1-Butanol	180-240	0.1-1	0.2 h^{-1}	100	99	3

DMA: dimethylamine; MPA: 3-mercaptopropionic acid; DMSO: dimethyl sulfoxide; THF: tetrahydrofuran; [EMIM]Cl: 1-ethyl-3-methylimidazolium chloride; [BMIM]Cl: 1-butyl-3-methylimidazolium chloride.

[a] One-pot production of 2,5-DMF from fructose.

step process to obtain 2,5-DMF from untreated corn stover. In the first step, $CrCl_3$ was used as a catalyst to dehydrate cellulose to 5-HMF in a mixture of HCl, N,N-dimethylacetylamine and LiCl, followed by hydrogenolysis of 5-HMF over a Cu-Ru catalyst. A final2,5-DMF yield of only 9 mol% was obtained. Hu et al.[35] and Zu et al.[14] claimed that Ru/C and Ru/Co_3O_4 catalysts led to very high 2,5-DMF yields of 75.1 mol% and 92.7 mol% from fructose, respectively. However, they also followed a two-step method, in which separation of 5-HMF from the dehydration products of fructose was performed prior to hydrogenolysis step. Very recently, Upare et al.[32] successfully produced 2,5-DMF in 92% overall yield from fructose in 1-butanol through a combination of dehydration over Amberlyst-15 and hydrogenolysis over the Ru–Sn/ZnO catalyst. They also followed a two-step process, in which 5-HMF was separated in the dehydration step. Dutta and Mascal[36] reported the use of 5-chloromethylfurfural, which could be easily separated from cellulosic biomass dehydration products, as a feedstock for 2,5-DMF production under mild conditions and predicted that an overall 2,5-DMF yield of up to 65 mol% could be obtained from carbohydrates. In Saha’s work,[10] one-pot production of 2,5-DMF from fructose by using $ZnCl_2$–Pd/C as a catalyst only achieved 22 mol% yield. By contrast, high 2,5-DMF yields (71-85 mol%) were achieved when 5-HMF was used as a substrate. A summary of the available literatures describing the production of 2,5-DMF from carbohydrates is provided in Table 1.

As reported, In all the two-step process, purification of 5-HMF is inevitable and the overall yield of 2,5-DMF from carbohydrates is unsatisfactory. We recently developed an effective method to synthesize 5-HMF from fructose in the presence of a Lewis-Brönsted acid mixture in N,N-dimethylformamide.[27] In order to simplify the reaction steps and avoid the complex purification process for 5-HMF, in the present article, we therefore attempt to develop a one-pot process for producing 2,5-DMF from fructose with a high yield.

Results and Discussion

Determination of a suitable solvent for 2,5-DMF production

Combination of fructose dehydration and 5-HMF hydrogenolysis to achieve 2,5-DMF by a one-pot process requires a suitable solvent which is beneficial to both the steps. Different solvents were evaluated for the individual dehydration and hydrogenolysis steps, and the results are shown in Table 2. It can be seen that the effects of the solvents on the two steps were significantly different. For example, in the case of ionic liquid 1-methyl-3-butyl imidazolium chloride ([BMIM]Cl) as the solvent, fructose could be almost completely dehydrated (entry 1), and the highest 5-HMF yield of 58.5 mol% was achieved within 30 min under the reaction conditions used. However, for the 5-HMF Hydrogenolysis step, a 2,5-DMF yield.

Table 2 Dehydration of fructose and hydrogenolysis of 5-HMF in various solvents

Solvent	Fructose to 5-HMF				5-HMF to 2,5-DMF		
	Entry	Fru./Sol. (g/ml)	Fru. Conversion (mol%)	5-HMF yield (mol%)	Entry	5-HMF conversion (mol%)	2,5-DMF yield (mol%)
[BMIM]Cl	1	0.05/2	>99	58.5	6	30.0	9.0
1,4-Dioxane[a]	2	1/100	88	26.6	7	76.7	N.D.[b]
DMSO	3	5/100	>99	48.3	8	99.2	75.3
N,N-dimethylformamide	4	5/100	>99	44.3	9	100	73.8
THF[b]	5	0.15/100	>99	N.D.[c]	10	100	90.1
Methanol		-	-	-	11	97.4	44.2
Ethanol		-	-	-	12	96.8	38.0
Isopropanol		-	-	-	13	100	13.8
1-Butanol		-	-	-	14	87.3	47.6

Reaction conditions for fructose dehydration: catalyst, 26.9 mol% of $AlCl_3$ (based on fructose); temperature, 120 °C; reaction time, 30 min. Reaction conditions for hydrogenolysis of 5-HMF: 5-HMF, 1 g; solvent, 60 ml; catalyst, 0.2 g of Ru/C (5 wt%); temperature, 220 °C; H_2 pressure, 0.7 MPa; reaction time, 3 h; agitation speed, 600 rpm.

[a] Reaction was conducted at 101 °C; [b] Reaction was conducted at 66 °C. [c] N.D. denotes not being detected.

Table 3 Catalytic performance of different commercially available catalysts for the hydrogenolysis of 5-HMF to 2,5-DMF.

Entry	catalyst	5-HMF conversion (mol%)	2,5-DMF yield (mol%)
15	Raney Co	100	22.2
16	Raney Ni	76.9	9.2
17	5 wt% Pt/C	100	10.5
18	5 wt% Ir/C	92.0	13.5
19	5 wt% Pd/C	28.9	16.3
20	5 wt% Ru/C	100	73.8
21	5 wt% Rh/C	82.0	16.8

Reaction conditions: 5-HMF, 1 g; N,N-dimethylformamide , 60 ml; catalyst, 0.2 g; temperature, 220 °C; H_2 pressure, 0.7 MPa; reaction time, 3 h; agitation speed, 600 rpm.

only 9.0 mol% (entry 6) was obtained in the presence of the same ionic liquid, which was similar to that reported by Chidambaram and Bell.[22] THF was considered as a favourable solvent for 5-HMF hydrogenolysis to 2,5-DMF.[10, 14, 23, 24, 35] A 2,5-DMF yield as high as 90.1 mol% (entry 10) was obtained in THF within our experiment range. However, it was infeasible for fructose dehydration because that the solubility of fructose in THF is rather low (0.15 g/100 g) and the solvent is unstable in acidic atmospheres.[37] Thus, 5-HMF product was not detected in the fructose dehydration step (entry 5) when THF was used as a solvent. For the same reasons, C1-C4 alcohols were not ideal solvent candidates for the integration of dehydration and hydrogenolysis processes (entries 11-14). Moreover, when alcohols were used as solvents, 5-HMF tended to form dihydroxymethylfuran or be deep hydrogenated to 2,5-dimethyltetrahydrofuran.[38] As seen in Table 2, when N,N-dimethylformamide was used as the solvent, satisfactory 5-HMF yield in the fructose dehydration step (44.3 mol%, entry 4) and 2,5-DMF yield in the 5-HMF hydrogenolysis step (73.8 mol%, entry 9) were achieved. Similar results were obtained in the case of dimethyl sulfoxide (DMSO) (48.3 mol% in entry 3 and 75.3 mol% in entry 8), indicating polar aprotic solvents like THF, N,N-dimethylformamide and DMSO having lone pair electrons may be beneficial to the formation of 2,5-DMF. However, DMSO is one of the sulphur compounds, which can partially poison and deactivate the Ru/C catalyst used in the hydrogenolysis step by chemisorption on the catalyst surface[39]. Moreover, even trace amounts of DMSO in the products can introduce an unpleasant smell that is difficult to remove.[27] Therefore, we selected N,N-dimethylformamide as the appropriate solvent for the one-pot conversion of fructose to 2,5-DMF in the following research.

To our surprise, when 1,4-dioxane was used as solvent for hydrogenlysis of 5-HMF, the yield of 2,5-DMF was almost not detectable, which is rather different from the highest yield of 2,5-DMF obtained in THF, although these two solvents have very similar molecular structure. Actually, this phenomenon has already been observed,[40, 41] in which 5-HMF could be swithcably synthesized to different products more than 2,5-DMF in the presence of 1,4-dioxane at different catalytic systems.

Determination of suitable metal catalyst for 5-HMF hydrogenolysis step

Although several metal catalysts, including Ni, Co, Cu, Pd, Pt, Rh, Ru, and Au, have been applied to 5-HMF hydrogenolysis in the presence of various solvents, such as THF, toluene, 1,4-dioxane, ionic liquids, and water (as shown in Table 1), no results about N,N-dimethylformamide as a single solvent for this reaction have been reported. We therefore tested the performance of several commercially available metal catalysts for 5-HMF hydrogenolysis in the presence of N,N-dimethylformamide, as shown in Table 3. Among all of the catalysts tested, Ru/C showed the highest catalytic performance, achieving a 5-HMF conversion of 100 mol% and a 2,5-DMF yield of 73.8 mol% (entry 6 in Table 3). Raney Co and Ni catalysts achieved good 5-HMF conversion, but their selectivities toward 2,5-DMF were only 22.2 mol% and 9.2 mol% (entries 15 and 16 in Table 3), respectively. Other noble metal catalysts unexpectedly gave unsatisfactory 5-HMF conversion and 2,5-DMF yields. Therefore, we selected Ru/C as the hydrogenolysis catalyst for subsequ-ent experiments.

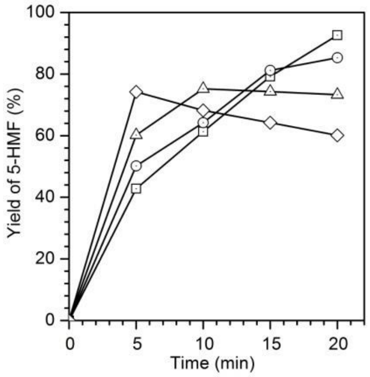


Fig. 1 Effect of reaction temperature on the production of 5-HMF from fructose over Lewis-Brönsted acids. *Reaction conditions*: fructose, 5 g; N,N-dimethylformamide, 60 ml; catalyst, the mole ratio of $AlCl_3$: H_2SO_4: H_3PO_4 =1:2.7:4; reaction time, 20 min; agitation speed, 600 rpm. □ 120 °C, ○ 150 °C, △ 180 °C and ◇ 220 °C.

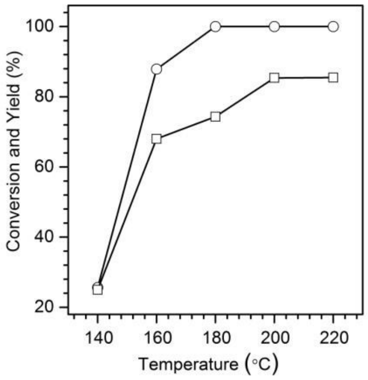


Fig. 2 Effect of reaction temperature on the production of 2,5-DMF from 5-HMF over 5 wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; catalyst, 0.2 g; H_2 pressure, 0.7 MPa; reaction time, 12 h; agitation speed, 600 rpm. ○ conversion and □ yield.

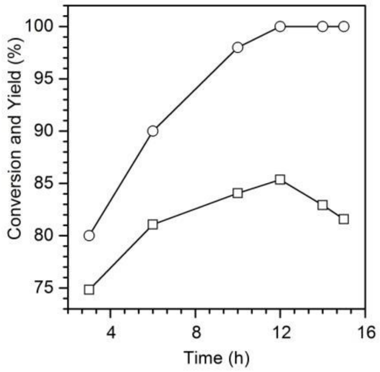


Fig. 3 Effect of reaction time on the production of 2,5-DMF from 5-HMF over 5 wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; catalyst, 0.2 g; H_2 pressure, 0.7 MPa; temperature, 200 °C; agitation speed, 600 rpm. ○ conversion and □ yield.

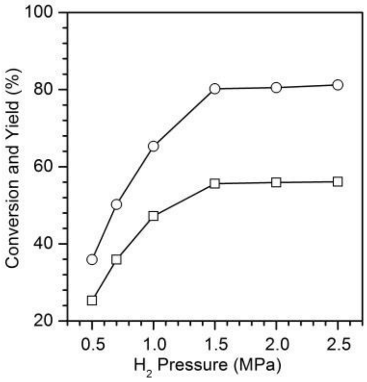


Fig. 4 Effect of H_2 pressure on the production of 2,5-DMF from 5-HMF over 5 wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; catalyst, 0.2 g; temperature, 180 °C; reaction time, 3 h; agitation speed, 600 rpm. ○ conversion and □ yield.

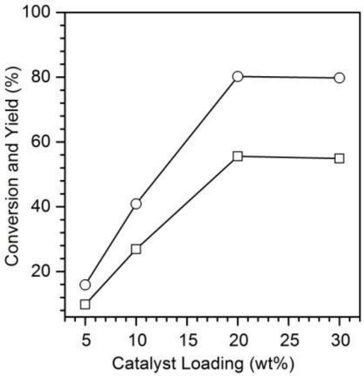


Fig. 5 Effect of Ru/C catalyst loading on the production of 2,5-DMF from 5-HMF over 5 wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; temperature, 180 °C; H_2 pressure, 1.5 MPa; reaction time, 3 h; agitation speed, 600 rpm. ○ conversion and □ yield.

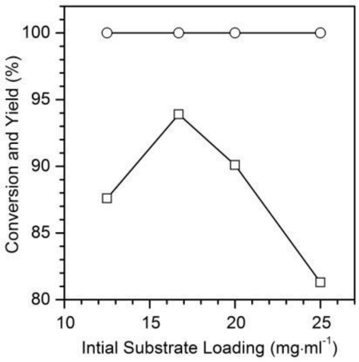


Fig 6 Effect of initial substrate concentration on the production of 2,5-DMF from 5-HMF over 5 wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; catalyst, 0.2 g; temperature, 200 °C; H_2 pressure, 1.5 MPa; reaction time, 12 h; agitation speed, 600 rpm. ○ conversion and □ yield.

Optimization of reaction conditions for single dehydration and hydrogenolysis step

Fructose dehydration in the presence of N,N-dimethylformamide has previously been studied by using a mixture of Lewis-Brönsted acids as the catalyst, in which a maximum 92.6 mol% yield of 5-HMF with a nearly 100% conversion of fructose could be achieved at 120 °C within 20 min when the mole ratio of $AlCl_3$, H_2SO_4 and H_3PO_4 was 1:2.7:4.[27] Here, we further studied the effect of reaction temperatures ranging from 120 °C to 220 °C on 5-HMF yield in order to adapt the followed hydrogenolysis step. As shown in Figure 1, the reaction rates increased with temperature, while the time needed to achieve the maximum 5-HMF yield decreased from 5 min at 220 °C to 20 min at 120 °C. However, the maximum yield of 5-HMF tended to decrease by ca. 20 mol% over the temperature increased.

Hydrogenolysis of 5-HMF over Ru/C was further optimized by varying several reaction parameters, such as reaction temperature, time, hydrogen pressure, catalyst loading, and initial substrate concentration. The reaction temperature was tested in the range of 140 °C to 220 °C. As shown in Figure 2, 5-HMF conversion increasing with temperature, although 2,5-DMF yield first increased sharply from 140 °C to 160 °C and then gradually increased when the reaction temperature was higher than 180 °C. Conversion of 5-HMF reached 100 mol% at 180 °C, and the corresponding 2,5-DMF yield was 74.3 mol%. At 200 °C, 2,5-DMF yield plateaued, and further increasing reaction temperature led to slight declines in 2,5-DMF yield. Besides, lower temperature is beneficial to obtain higher 5-HMF yield in the dehydration step and inhibit unwanted side reactions. We therefore considered 200 °C as the appropriate reaction temperature for subsequent studies.

The reaction time for hydrogenolysis of 5-HMF to 2,5-DMF was optimized at 200 °C. As shown in Figure 3, 5-HMF hydrogenolysis proceeded quickly within the first 3 h to achieve a 5-HMF conversion and a 2,5-DMF yield of 80.2 mol% and 74.8 mol%, respectively. Afterward, the reaction rate gradually slowed down. After 12 h, 100 mol% of 5-HMF conversion and 85.5 mol% of 2,5-DMF yield were obtained. Further increasing the reaction time might result in decomposition of 2,5-DMF to other by-products, as 2,5-DMF yield declined with the reaction time being extended from 12 h to 15 h. Thus, we considered 12 h as the optimal reaction time.

Hydrogen pressure was optimized in the range of 0.5-2 MPa at 180 °C and 3 h as shown in Figure 4. It can be seen that both 5-HMF conversion and 2,5-DMF yield consistently increased with hydrogen pressure from 0.5 MPa to 1.5 MPa and plateaued while hydrogen pressure is larger than 1.5 MPa. we therefore considered 1.5 MPa as the optimal hydrogen pressure.

Ru/C catalyst loadings of 5 wt%, 10 wt%, 20 wt%, and 30 wt% (mass ratio of wet Ru/C to 5-HMF) were then investigated (Figure 5). When Ru/C loading was less than 20 wt%, 2,5-DMF yield increased with increasing Ru/C loading. Further increasing Ru/C loading more than 20 wt%, however, led to a slight decrease in 2,5-DMF yield. Thus, we selected 20 wt% as the optimal catalyst loading.

The effect of initial 5-HMF concentration on hydrogenolysis of 5-HMF to 2,5-DMF was investigated in the range of 12.5-25 $mg \cdot ml^{-1}$ and finally we optimized 5-HMF concentration as 16.7 $mg \cdot ml^{-1}$ (Figure 6).

In summary of 5-HMF hydrogenolysis step, a maximum 2,5-DMF yield of 93.9 mol% might be obtained in N,N-dimethylformamide solvent at a temperature of 200 °C, H_2 pressure of 1.5 MPa, 5 wt% Ru/C catalyst loading of 20 wt% (relative to 5-HMF), initial 5-HMF concentration of 16.7 $mg \cdot ml^{-1}$, and reaction time of 12 h. The results obtained were fairly similar to those obtained when Ru/C was used with THF as the solvent,[35] indicating that N,N-dimethylformamide is another competitive solvent for 5-HMF hydrogenolysis.

One-pot production of 2,5-DMF from fructose

After having obtained the optimized reaction conditions for the individual dehydration step and hydrogenolysis step, we could build a one-pot process for the conversion of fructose to 2,5-DMF through a simple and effective way: a mixture of fructose (10 mmol), $AlCl_3$ (0.25 mmol), H_2SO_4 (0.7 mmol), H_3PO_4 (1.0 mmol), N,N-dimethylformamide (60 ml) and 5 wt% Ru/C (0.36 g) was added to the reactor and hydrogenated at 200 °C and 1.5 MPa H_2 pressure for 12 h. The highest 2,5-DMF yield of 66.3 mol% was finally obtained (entry 22, in Table 4). Further changing in the amounts and ratio of acids led to slight decrease in 2,5-DMF yield (entries 23-26 in Table 4). We believe that the 2,5-DMF yield of 66.3 mol% obtained in this work is the highest yield ever reported for the direct one-pot conversion of fructose to 2,5-DMF. A similar work[10] that used $ZnCl_2$-Pd/C bifunctional catalyst for the one-pot production of 2,5-DMF from fructose achieved only 22 mol% of 2,5-DMF yield. Such low yield might be due to the fact that THF used in that study was neither stable in Lewis acid nor favorable for fructose dehydration because of its low solubility.

Table 4 strategies for the one-pot conversion of fructose to 2,5-DMF.

Entry	Fructose (mmol)	$AlCl_3$ (mmol)	H_2SO_4 (mmol)	H_3PO_4 (mmol)	Con. (mol%)	Yield (mol%)
22	10	0.25	0.7	1	>99	66.3
23	10	0.42	1	1.5	>99	58.5
24	10	0.25	-	2	>99	47.3
25	10	0.25	2	-	>99	53.1
26	10	0.25	-	-	>99	47.6
27[a]	10	0.25	0.7	1	>99	40.2
28[b]	10	-	-	-	>99	35.1

Reaction Conditions: catalyst: 0.36 g of Ru/C (5 wt%); N,N-dimethylformamide, 60 ml; temperature, 200 °C; H_2 pressure, 1.5 MPa; reaction time, 12 h; agitation speed, 600 rpm.

[a] Acids were removed between the dehydration and hydrogenolysis process.

[b] Hydrogenolysis of fructose in the absence of acids.

In general, researchers prefer to a two-step process,[12, 13, 35] i.e., fructose dehydration → 5-HMF purification → 5-HMF hydrogenolysis, instead of a one-pot reaction, because the reaction conditions for these two consecutive reactions do not always match. Although increased yields of the target product might be achieved at each step, the difficulty in 5-HMF purification may lead to a very low overall 2,5-DMF yield. For comparison, a similar two-step process wherein removal of the acid catalyst by sodium carbonate was performed instead of full purification of 5-HMF in the present work, and a final 2,5-DMF yield of 40.2 mol% was obtained (entry 27, Table 4). Given that fructose dehydration has already been optimized to produce 92.6 mol% of 5-HMF, the 2,5-DMF yield from 5-HMF in the second step was then estimated to be 43.6 mol%, which was much lower than the case when pure 5-HMF was used as the substrate for the hydrogenolysis step (93.9 mol%). This finding could be mainly attributed to polymerization reactions between 5-HMF and other by-products, which were frequently observed during fructose dehydration.[17, 24, 40] Moreover, the overall 2,5-DMF yield in our two-step process was far lower than that obtained in our one-pot process (40.2 mol% vs. 66.3 mol%) because in the latter case the acids can stabilize 5-HMF against thermal decomposition and polymerization with other active by-products, as verified by our previous studies[16, 17] and several other laboratories.[6, 27]

The mixture of Lewis and Brönsted acid is inevitable for the one-pot process. When the acid catalysts were absent, a decreased 2,5-DMF yield of 35.1 mol% (entry 28) was obtained Given that a 2,5-DMF yield of 93.9 mol% was obtained from 5-HMF hydrogenolysis, the overall yield of 5-HMF from dehydration of fructose was estimated to be around 37.4 mol%, which is even lower by 7 mol% comparing to the yield in the single dehydration step without any acid catalyst (44.3 mol%, entry 4).

Recyclability of catalyst

The recyclability of Ru/C catalyst was determined for both 5-HMF hydrogenolysis and the one-pot conversion of fructose to 2,5-DMF. After reaction, the Ru/C catalyst was centrifugated, washed with N,N-dimethylformamide, and returned to the reactor for reuse. Relevant results are shown in Figure 7. It can be seen that Ru/C could be reused at least three times in both the cases with only approximately 5-10 mol% decrease in 2,5-DMF yield. Further study on improving the stability of Ru-based catalysts is ongoing in our laboratory.

Intermediates and possible mechanism for 5-HMF hydrogenolysis step

We analyzed the reaction mixtures by using gas chromatography-mass spectrometry (GC-MS) to better understand the pathway of 5-HMF hydrogenolysis to 2,5-DMF. Besides 2,5-DMF, four other by-products, including 5-methyl-furfural (5-MF), 5-methylfurfuryl alcohol (MFA), furfuryl alcohol (FA), and 2-methylfuran (2-MF), were detected in the reaction system. The time course of the reaction components was shown in Figure 8.

Previous work has identified two pathways to reach the target 2,5-DMF, i.e., (1) hydrogenation of the aldehyde group in 5-HMF to form dihydroxymethylfuran (DHMF), followed by individual hydrogenolysis of the two hydroxyl groups,[10, 23, 35] and

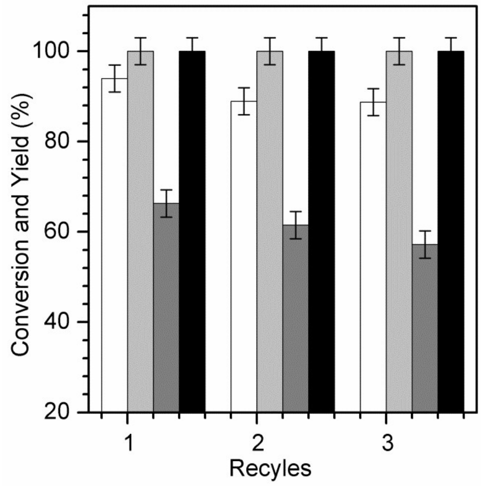


Fig. 7 Recyclability of 5 wt% Ru/C catalyst in hydrogenolysis of 5-HMF and the one-pot conversion of fructose process. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; catalyst, 0.36 g; H_2 pressure, 1.5 MPa; temperature, 200 °C; reaction time,12 h; agitation speed, 600 rpm. White bar, yield of 2,5-DMF in hydrogenolysis of 5-HMF; light grey bar, conversion of 5-HMF; dark grey bar, yield of 2,5-DMF in the one-pot conversion of fructose; black bar, conversion of fructose.

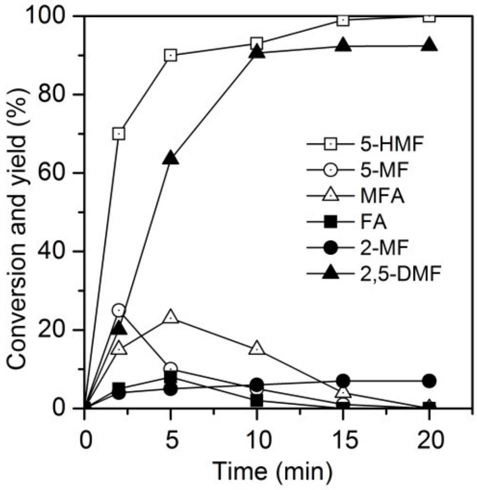
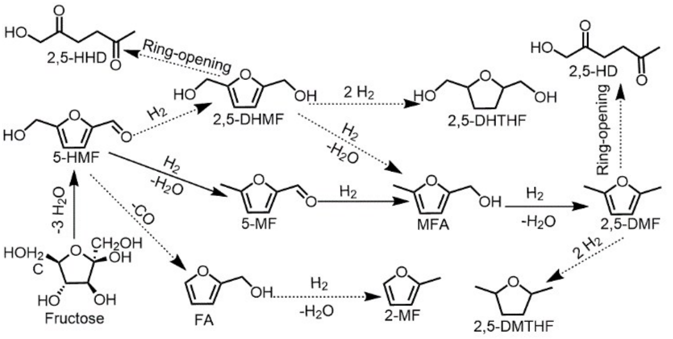


Fig. 8 Time course of components during hydrogenolysis of 5-HMF over 5wt% Ru/C catalyst. *Reaction conditions*: 5-HMF, 1 g; N,N-dimethylformamide, 60 ml; catalyst, 0.2 g; H_2 pressure, 1.5 MPa; temperature, 200 °C; agitation speed, 600 rpm. The intermediate components was quantified through GC analysis by assuming their correction factors to 2,5-DMF equal 1.



Scheme 1 Plausible Mechanism for the hydrogenolysis of 5-HMF to 2,5-DMF.

(2) hydrogenolysis of the hydroxyl group in 5-HMF to form 5-MF, the aldehyde group.[40] Some researchers consider that these two pathways occur in the same reaction bulk while the DHMF pathway is processed much faster than 5-MF pathway[4, 22, 43] and tends to occur at lower temperatures.[15, 38, 40] Our GC-MS analysis detected no DHMF in the system over the entire reaction process. By contrast, large amounts of 5-MF and MFA were detected during the first hour of reaction. We therefore deduce that the 5-MF pathway (solid line in Scheme 1) might be followed in our newly developed reaction bulk where N,N-dimethylformamide was used as the solvent, in accordance with the work of Kong et al.[40] Theoretically, current experimental data can not fully rule out the DHMF pathway since there still has the possibility that DHMF converts immediately to the downstreaming intermediates once it is generated from 5-HMF by hydrogenation of carbonyl group at such high temperature. Further kinetics study on the hydrogenolysis of those intermediates such as DHMF, 5-MF and MFA is needed to obtain a more sounded reaction mechanism.

Two other by-products, namely, FA and 2-MF, might be generated from 5-HMF decarbonylation and the following FA hydrogenolysis.[7, 41] No furan ring-hydrogenated by-products,[9, 12, 22] i.e., 2,5-dihydroxymethyl tetrahydrofuran or 2,5-dimethyltetrahydrofuran, or ring-opened by-products,[19, 44] e.g., (5-hydroxy-2,5-hexanedione) or 2,5-hexanedione, were detected during our experiment, which indicates that deep hydrogenation does not occur in our reaction process.

Conclusions

The production of 2,5-DMF from hydrogenolysis of 5-HMF is a highly attractive route. In order to avoid the difficulty in the purification of 5-HMF from the dehydration products of fructose, we have developed a one-pot process for direct conversion of fructose to 2,5-DMF, in which N,N-dimethylformamide was demonstrated as the optimal solvent.

At first, the reaction conditions for the 5-HMF hydrogenolysis step were optimized as follows: reaction temperature of 200 °C, hydrogen pressure of 1.5 MPa, 5 wt% Ru/C catalyst loading of 20 wt% (relative to 5-HMF), initial 5-HMF concentration of 16.7 mg·ml^{-1}, and reaction time of 12 h. Under these conditions, a 2,5-DMF yield up to 93.9 mol% was achieved.

A catalysis system with a Lewis-Brönsted acid mixture and Ru/C in N,N-dimethylformamide solvent was then developed for the one-pot conversion of fructose to 2,5-DMF. A maximum yield of 66.3 mol% was achieved at the following reaction conditions: 10 mmol of fructose, 0.25 mmol of $AlCl_3$, 0.7 mmol of H_2SO_4, 1.0 mmol of H_3PO_4, 0.2 g of 5 wt% Ru/C, 60 ml of N,N-dimethylformamide, 200 °C of reaction temperature and 12 h for reaction time. This is the highest 2,5-DMF yield ever reported on the one-pot strategy from carbohydrates. Ru/C catalyst could be reused at least three times with slight decrease in 2,5-DMF yield for both the individual hydrogenolysis step of 5-HMF and the one-pot conversion of fructose. We suggest that this simple, efficient, and renewable process for the production of 2,5-DMF directly from one-pot conversion of fructose will promote the wide adoption of 2,5-DMF as a fossil fuel alternative. And the method developed here is very useful for the development of effective conversion of biomass into important platform chemicals and biofuels.

Experimental Section

Materials 5-HMF (>99.9%) was purchased from Tengzhou Runlong Flavors and Fragrances Co., Ltd. 2,5-DMF standard was purchased from Aladdin Reagent Co., Ltd. Metal catalysts, including Raney Co and Ni, Pt/C, Ir/C, Pd/C, Ru/C and Rh/C, were purchased from Shanghai Eybridge Co., Ltd. The loadings of the noble metals were 5 wt%. Other chemicals used, including fructose (purity, 99%), $AlCl_3$, inorganic acids, and organic solvents, were analytically pure and purchased from Sino-pharm Chemical Reagent Co., Ltd. All of the solvents used in the reactions were passed through a 4A molecular sieve and reboiled to remove water.

Production of 5-HMF

The production of 5-HMF from fructose dehydration was conducted in a 100 ml of stainless autoclave equipped with a mechanical stirring impeller. In a typical experiment, 1 g of fructose, 0.2 g of $AlCl_3$, 40 mg of concentrated sulfuric acid (98 wt%), 60 mg of concentrated H_3PO_4 (98 wt%) and 60 ml of N,N-dimethylformamide were successively added into the autoclave. The mixture was stirred and incubated in an oil bath that had been preheated to designated temperatures. The samples were withdrawn at specified intervals. Each reaction was repeated more than twice, and results were presented as averaged data.

Production of 2,5-DMF

The production of 2,5-DMF from 5-HMF hydrogenolysis was conducted in the same reactor as that used for fructose dehydration process. In a typical experiment, the reactor was charged with catalyst (0.2 g of 5 wt% Ru/C), substrate (1 g of 5-HMF), and 60 ml of N,N-dimethylformamide solvent. Afterwards, the reactor was sealed, purged, and pressurized with H_2 (0.7 MPa). The reaction mixture was stirred at 600 rpm and incubated in an oil bath at a designated temperature. After reaction, the reactor was cooled to room temperature, and the reaction solution was centrifugated and sampled for analysis. For the one-pot production of 2,5-DMF from fructose, a mixture of fructose (10 mmol), $AlCl_3$ (0.25 mmol), H_2SO_4 (0.7 mmol), H_3PO_4 (1.0 mmol), N,N-dimethylformamide (60 ml) and 5 wt.% Ru/C (0.2 g) was added into the reactor and the reaction was conducted at 200 °C and 1.5 MPa H_2 pressure for 12 h.

Catalyst recyclability study

The recyclability of Ru/C catalyst for both 5-HMF hydrogenolysis and the one-pot conversion of fructose to 2,5-DMF were determined. After reaction, the Ru/C catalyst was centrifugated, washed several times with N,N-dimethylformamide, and returned to the reactor for the next cycle. The supernatant of each cycle was analyzed by gas chromatography (GC) and high-performance liquid chromatography (HPLC) for quantification of reaction components.

Product analysis

The analytical method described in our previous reports was adopted.[16, 17] Fructose was analyzed with a HPLC (detector: Waters 410 Differential Refractometer; Aminex HP X-87H column, 9 μm, 300 × 7.8 mm) with 5 $\text{mmol}\cdot\text{l}^{-1}$ H_2SO_4 in ultrapure water as the mobile phase flowing at a rate of 0.6 $\text{ml}\cdot\text{min}^{-1}$ and a column temperature of 60 °C. 5-HMF and other components were analyzed with an Agilent 7890 GC equipped with an HP-5 capillary column (30.0 m × 0.32 mm × 0.25 μm) and a flame ionization detector. The injector temperature was set at 250 °C and the sampling volume was 0.4 μl. The detector temperature was 260 °C. The split ratio was 1:10. The column temperature was raised from 100 °C to 250 °C at a heating rate of 5 $°\text{C}\cdot\text{min}^{-1}$ and then maintained at 250 °C for 10 min. 2,5-DMF was identified by its retention time in comparison with a standard sample and through GC-MS analysis. 5-HMF and 2,5-DMF were quantified by using n-dodecane as an internal standard. GC-MS analysis was performed with an Agilent 6890 GC system coupled to a mass spectrometer equipped with an Agilent 5973 quadrupole mass analyzer. Chromatographic analysis was conducted with an injector temperature of 280 °C and an HP-5 capillary column (30.0 m × 0.25 mm × 0.32 μm) with helium (99.999%) flow rate of 2.0 $\text{ml}\cdot\text{min}^{-1}$ and a 1:10 split ratio. The oven was heated using the following temperature program: initial temperature of 100 °C increased to 250 °C at a heating rate of 5 $°\text{C}\cdot\text{min}^{-1}$ and maintained for 10 min. The mass spectrometer was operated in electron ionization mode at an energy value of 70 eV.

Acknowledgements

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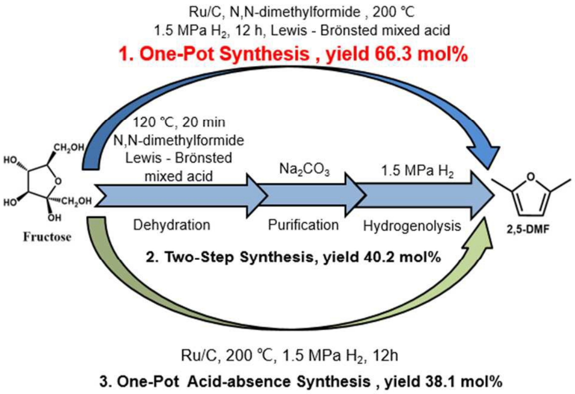

A one-pot process for the production of 2,5-dimethylfuran from fructose by using Ru/C and Lewis-Brönsted acid mixtures as catalyst.