Transformation of Glucose to 5-Hydroxymethyl-2-furfural by SiO₂-MgCl₂ Composite

Masahide Yasuda,* Yasuhisa Nakamura, Jin Matsumoto, Haruhiko Yokoi, and Tsutomu Shiragami

Department of Applied Chemistry, Faculty of Engineering, University of Miyazaki, 1-1 Gakuen-Kibanadai-Nishi, Miyazaki 889-2192

Received December 1, 2010 E-mail: yasuda@cc.miyazaki-u.ac.jp

5-Hydroxymethyl-2-furfural (2a) was formed in a 70% yield by dehydration of glucose in MeCN at 140 °C in an autoclave using a composite of MgCl₂ with silica gel which served as an acid catalyst under dry conditions. 10% and 32% yields of 2a were obtained from mannose and galactose, respectively.

Chemical transformation of biomass to organic chemicals has been receiving much attention from the standpoint of organic synthesis using a renewable carbon source.¹ Saccharides 1 are C5 and C6 carbon sources available from biomass. Especially glucose (1a) is an abundant monosaccharide obtained by the saccharification of cellulose and starch. A typical transformation of 1 is the transformation from hexose and pentose to 5-hydroxymethyl-2-furfural (2a) and 2-furfural (2b) which are versatile compounds for the transformation to a variety of chemicals (Scheme 1). The formation of 2 from aldose proceeded via aldose-ketose (A-K) isomerization of 1 and the successive dehydration in the presence of acid catalysts.² Instead of mineral acid such as the H₂SO₄, H₃PO₄, or HI used in earlier studies,³⁻⁵ a variety of heterogeneous catalysts involving solid acid (H-form zeolite,⁶ ion-exchange resins,⁷ and metal oxide⁸) and protic ionic liquids⁹ have been used in the transformation of 1 to 2 for convenience of separation and recycling.

Recently we have studied the application of a composite (3; SiO₂-MCl₂) of MCl₂ (M = Mg and Ca) with silica gel which can generate protons under dry conditions (eq 1 in Scheme 2).¹⁰ In the presence of H₂O, **3a** (M = Mg) readily turned neutral without the addition of other alkali (eq 2). We



Under dry conditions



In the presence of H₂O

$$\begin{array}{c} Si = 0 \\ O \\ Si = 0 \end{array} \qquad M + 2H_2O \longrightarrow O \\ Si = OH \end{array} + M(OH)_2 \qquad (2)$$

Scheme 2.

have applied the water-dependant pH-change to develop an SiO_2 -MgCl₂-porphyrin composite acting as humidity indicators of desiccants.¹¹ Under dry conditions the protonated porphyrin was formed and turned to free base porphyrins under wet conditions, resulting in the color change from green to pink-orange. The acidity (p K_a) of **3a** was estimated to be 1.7 under dry conditions.¹² Thus, it was found that the pH of **3** can be controlled by the presence of water. If **3** can catalyze the dehydration of **1**, it will provide an environmentally conscious process without requiring strong acid and alkali.

SiO₂ (1.0 g; 40 μ m ϕ ; Fuji Silysia BW 300) was added to a MeOH solution (40 cm³) of MgCl₂•6H₂O (68–806 mg). After standing for 3 h at room temperature, the solvent was evaporated and dried under reduced pressure at 50 °C for 24 h to give **3a** where the content of MgCl₂ was 3–38 wt%/SiO₂. Also the SiO₂–CaCl₂ composite **3b** with 12–31 wt%/SiO₂ content of CaCl₂ was prepared.

1a was soluble in highly polar solvents such as dimethyl sulfoxide (DMSO) and N,N-dimethylformamide but the separation of 2a from these solvents was troublesome in the followup procedure.¹³ Also toluene where **1a** was insoluble was poor solvent for the formation of 2a. Therefore, 1a (0.5 g) and SiO₂ (1.0 g)-MCl₂ **3** were suspended in MeCN (40 cm^3) where **1a** was slightly soluble and then heated under stirring in an autoclave at various temperatures. After the reaction, 3 was separated from the reactants by filtration and then the solvent was evaporated to give crude 2a. The 2a was purified by column chromatography. The yields are summarized in Table 1. The yield of 2a was plotted against the content of MCl₂ in 3 (Figure 1). The optimized content of MgCl₂ was $32 \text{ wt } \%/\text{SiO}_2$. The reaction of **1a** using SiO₂ without the MCl₂ did not provide 2a at all (Run 5). Moreover, the SiO₂-CaCl₂ composite 3b was ineffective for the formation of 2a (Run 6). Here, the formed H₂O was removed from the solvent by adsorption with SiO_2 to maintain the acidic condition of 3. The maximum yield of 2a from 1a was 70% which was obtained from the reaction at 140 °C for 24 h using 3a with 32 wt %/ SiO₂ of the content of MgCl₂ (Run 2 in Table 1). This exceeded the maximum yields $(53\%^2 \text{ and } 58\%^{14})$ reported for the heterogeneous catalytic formation of 2a from 1a so far. In homogeneous catalytic reaction, 90% yield was reported for formation of 2a from 1a using CrCl₃ in ionic liquid under microwave irradiation.¹⁵

Time-conversion plots for the transformation from **1a** to **2a** are shown in Figure 2. The yield of **2a** reached its maximum at

Table 1.	Formation	of Furfural	Derivatives	2 from	Saccha-
rides 1	Using SiO	-MCl ₂ Cor	nposite 3 ^{a)}		

Run	1	$3 (MCl_2/wt \%)^{b)}$	Temp/°C ^{c)}	2 (Yield/%)
1	1a	SiO_2-MgCl_2 (32)	160	2a (72)
2	1a	SiO_2-MgCl_2 (32)	140	2a (70)
3	1a	SiO_2-MgCl_2 (32)	120	2a (1)
4	1a	SiO ₂ –MgCl ₂ (32)	100	2a (0)
5	1a	SiO ₂	140	2a (0)
6	1a	SiO_2 -CaCl ₂ (25)	140	2a (19)
7	1b	SiO_2-MgCl_2 (32)	140	2a (10) [9] ^{d)}
8	1c	SiO_2-MgCl_2 (32)	140	2a (32) [11] ^{d)}
9	1d	SiO_2-MgCl_2 (32)	140	2a (82)
10	1e	SiO_2-MgCl_2 (32)	140	2a (32)
11	1f	SiO_2-MgCl_2 (32)	140	2a (10)
12	1g	SiO_2-MgCl_2 (32)	140	2a (31)
13	1h	SiO ₂ -MgCl ₂ (23)	180	2b (17) ^{e)}

a) Reaction was performed for MeCN (40 cm^3) containing **1** (0.5 g) and SiO₂ (1.0 g)-MCl₂ **3** at a given temperature for 24 h in autoclave. b) The values in parenthesis were the content of MCl₂ (wt%) in SiO₂. c) Reaction temperature. d) In MeCN-DMSO (9:1, 40 cm^3) at 140 °C for 24 h. e) Reaction was performed for MeCN (40 cm^3) containing **1** (2.5 g) and SiO₂ (1.0 g)-MgCl₂ (0.23 g) at 180 °C for 1.5 h.



Figure 1. Plots of yield of 5-hydroxymethyl-2-furfural (2a) against the contents of MgCl₂ (○) and CaCl₂ (◆) in SiO₂-MCl₂ composites 3 in the reaction of 1a at 140 °C for 24 h.

18 h. The dehydration reaction of **1a** was compared with that of other aldoses such as mannose (**1b**) and galactose (**1c**) and ketoses such as fructose (**1d**) and sorbose (**1e**) (Scheme 3). The conversions of **1b** and **1c** were slow. The conversion of **1d** was similar to the case of **1a**. Although A–K isomerization of both **1a** and **1b** gave the same **1d**, the conversion of **1b** was very slow compared with that of **1a**. Ketohexoses are known to produce **2a** more efficiently than aldohexoses.¹⁶ Therefore, it was suggested that the A–K isomerization was the rate-determining step in the case of **1b**. Ebitani et al. have promoted A–K isomerization of **1** using a combination of basic hydrotalcite and acidic Amberlyst-15[®].¹⁴ Moreover, it was suggested that *cis*-elimination of H₂O from the C-4 and C-5 positions of



Figure 2. Time-conversion plots of the yields of 2a in the reaction of glucose (1a; ○), mannose (1b; △), galactose (1c; ◇), fructose (1d; ●), and sorbose (1e; ▲) under 140 °C using the SiO₂-MgCl₂ (32 wt %).



Scheme 3. Monosaccharides 1a–1c, 1e, and 1h shown by Fisher projection form and fructose (1d) and disaccharides 1f and 1g written by furanose and pyranose forms.

ketoses is preferable since the conversion of 1c and 1e was slower than that of 1a and 1d. It has been reported that DMSO performs effectively as base for dehydration.¹⁷ In the present cases, however, the reaction of 1c in MeCN–DMSO (v/v 9:1) could not enhance the yield of 2a (Runs 7 and 8).

The **2a** was obtained in 10% and 31% yields from disaccharides such as cellobiose (**1f**) and sucrose (**1g**), respectively (Table 1, Runs 11 and 12). The bond-fission of the β -1,4-bond in **1f** showed the possibility of the formation of **2a** from cellulose. However, 2-furfural (**2b**) was formed from xylose (**1h**) in only a 17% yield under the optimized reaction conditions at 180 °C for 1.5 h using **3a** where the content of MgCl₂ was 23 wt %/SiO₂ (Run 13). These show that **3a** is a poor catalyst for the A–K isomerization of **1h**.

Thus, the **3a** catalyzed specifically under the dehydration of mono- and disaccharides containing glucose unit which is an abundant biomass. Since **3a** was simple composite composed of only light elements such as Mg, Si, and Cl, a low environmental damage process will be constructed in transformation from biomass to commodities.

Experimental

Materials and Instruments. Saccharides **1** were purchased from Wako Chemicals as D-forms except for L-sorbose. ¹H and ¹³C NMR spectra were taken on a Bruker AV 400M spectrometer for CDCl₃ solutions with tetramethylsilane used as an internal standard.

Dehydration of 1 in the Presence of 3. Typical procedure for the formation of **2a** from **1a** was as follows: **3a** was dried by heating at 50 °C for 3 h under reduced pressure before use. **1a** (0.5 g) and **3a** (1.0 g) were placed in an autoclave vessel. Water-free MeCN (40 cm^3) was introduced into the vessel and heated at 140 °C under stirring in the autoclave. The pressure reached 0.4 MPa. After reaction for 24 h, **3a** was separated from the reactants by filtration and then washed with CHCl₃. The solvent was evaporated to give an oily residue. **2a** was isolated from the residue by column chromatography on SiO₂ (Fuji Silysia BW 300) using CHCl₃ as an eluent. The structure of **2a** was identified by comparison of NMR spectra with an authentic sample.

5-Hydroxymethyl-2-furfural (2a): ¹H NMR: δ 4.72 (s, 2H), 6.52 (d, J = 8.7 Hz, 1H), 7.22 (d, J = 8.7 Hz, 1H), 9.59

(s, 1H); ¹³C NMR: δ 57.02, 110.06, 124.11, 151.96, 161.44, 173.05.

2-Furfural (2b): Oil. ¹H NMR: δ 6.63 (dd, J = 3.6, 1.6 Hz, 1H), 7.29 (d, J = 3.6 Hz, 1H), 7.72 (brt, J = 1.6 Hz, 1H), 9.67 (s, 1H); ¹³C NMR: δ 112.42, 121.63, 148.08, 152.64, 177.59.

References

1 X. Tong, Y. Ma, Y. Li, Appl. Catal., A 2010, 385, 1.

2 J. N. Chheda, Y. Román-Leshkov, J. A. Dumesic, Green Chem. 2007, 9, 342.

3 D. W. Harris, M. S. Feather, J. Org. Chem. 1974, 39, 724.
4 B. F. Kuster, H. S. van der Baan, Carbohydr. Res. 1977, 54, 165.

5 C. J. Moye, R. J. Goldsack, J. Appl. Chem. 1966, 16, 206.
6 S. Lima, M. Pillinger, A. A. Valente, Catal. Commun. 2008, 9, 2144.

7 Y. Nakamura, S. Morikawa, *Bull. Chem. Soc. Jpn.* **1980**, 53, 3705; J. N. Chheda, J. A. Dumesic, *Catal. Today* **2007**, *123*, 59.

8 K. Shimizu, R. Uozumi, A. Satsuma, *Catal. Commun.* 2009, 10, 1849.

9 X. Tong, Y. Ma, Y. Li, Carbohydr. Res. 2010, 345, 1698.

10 L. G. Gordeeva, I. S. Glaznev, E. V. Savchenko, V. V. Malakhov, Y. I. Aristov, *J. Colloid Interface Sci.* **2006**, *301*, 685.

11 Y. Fueda, J. Matsumoto, T. Shiragami, K. Nobuhara, M. Yasuda, *Chem. Lett.* 2007, *36*, 1246.

12 The pK_a of **3a** was determined to be 1.7 since the **3a** protonated a half of tetra(4-methoxycarbonylphenyl)porphyrin whose conjugated acid has 1.7 of pK_a .

13 K. Seri, Y. Inoue, H. Ishida, Chem. Lett. 2000, 22.

14 A. Takagaki, M. Ohara, S. Nishimura, K. Ebitani, *Chem. Commun.* **2009**, 6276.

15 C. Li, Z. Zhang, Z. K. Zhao, *Tetrahedron Lett.* **2009**, *50*, 5403.

16 M. J. Antal, Jr., W. S. L. Mok, G. N. Richards, *Carbohydr: Res.* **1990**, *199*, 91.

17 A. S. Amarasekara, L. D. Williams, C. C. Ebede, *Carbohydr. Res.* 2008, *343*, 3021.