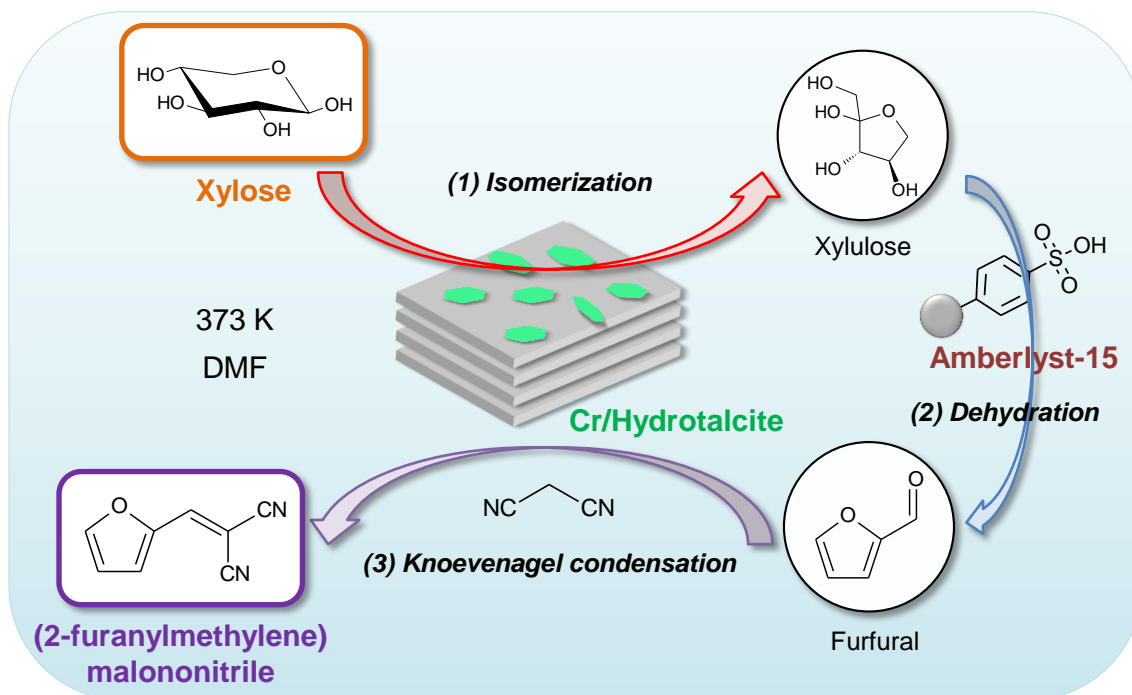


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One-Pot Synthesis of Furfural Derivatives from Pentoses using Solid Acid and Base Catalysts

Mahiro Shirotori, Shun Nishimura, and Kohki Ebitani*

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One-pot synthesis of (2-furanylmethylene)malononitrile, a Knoevenagel product of furfural with malononitrile, from xylose efficiently proceeded by combined use of acid Amberlyst-15 and acid-base Cr/hydroxalacites with 44% yield. Structural characterizations were carried out using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), X-ray absorption spectra, and nitrogen adsorption measurements. The Lewis acidic properties of a highly active Cr/HT were investigated using Meerwein-Ponndorf-Verley (MPV) reaction. It was confirmed that the prepared Cr/HT possessed the Lewis acid Cr₂O₃ on HT surface. Thus, the combined use of dispersed Lewis acid Cr₂O₃ and Brønsted base HT facilitated the isomerization step of aldose into ketose, and strongly promoted activity for the synthesis of furfural derivatives from aldoses through isomerization, dehydration and Knoevenagel condensation reactions in one-pot manner.

Introduction

Biomass resources have attracted much attention because they can serve as a sustainable source of renewable fuels and chemicals in a carbon-neutral fashion.¹⁻³ Lignocellulosic biomass, the most abundant woody biomass, is mainly composed of monosaccharides in the form of cellulose, hemicellulose, and lignin.^{4,5} Conversion of xylose, a pentose derived from hemicellulose, into value-added chemicals such as ethanol, xylitol, furfural, furfuryl alcohol, levulinic acid, and γ -valerolactone is one of reactions worth conducting in biorefinery. Especially, furfurals have been extensively focused on fabrications of the practical uses of biomass resources because they have great potentials as non-petroleum building blocks in the production of fine chemicals, polymers, and pharmaceuticals.⁵⁻⁹

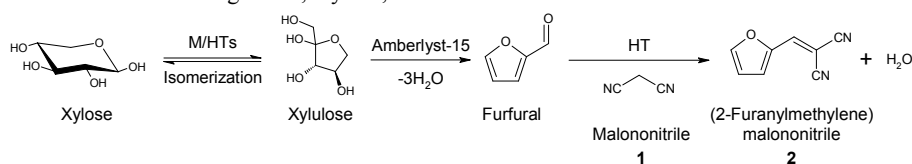
Moreau et al. have reported the synthesis of furfural from xylose in good selectivity (90-95%) over solid acid catalysts such as H-mordenite and H-Y faujasite.¹⁰ Furthermore dehydration of xylose to furfural is examined using various solid acid catalysts like Nafion 117,¹¹ ion-exchange resins,¹² sulfated zirconia,¹³ porous niobium silicates,¹⁴ sulfonic acid modified mesoporous shell silica bead,¹⁵ and zeolite-based catalysts.¹⁶⁻²¹ However, these reactions were performed at high temperature (>423 K).

In advanced researches, it was demonstrated that furfurals were effectively formed from aldoses such as glucose, xylose, and

arabinose in a one-pot manner involving isomerization of aldose into ketose catalyzed by solid base hydroxalacite and successive dehydration of ketose into the corresponding furfurals by Brønsted acid Amberlyst-15 at 373 K.²²⁻²⁴ Binder et al.²⁵ and Suzuki et al.²⁶ have reported the conversion of xylose into furfural under a mild condition (373 K) using CrCl₂ with LiBr and SO₄²⁻/SnO₂. These reports proposed that Lewis acid of CrCl₃ or SnO₂ promoted isomerization of xylose (aldopentose) to xylulose (ketopentose), and then co-existing Brønsted acid catalyzed the further dehydration to furfural.

Many researchers reported that furfural derivatives obtained by C-C bond formation such as aldol condensation can be converted into chemicals and biofuel alkanes.²⁷⁻³² The Knoevenagel condensation, a C-C bond formation of carbonyl compounds (aldehyde and ketones) with active methylene compounds, of furfural can also provide value-added furfural derivatives. Soliman et al. demonstrated that (2-furanylmethylene) malononitrile (**2**, in Scheme 1), a Knoevenagel product of furfural with malononitrile, is expected as a semiconducting organic material such as photovoltaic devices fabrication.³³

Mg-Al hydroxalacite (HT; [Mg²⁺_{1-x}Al³⁺_x(OH)₂]^{x+} Aⁿ⁻_{x/n}mH₂O) is the most well-known layered double hydroxides (LDHs) which is composed of brucite-like positively charged two-dimensional sheets and interlayer anions Aⁿ⁻ such as carbonate and hydroxide. HT is generally used as a Brønsted base catalyst for



Scheme 1 One-pot synthesis of (2-furanylmethylene)malononitrile from xylose.

epoxidation,^{34,35} transesterification,³⁶ aldol condensation,^{37,38} and the Knoevenagel reaction.³⁹⁻⁴¹ Although HT is known as an effective support,⁴²⁻⁴⁷ it has been rarely used for the synthesis of furfural from pentoses and the Knoevenagel condensation of furfural.

Herein, we report (1) the Knoevenagel condensation of furfural using HT as a solid base catalyst and (2) a direct synthesis of (2-furanylmethylene)malononitrile from xylose using various metal supported HTs (M/HTs) and solid acid Amberlyst-15 catalysts in a one-pot manner (Scheme 1). Though there were many previous reports about the Knoevenagel condensation of various aldehyde over HT catalyst such as benzaldehyde,³⁹⁻⁴¹ salicylaldehyde,³⁹ 4-methylbenzaldehyde,³⁹ and so on, this is the first report about the application of HT for the Knoevenagel condensation of furfural and *in situ* formed furfural from xylose and arabinose.

Experimental

Materials and synthesis of M/HTs catalyst

Mg-Al hydrotalcite (HT) (AD500NS; Mg/Al = 3.1, MgO 38.1%, Al₂O₃ 15.7%, CO₂ 8.1%) were purchased from Tomita Pharmaceutical Co., Ltd.. Stannic chloride pentahydrate (SnCl₄·5H₂O), chromium chloride hexahydrate (CrCl₃·6H₂O), lanthanum chloride heptahydrate (LaCl₃·7H₂O), ferric chloride hexahydrate (FeCl₃·6H₂O), zirconium oxychloride octahydrate (ZrCl₂O·8H₂O), and nickel chloride hexahydrate (NiCl₂·6H₂O) were supplied by Wako Pure Chemical Ind., Ltd. Co. whereas copper chloride dihydrate (CuCl₂·2H₂O) and *N,N*-dimethylformamide (DMF) were served from Kanto Chem. Co. Ltd..

The metal supported hydrotalcites (M/HTs) were prepared by an impregnation method (adsorption) using HT and an aqueous solution of various metal chlorides: each metal chloride was dissolved in 100 mL of water, then 2 g of HT was added. The metal content was adjusted to 9 wt% in theory. After stirred at 353 K for 24 h, the obtained paste was filtered, washed with 2 L of distilled water, and then dried at 383 K for overnight.

Reactions

All reactions were performed in a Schlenk tube attached with a reflux condenser under an N₂ flow (30 mL min⁻¹). The reaction was typically performed using 0.1-0.2 g of solid base HT and/or 0.1 g of solid acid Amberlyst-15 in 3 mL of DMF at 373-393 K. For the Knoevenagel condensation reaction of furfural, 1 mmol of furfural and 1.2 eq. of active methylene compounds were used. The yields of the Knoevenagel products were calculated on the basis of furfural. One-pot synthesis of furfural derivatives from pentoses was carried out *via* a two-step reaction without catalyst separation: Step 1) the one-pot conversion of pentoses into furfural using solid acid and base catalysts, and Step 2) the reaction mixture after the Step 1 was cooled down to room temperature without stirring, then donor compound was added, thereafter, the following Knoevenagel condensation was conducted under vigorous stirring. The yields of furfural and furfural derivatives were calculated on the basis of xylose. All products were analyzed by a GC-FID (SHIMADZU, GC-2014) equipped with a non-polar column (Agilent, DB-1).

Characterizations

X-ray diffraction (XRD) patterns were collected on a SmartLab (Rigaku) using a Cu K α X-ray source (40 kV, 30 mA). XRD patterns were compared with a data base in the international centre for diffraction data (ICDD). Nitrogen adsorption measurements were carried out to determine the BET (Brunauer-Emmett-Teller) specific surface area. The measurements were conducted at 77 K on a Belsorp-max (BEL, Japan, Inc.). X-ray photoelectron spectroscopy (XPS) analyses were performed with a Kratos AXIS-URTRA DLD (SHIMADZU) using a monochromatic Al K α source (10 mA, 15 kV). The binding energies were calibrated with C 1s level (284.5 eV) as the internal standard. X-ray absorption spectra in Cr *K*-edge were recorded at a BL5S1 of Aichi Synchrotron Radiation Research Center (2nd period, 2013). All samples were grained and pressed to a pellet (\varnothing = 10 mm). The energy for Cr *K*-edge XAFS spectra were adjusted at the edges of Cu foil (8.9800 keV). Double Si(111) single crystals were used for division of energy. The obtained spectra were analyzed with the REX2000 software (ver. 2.5.92, Rigaku).

Results and discussion


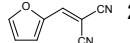

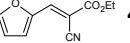

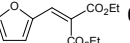

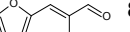
The Knoevenagel condensation of furfural

Preliminary, we examined the Knoevenagel condensation of furfural over the base HT catalyst with various active methylene compounds of malononitrile (**1**), ethyl cyanoacetate (**3**), diethylmalonate (**5**) or propionaldehyde (**7**). These results were shown in Table 1. The Knoevenagel condensation of furfural with malononitrile (**1**) was successfully performed over HT catalyst; it afforded (2-furanylmethylene)malononitrile (**2**) in >99% yield (entry 1). The typical solid base catalysts of MgO, Mg(OH)₂, CaO and NaHCO₃ also showed good or less activity for the reaction but HT catalyst exhibited the best catalytic activity among them (entries 2-6). Thus, HT was further applied to the Knoevenagel condensation of furfural with various active methylene compounds of **3**, **5** and **7**. In the reaction of furfural with **3** (entry 7), the HT catalyst gave 93% conversion of furfural and 73% yield of ethyl-(2E)-2-cyano-3-(2-furyl)acrylate (**4**). On the other hand, in the reaction with **5**, the corresponding diethyl 2-furfuryliden malonate (**6**) was obtained only a 22% yield (entry 8) because of low acidic strength of **5** (*p*K_a ~ 13). However, when the amount of HT was increased to 0.2 g, the reaction was promoted and yielded **6** with 41% (entry 8b). The HT catalyst also showed a good activity for the reaction of **7** and furfural; it afforded 3-(2-furyl)-2-methylacrolein (**8**) with 71% yield in 1 h (entry 9b). From these results, it was indicated that the HT exhibited a good activity for the Knoevenagel condensation of furfural with various active methylene compounds such as nitrile, aldehyde and ester.

One-pot synthesis of furfural derivatives from xylose

In the next stage, the one-pot synthesis of furfural derivatives from xylose using solid acid Amberlyst-15 and base HT was attempted. The results are shown in Table 2. A combined use of Amberlyst-15 and HT gave 21% yield for the one-pot synthesis of **2** from xylose (entry 1). In the reaction with **3** or **5**, 7% or 4% yield of **4** or **6** was formed with 14% and 12% yield of furfural intermediate, respectively (entries 2 and 3). On the other hand, when active methylene compounds (**7**) were used for one-pot

Table 1 The Knoevenagel condensation of furfural with various active methylene compounds^a

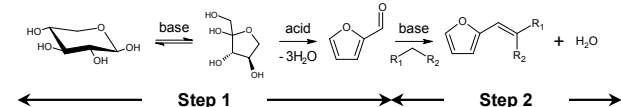
Entry	Donor	Product	Catalyst	Time	Conversion of furfural /%	Yield of product /%
1	 1	 2	HT	15 min	>99	>99
2			MgO	15 min	>99	>83
3			Mg(OH) ₂	15 min	>99	>83
4			CaO	15 min	>99	>01
5			NaHCO ₃	15 min	>99	>64
6			—	15 min	>26	>15
7	 3	 4	HT	01 h	>93	>73
8	 5	 6	HT	18 h	>54, 79 ^b	>22, 41 ^b
9	 7	 8	HT	01 h	>57, 84 ^b	>52, 71 ^b

^aReaction conditions: furfural (1 mmol), donor (1.2 mmol) catalyst (0.1 g, ^b0.2 g), DMF (3 mL), Temp. (373 K, ^c393 K), N₂ flow (30 mL min⁻¹).

synthesis, no Knoevenagel product was observed (entry 4); nevertheless the donor conversion was high. Even though the used catalysts of HT and Amberlyst-15 were removed after the Step 1 and fresh base HT catalyst was added for a further Knoevenagel condensation reaction with **7**, the Knoevenagel product (**8**) was not obtained (entry 4d). These results suggested that no activity in the one-pot synthesis of **8** was resulted in the degradation of HT during Step 1. Because the donor of **7** was aldehyde type, one of the active functional groups, the reaction between donor **7** and xylose, xylulose and/or some degradation products would occurred preferentially, and the successive Knoevenagel condensation was prohibited. Arabinose, a structural isomer of xylose, was also examined as substrate for one-pot synthesis of **2**. In the case of arabinose, a combined use of HT and Amberlyst-15 gave 17% of **2** (entry 5).

In order to elucidate the reaction pathway, time-course of the

Table 2 One-pot synthesis of furfural derivatives from pentoses^a



Step 1: Pentose → Furfural (loss of 3H₂O)

Step 2: Furfural + R₁-CH₂-R₂ → Furfural derivative + H₂O

Entry	Donor	Product	Conv. of donor /%	Yield /%	
				furfural	Product
1	1	2	>60	000	021
2	3	4	>18	014	007
3 ^b	5	6	>48	012	004
4	7	8	>98, 90 ^d	019, 12 ^d	000
5 ^c	1	2	057	000	017

^aReaction conditions: Step 1) xylose (0.67 mmol), HT (0.2 g), Amberlyst-15 (0.1 g), DMF (3 mL), 373 K, 3 h, N₂ flow (30 mL min⁻¹). Step 2) After the Step 1, the reaction mixture was cooled down to room temperature without stirring. Then 0.8 mmol of donor was added and restarted the reaction. 1 h, N₂ flow (30 mL min⁻¹). ^b393 K, Step 2 (18 h). ^cArabinose (0.67 mmol) was used as the substrate. ^dAfter the Step 1, catalysts were removed and fresh HT was added for Step 2.

one-pot synthesis of **2** from xylose was monitored (Figure 1). In the Step 1 (conversion of xylose toward furfural), furfural yield gradually increased with increasing reaction time. This step depend on the reactions of isomerization of xylose to xylulose and further dehydration of xylulose to furfural reported in our previous report.²² After the addition of **1**, furfural was immediately consumed, and the product **2** was formed (Step 2). Furfural intermediate was consumed completely for 1 h of the Step 2. These results clearly indicate that the one-pot reaction involves three elemental reactions; (i) isomerization of xylose into xylulose catalyzed by solid base HT, (ii) dehydration of xylulose into furfural by solid Brønsted acid Amberlyst-15, and (iii) the Knoevenagel condensation of furfural by solid base HT to yield the corresponding Knoevenagel products.

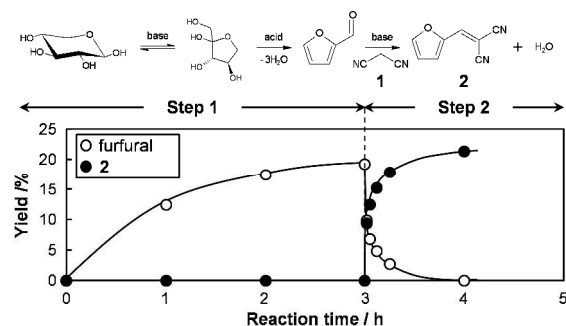


Figure 1 Time-course of the one-pot synthesis of (2-furanylmethylene) malononitrile (**2**) from xylose. Reaction conditions: Step 1) xylose (0.67 mmol), HT (0.2 g), Amberlyst-15 (0.1 g), DMF (3 mL), 373 K, N₂ flow (30 mL min⁻¹). Step 2) After the step 1, the reaction mixture was cooled down to room temperature without stirring. Then 0.8 mmol of **1** was added and restarted the reaction.

Catalytic performances and structural properties of metal supported hydrotalcites (M/HTs)

Isomerization of aldopentose into ketopentose is a static reaction whereas following dehydration of ketopentoses and Knoevenagel condensation are one-way reactions in the one-pot synthesis of

furfural derivatives from aldopentoses. Because the yield of intermediate furfural was limited at ~20% from xylose over bare HT and Amberlyst-15 catalysts, the following yield of **2** could not reach above that value. Thus, enhancement of the former isomerization reaction is a crucial point for the one-pot synthesis of furan derivatives. In order to increase the yield of the Knoevenagel product in one-pot synthesis from aldopentoses, various metal supported HTs (M/HTs) catalysts were prepared and applied for the one-pot reaction. Cr, Sn, Zr, Ni, La, Fe and Cu were selected as the metal species for promoting the isomerization reaction.

Figure 2(A) shows the results for one-pot synthesis of **2** from xylose using Amberlyst-15 and various M/HTs. Remarkably, the combined use of Amberlyst-15 and Cr/HT or Sn/HT resulted in 44% and 34% yield of **2**, respectively. The pairs of Amberlyst-15 and Cr/HT or Sn/HT showed better catalytic activities than that of Amberlyst-15 and Zr/HT, Ni/HT or La/HT catalysts. The activities of Fe/HT and Cu/HT were lower than bare HT. Moreover, though bare HT produced only **2** as a furfural product, some of M/HTs gave not only **2** but also intermediate furfural in one-pot synthesis. These results suggested that M/HTs possessed smaller number of base sites than HT itself. In fact, when we applied the Cr/HT for the Knoevenagel condensation of furfural with **1** under the same reaction condition as entry 1 in Table 1, it showed 97% conversion of furfural and 97% yield for **2**. These values were slightly less than the case of bare HT (>99%; Table 1, entry 1). The one-pot synthesis from arabinose was also examined with a highly active Cr/HT and Sn/HT catalyst (Figure 2(B)). These Amberlyst-15 and Cr/HT or Sn/HT gave 42% and 34% yields of **2**, respectively. From these results, it was demonstrated that Cr/HT and Sn/HT effectively increased the activity for one-pot synthesis of **2** from aldopentoses such as xylose and arabinose in comparison of bare HT.

The reaction mixture obtained after a one-pot formation of **2** from xylose using the Cr/HT and Amberlyst-15 was filtered, and

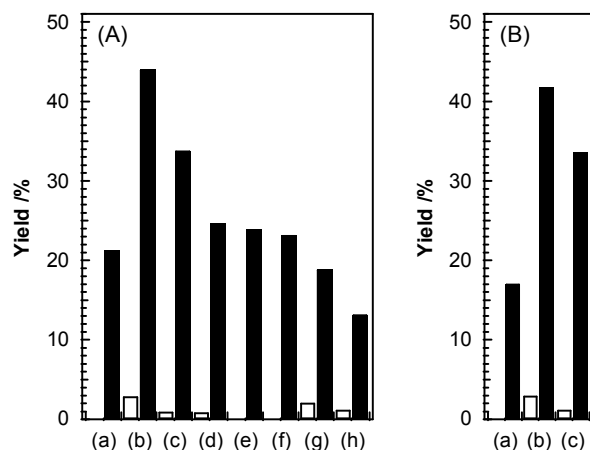


Figure 2 Yields of (■) (2-furanylmethylene)malononitrile (**2**) and (□) furfural in the one-pot transformation of (A) xylose and (B) arabinose with a combined use of Amberlyst-15 and (a) HT or various M/HTs (M: (b) Cr, (c) Sn, (d) Zr, (e) Ni, (f) La, (g) Fe, and (h) Cu) catalysts. Reaction conditions: Step 1) pentoses (0.67 mmol), M/HT (0.2 g), Amberlyst-15 (0.1 g), DMF (3 mL), 373 K, 500 rpm, 3 h, N₂ flow (30 mL min⁻¹). Step 2) After the Step 1, the reaction mixture was cooled down to room temperature without stirring. Then 0.8 mmol of donor was added and restarted the reaction. 373 K, 500 rpm, 1 h, N₂ flow (30 mL min⁻¹).

then the filtrate was analysed by ICP-AES to check the amount of eluted Cr species. No leached Cr was observed in the solution (below the detection limit of 30 ppb). However, in the reuse experiments, the yield of **2** was gradually decreased with increase of the amount of furfural intermediate (See Figure S2, ESI†). These deactivations were likely due to the adsorption of intermediate and/or other by-products onto the Cr/HT because color of the Cr/HT was changed from green to dark-brown before and after the 1st reaction.

XRD patterns of various M/HTs and original HT as a reference were examined (Figure 3). All prepared M/HTs had a layered double hydroxide (LDH) structure of HT origin. The XRD patterns of Cr/HT, Sn/HT, Zr/HT, Ni/HT and Fe/HT had no other peaks. Since the reflection peaks attributed to LDH structure were same with the original HT, the supported metal species were widely dispersed on HT surface in the cases of them. By contrast, La/HT and Cu/HT showed another peak which was different from LDH structure. These peaks were similar to that of La(OH)(NO₃) like or LaAlO₃ structure and CuAlO₂, respectively.

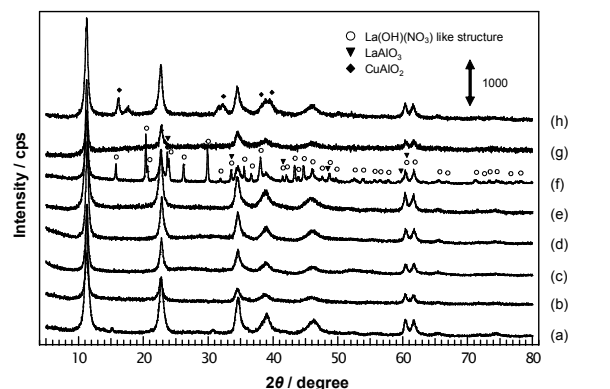


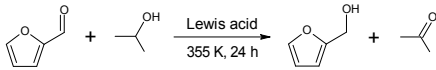
Figure 3 XRD patterns of HT and various M/HTs; (a) bare HT, (b) Cr/HT, (c) Sn/HT, (d) Zr/HT, (e) Ni/HT, (f) La/HT, (g) Fe/HT and (h) Cu/HT.

BET specific surface areas of M/HTs were also listed in Table S1 in ESI†. By supporting Cr, Sn, Zr or Fe onto HT, the surface area increased up to 2 - 3 times comparing from parent HT (45 m² g⁻¹), and Cr/HT showed the highest value (130 m² g⁻¹). Nevertheless Fe/HT also has high surface area (124 m² g⁻¹), its activity was not high (19% yield of **2** as mentioned in Figure 2(A)). It seemed that the surface area of catalyst scarcely impacted on the one-pot synthesis of furfurals from pentoses but the kinds of supported metal played a significant role for their catalytic activity in the one-pot reaction.

To determine the oxidation states of highly active Cr/HT and Sn/HT, XPS experiment was conducted (Figure S1, ESI†). The XPS analysis of Cr 2p_{3/2} showed a peak at 576.5 eV which was assigned to the Cr₂O₃⁴⁸ whereas the XPS analysis of Sn 3d_{5/2} showed a peak at 486.0 eV corresponding to the SnO and/or SnO₂.⁴⁹ Presence of the Cr₂O₃ in Cr/HT was also supported by Cr *K*-edge XANES analysis (See Figure S2, ESI†). These Cr and Sn oxides were conventionally well-known as the strong Lewis acid. Therefore, we suggested that the combined use of Lewis acid derived from supported metal and base site on HT support facilitated the isomerization step of aldopentoses into ketopentoses, and which achieved their high activities.

The Lewis acidity of the Cr/HT is verified by the catalytic activity for Meerwein-Ponndorf-Verley (MPV) reaction of furfural in 2-propanol toward furfuryl alcohol (FA) (Table 3)†. It has been known that the Lewis acid sites are able to catalyze the MPV hydride transfer reaction.⁵⁰⁻⁵³ As shown in entry 3, a typical Lewis acid $\gamma\text{-Al}_2\text{O}_3$ showed high catalytic activity for the MPV reduction of furfural while the reaction did not proceed at all in the case of Brønsted acid Amberlyst-15 or blank test (entries 4 and 5). These results clearly suggested that this reaction was promoted by Lewis acid sites. In the presence of base HT, although the conversion of furfural was low, a little FA product was observed (entry 2). This seemed that one of a local location of HT surface composed by the metal oxide structure such as Mg-O-Al and which might catalyze the MPV reduction as the Lewis acid sites (though it was tiny amounts of). Nevertheless, the Cr/HT showed a much higher catalytic activity than the bare HT with 33% yield of FA. In addition, the selectivity of FA also increased up to 81% from 63%. These results strongly indicated that the dispersed Cr_2O_3 species can promote the MPV hydride transfer reaction more effectively than bare HT as Lewis acid; *i.e.* Cr/HT possessed not only Brønsted base sites of HT but also Lewis acid sites of Cr_2O_3 , and they cooperatively proceeded the isomerization reaction of aldopentoses into ketopentoses in the one-pot reaction.

Table 3 MPV reduction of furfural by various solid catalysts^a



Entry	Catalyst	Conversion /%	Yield of FA /%	Selec. of FA /%
1	Cr/HT	040	033	081
2	HT	014	009	063
3	$\gamma\text{-Al}_2\text{O}_3$	080	074	093
4	Amberlyst-15	034	000	000
5	—	010	000	000

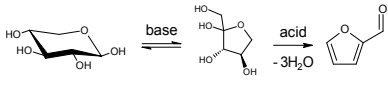
^aReaction conditions: furfural (1.3 mmol), 2-propanol (83 mmol), catalyst (0.1 g), 355 K, 24 h, 500 rpm.

Role of dispersed Cr_2O_3 on hydrotalcite

In order to evaluate the role of Cr_2O_3 on HT, the one-pot synthesis of furfural from xylose *via* the isomerization of xylose into xylulose and dehydration of xylulose into furfural in various combination with HT, Cr/HT, Cr_2O_3 and/or Amberlyst-15 catalysts were examined as shown in Table 4. The use of Amberlyst-15 alone gave poor furfural yield (4%) (entry 6) because Amberlyst-15 cannot promote the isomerization of xylose into xylulose under such a low temperature (373 K). Besides, in the presence of HT, no production of furfural was observed (entry 8). This means that HT is not effective for dehydration of pentoses. An efficient production of furfural was obtained in the combined use of Amberlyst-15 and Cr/HT with 36% yield (entry 1) which was a much higher value than the dehydration of xylose but it could promote the isomerization of xylose into xylulose more than original HT. The physical mixture of HT, Amberlyst-15, and Cr_2O_3 was also tested for the one-pot reaction, and it showed a little improvement of furfural yield to 21% in comparison with 19% for the pair of HT and Amberlyst-15 (entries 3 and 4). In addition, when $\gamma\text{-Al}_2\text{O}_3$ possessing the

higher activity in Lewis acid reaction of MPV reduction was used in instead of Cr_2O_3 , the one-pot furfural synthesis was slightly promoted; 26% yield of furfural was obtained (entry 2). However, these activities were less than the combined use of Cr/HT and Amberlyst-15 (36%, entry 1). These results strongly suggested that the concert effect of Brønsted base HT and Lewis acid Cr_2O_3 or $\gamma\text{-Al}_2\text{O}_3$ is effective for the one-pot synthesis of furfural from xylose, and the Cr_2O_3 species well-dispersed on HT surface (Cr/HT) is the best structure for promoting their correlations (entries 1-3). It is noted that neither use of bulk Cr_2O_3 nor combined use of bulk Cr_2O_3 and Amberlyst-15 were ineffective for the one-pot synthesis of furfural from xylose (entries 5 and 9). These results indicated that the bulk Cr_2O_3 has no activity for both isomerization of aldopentoses into ketopentoses and dehydration of pentoses into furfural, however dispersed Cr_2O_3 species can act as promoter for the isomerization step catalyzed by HT base site (entry 1). Amberlyst-15 and bare HT (19%) (entry 4)†. Because the furfural synthesis from xylose scarcely proceeded by Cr/HT (entry 7), it was clearly shown that the Cr/HT was not effective for direct

Table 4 One-pot synthesis of furfural from xylose^a



Entry	Catalyst A	Catalyst B	Yield /%
1	Cr/HT	Amberlyst-15	036
2	HT + $\gamma\text{-Al}_2\text{O}_3$ ^b	Amberlyst-15	026
3	HT + Cr_2O_3 ^c	Amberlyst-15	021
4	HT	Amberlyst-15	019
5	Cr_2O_3	Amberlyst-15	004
6	—	Amberlyst-15	004
7	Cr/HT	—	001
8	HT	—	000
9	Cr_2O_3	—	000

^aReaction conditions: xylose (0.67 mmol), catalyst A (0.2 g), ^bHT (0.174 g) + $\gamma\text{-Al}_2\text{O}_3$ (0.026 g), ^cHT (0.174 g) + Cr_2O_3 (0.026 g), catalyst B (0.1 g), DMF (3 mL), 373 K, 3 h, N_2 flow.

Reaction mechanism

Finally, the reaction mechanism of direct synthesis of furfural from xylose using Cr/HT and Amberlyst-15 is considered. It has been known that the isomerization of aldose into ketose is catalyzed by both Lewis acid and base through hydride shift^{54,55} and proton shift,^{56,57} respectively. For instance, glucose (aldohexose) conversion into 5-hydroxymethylfurfural through the intermediate formation of fructose (ketoheptose) using Lewis acidic CrCl_2 is reported by Pidko et al.⁵⁴ The initial attack by chromium(II) chloride to O1 results the glucopyranose ring opening. The reactive metal chloride is able to directly coordinate the substrate at the O1H site. Formation of the coordination complex with glucose initiates the isomerization reaction involving the transient formation of binuclear Cr complexes that substantially stabilizes the activated anionic sugar intermediates.⁵⁴ Ekeberg et al. reported that the isomerization of aldoses into ketoses catalyzed by base pyridine proceeds *via* the Lobry de Bruyn-Alberda van Ekenstein transformation.^{56,57} It is generally agreed that the Lobry de Bruyn-Alberda van Ekenstein

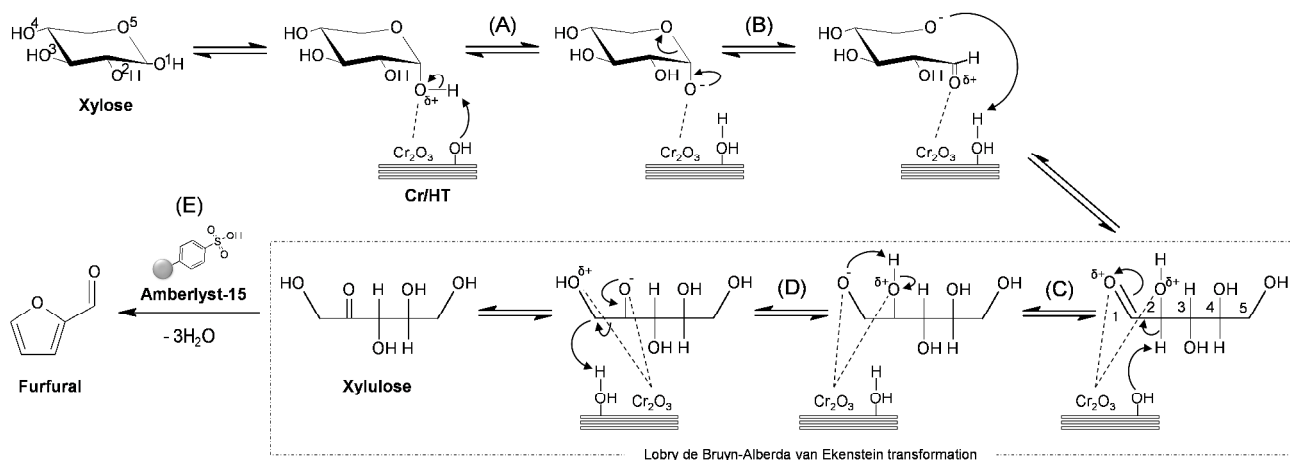


Figure 4 Proposed reaction path of direct synthesis of furfural from xylose using Cr/HT and Amberlyst-15.

transformation proceeds *via* an enediol intermediate.⁵⁸ Despite being a too weak base to remove the proton from O1, pyridine is a good proton acceptor and cause polarisation of the O-H bond. It increased negative charges on O1, and which facilitates the ring opening. A proton shift will lead to a pseudo-cyclic 1,2-enediol intermediate.⁵⁷

Based on these references, we propose the isomerization of xylose (aldopentose) into xylulose (ketopentose) over the Cr/HT catalyst as described in Figure 4, which proceeds *via* ring-opening reaction and Lobry de Bruyn-Alberda van Ekenstein aldoses-ketose transformations. Lewis acidic sites of dispersed Cr_2O_3 itself possibly catalyze the isomerization of aldose into ketose *via* the direct hydride shift mechanism,^{54,55} however, in the case of isomerization over the Cr/HT, it is proposed that the main active site would not be the Lewis acid Cr_2O_3 sites but the Brønsted base site on HT since the dispersed Cr_2O_3 species supported on various metal oxides exhibited less activities than the Cr/HT (Figure S4, ESI†). The reaction is initiated by the direct coordination of xylose with the Lewis acidic Cr_2O_3 center ($\text{Cr}_2\text{O}_3 \cdots \text{O}1$, (A)). This increases positive charge on O1, and bond strength between O1 and O1H became weaker. Then the HT base site facilitates the deprotonation of the O1H, and xylopyranose is transformed to open-xylose (B). The C2H of open-xylose, an α -proton of carbonyl, is easily deprotonated by HT base (C). The generated 1,2-enediol (enolate) intermediate would form the coordination complex with Lewis acidic Cr_2O_3 on HT, and then open-xylulose is constituted by a proton shift from O2 to O1 (D) and protonation of C1H. Then, the generated xylulose will be dehydrated to furfural by Brønsted acid Amberlyst-15 (E). In our developed study, combined use of Cr/HT and Amberlyst-15 can provide catalytic reaction system which Lewis and Brønsted acid, and Brønsted base active sites act concertedly, and achieved the one-pot synthesis of furfural derivatives from xylose and arabinose.

Conclusions

As a solid base catalyst, hydrotalcite (HT) showed good activity for the Knoevenagel condensation of furfural with various active methylene compounds such as nitrile, aldehyde, and ester. Direct synthesis of (2-furanylmethylene)malononitrile from pentoses *via*

the (i) isomerization, (ii) dehydration, and (iii) the Knoevenagel condensation proceeded in one-pot manner by using heterogeneous acid Amberlyst-15 and base HT. Cr/HT was found to be an excellent catalyst for the one-pot synthesis of (2-furanylmethylene)malononitrile with 44% yield. The oxidation state of Cr species on Cr/HT is similar to that of Cr_2O_3 which is known as strong Lewis acid. We suggested that the combined use of dispersed Cr_2O_3 as Lewis acid and Brønsted base sites of HT facilitated the isomerization step of aldopentoses into ketopentoses, and achieved a good activity.

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Notes and references

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† Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/b000000x/

‡ Generally, the acidic properties of solid catalysts were investigated using pyridine adsorbed FT-IR technique; however, the large bands for –OH groups derived from water molecules in HT structure concealed the small bands from adsorbed pyridine species; *i.e.* the pyridine-IR spectra could not use for the Cr/HT to check the Lewis acidity.

¶ Activity for the one-pot synthesis of furfural from xylose with a combination of bare HT and Amberlyst-15 was less than our previous report (ref. 22). We supposed that this discrepancy might be arisen from the differences in the Lot of HT whose property effected on the rate-determination step of isomerization in the one-pot synthesis of furfural.

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