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Stereoselective Intramolecular Dehydration of 2,5-Hexanediol in High-Temperature Liquid Water with High-Pressure Carbon Dioxide

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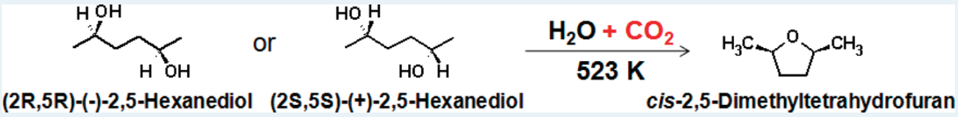

ABSTRACT: Intramolecular dehydration of chiral 2,5-hexanediol, (2*R*,5*R*)-(−)-2,5-hexanediol (2*R*,5*R*-HDO) or (2*S*,5*S*)-(+)-2,5-hexanediol (2*S*,5*S*-HDO), to *cis*-2,5-dimethyltetrahydrofuran (*cis*-2,5-DMTHF) was studied in high-temperature liquid water at 523 K. The rate of dehydration could be enhanced by adding high-pressure carbon dioxide to the reaction system. Selectivity to *cis*-2,5-DMTHF was more than 85% in the total product mixture comprising *cis*- and *trans*-2,5-DMTHF from the dehydration of 2*R*,5*R*-HDO or 2*S*,5*S*-HDO at 523 K, indicating that the intramolecular dehydration proceeded mainly via an S$_N$2 pathway in high-temperature liquid water.

KEYWORDS: stereoselective, intramolecular, dehydration, high-temperature, chiral 2,5-hexanediol, 2*R*,5*R*-HDO, 2*S*,5*S*-HDO, *cis*-2,5-DMTHF

The chemical transformation techniques of converting biomass-derived carbohydrates to valuable compounds are indispensable for establishing a sustainable society.[1−3] Dehydration reactions of biomass-derived carbohydrates, which are polyalcohol compounds such as fructose, sorbitol, and glycerol in most cases, are important to obtain valuable products with desired boiling points, water solubilities, octane numbers, and viscosities.[4] The chemistry of intramolecular dehydration of polyalcohol compounds provides a key technology for developing an efficient conversion process of biomass derivatives to useful materials.[5,6]

High-temperature liquid water has attracted much attention as a promising solvent and as an alternative to harmful organic solvents.[7,8] Self-ionization of water is highly feasible at higher temperature than that at ambient temperature, leading to high values of concentrations of proton and hydroxide ion which can enhance acid- or base-catalyzed reactions.[7,8] Furthermore, the addition of high-pressure carbon dioxide in high-temperature liquid water is reported to enhance the dehydration rate of polyalcohol compounds.[7−11] Carbon dioxide dissolves in water to form carbonic acid, accelerating the acid catalysis of high-temperature liquid water. The combination of water and carbon dioxide are environmentally benign because the added carbon dioxide can be separated easily by simple depressurization after the reaction.

In this paper, we report the stereochemistry of the intramolecular dehydration of 2,5-hexanediol (2,5-HDO) to 2,5-dimethyltetrahydrofuran (2,5-DMTHF) in high-temperature liquid water and high-pressure carbon dioxide. The dehydration reactions of (2*R*,5*R*)-(−)-2,5-hexanediol (2*R*,5*R*-HDO) or (2*S*,5*S*)-(+)-2,5-hexanediol (2*S*,5*S*-HDO) were reported previously to produce *cis*-2,5-dimethyltetrahydrofuran (*cis*-2,5-DMTHF) by phosphoric acid and both *cis*- and *trans*-2,5-dimethyltetrahydrofuran (*tarns*-2,5-DMTHF) were obtained using sulfuric acid.[12,13] In this work, we studied the intramolecular dehydration of 2,5-HDO without any strong inorganic acid and revealed the reaction mechanism of the dehydration in high-temperature liquid water.

The chiral reactants, 2*R*,5*R*-HDO and 2*S*,5*S*-HDO, were purchased from Wako Pure Chemical Industries, Ltd. and used without any further purification. The dehydration of 2,5-HDO (2*R*,5*R*-HDO or 2*S*,5*S*-HDO) was carried out in a batch reactor (inner volume: 6 cm^3) made of a SUS316 tube. 2,5-HDO aqueous solution (3 cm^3, 1 mol dm^{-3}) was loaded in the reactor, which was then purged with argon gas to remove air. Carbon dioxide (10 MPa) was then loaded in the reactor at 323 K. The reactor was submerged into a molten-salt bath at the desired reaction temperature for a given reaction time and then submerged into a water bath for cooling to ambient temperature.[14] A mixture of the reactant and liquid products was taken out from the reactor with distilled water and filtered to remove solid products. The amount of organic carbon in the liquid fraction was evaluated using a total organic carbon analyzer. The quantitative analysis of the liquid products was conducted by gas chromatography with a flame ionization detector (GC-FID) equipped with a DB-WAX capillary column (Agilent Technologies) using 1-propanol as an internal standard material. The products, *cis*-2,5-DMTHF and *trans*-2,5-DMTHF, were analyzed by two discriminable peaks of GC-FID and spectra of ^{1}H and ^{13}C NMR.

Dehydration of 1.0 mol dm^{-3} 2*R*,5*R*-HDO or 2*S*,5*S*-HDO proceeded slowly in water at 523 K (Figure 1) without adding carbon dioxide, as shown by the yield of product, 2,5-DMTHF, 6% even for 5 h. 2,5-DMTHF (mixture of *cis* and *trans* form) was the sole liquid product from the intramolecular dehydration of 2*R*,5*R*-HDO. The dehydration of 2*S*,5*S*-HDO in water at 523 K

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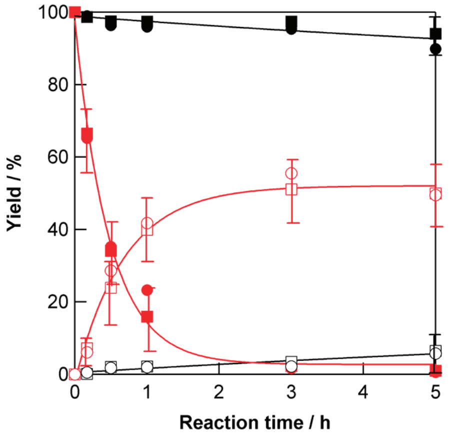


Figure 1. Yields of 2,5-DMTHF (sum of *cis* and *trans* form) and 2,5-HDO as a function of elapsed time for the 2*R*,5*R*-HDO or 2*S*,5*S*-HDO dehydration reactions at 523 K in water (initial 2,5-HDO concentration: 1.0 mol dm^{-3}; ●: 2*R*,5*R*-HDO, ○: 2,5-DMTHF from 2*R*,5*R*-HDO, ■: 2*S*,5*S*-HDO, □: 2,5-DMTHF from 2*S*,5*S*-HDO; carbon dioxide partial pressure: 0 (black) and 17.7 (red) MPa). The bars indicate the range of error for yields of 2*S*,5*S*-HDO and 2,5-DMTHF from 2*S*,5*S*-HDO.

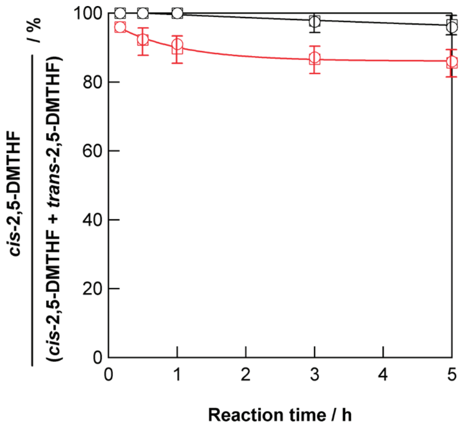


Figure 2. Percentage of *cis*-2,5-DMTHF in the product of total 2,5-DMTHF (sum of *cis* and *trans* form) as a function of elapsed time for the 2*R*,5*R*-HDO or 2*S*,5*S*-HDO dehydration reactions at 523 K in water (initial 2,5-HDO concentration: 1.0 mol dm^{-3}; reactant: 2*R*,5*R*-HDO (○), 2*S*,5*S*-HDO (□); carbon dioxide partial pressure: 0 (black) and 17.7 (red) MPa). The bars indicate range of error for the data of reactant 2*S*,5*S*-HDO.

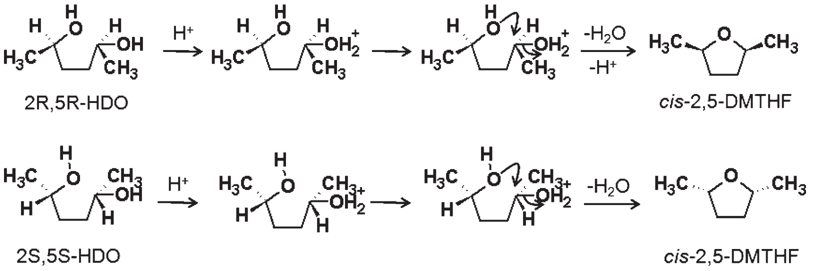
without carbon dioxide also provide 2,5-DMTHF (mixture of *cis* and *trans* form), of which yields were almost the same as those from the 2*R*,5*R*-HDO dehydration (Figure 1).

The dehydration of 2*R*,5*R*-HDO to 2,5-DMTHF was enhanced by the addition of high-pressure carbon dioxide (Figure 1). The initial formation rate of 2,5-DMTHF from the 2*R*,5*R*-HDO dehydration increased by more than 50 times by the addition of carbon dioxide. 2,5-DMTHF was the sole liquid product from the 2*R*,5*R*-HDO dehydration even when carbon dioxide was added. The dehydration of 2*S*,5*S*-HDO in water at 523 K in the presence of 10 MPa of carbon dioxide also proceeded much faster than that without carbon dioxide. The 2,5-DMTHF yields from 2*S*,5*S*-HDO in water at 523 K with the addition of carbon dioxide were almost the same as those from 2*R*,5*R*-HDO dehydration. The intramolecular dehydration reaction of 2,5-HDO to 2,5-DMTHF was catalyzed by the protons in high-temperature water,[12,13] the concentration of which was increased by the addition of high-pressure carbon dioxide because of the formation of carbonic acid.[7−11] The pH was estimated to be 4 in high-temperature liquid water (523 K) with high-pressure carbon dioxide (10 MPa).[15]

The material balance, defined as total yield of 2,5-HDO and 2,5-DMTHF, decreased with reaction time for the 2*R*,5*R*-HDO or 2*S*,5*S*-HDO dehydration with carbon dioxide. The material balance for the dehydration (3 h) of 2*R*,5*R*-HDO or 2*S*,5*S*-HDO in the presence of carbon dioxide was 60%, equivalent to the amount of total organic carbon estimated as 60% in the liquid phase. This result indicated that the products in the liquid phase were only 2,5-HDO and 2,5-DMTHF and that the solid products, such as polymers, would be formed during the dehydration of 2,5-HDO in high-temperature liquid water. We investigated the stability of 2,5-DMTHF (mixture of *cis* and *trans* form) in water at 523 K in the same reaction conditions as those for the 2,5-HDO dehydration reaction, using 0.3 mol dm^{-3} 2,5-DMTHF aqueous solution instead of 2,5-HDO aqueous solution. The reverse reaction (formation of 2,5-HDO) was not observed during the high-temperature water treatment of 2,5-DMTHF, and the recovery yield of 2,5-DMTHF was 50% for 3 h at 523 K under both conditions, with and without carbon dioxide. The total organic carbon (50%) in the liquid phase after the high-temperature water treatment of 2,5-DMTHF was almost the same as the recovery yield of 2,5-DMTHF, indicating that no liquid products were formed from 2,5-DMTHF and that solid products would be formed by the ring-opening polymerization of 2,5-DMTHF. We also carried out the dehydration of 2*R*,5*R*-HDO to 2,5-DMTHF in high-temperature liquid water at the higher reaction temperature of 573 K with and without carbon dioxide. The reactant 2*R*,5*R*-HDO almost disappeared within 0.5 h at 573 K with carbon dioxide; however, the 2,5-DMTHF yield was only 30%. The total organic carbon was also 30% in the liquid phase after the dehydration reaction, indicating that polymerization reaction would occur predominantly at 573 K.

Figure 2 shows the percentage of *cis*-2,5-DMTHF (*cis* selectivity) in the total product mixture of *cis*- and *trans*-2,5-DMTHF from the dehydration of 1.0 mol dm^{-3} 2*R*,5*R*-HDO or 2*S*,5*S*-HDO in water at 523 K. The *cis* selectivities of 2,5-DMTHF from 2*R*,5*R*-HDO dehydration were almost the same as those from 2*S*,5*S*-HDO dehydration under all the experimental conditions (Figure 2), indicating that dehydration reactions of 2*R*,5*R*-HDO and 2*S*,5*S*-HDO in high-temperature liquid water were identical in terms of product yields (Figure 1) and selectivities (Figure 2). The *cis* selectivities of 2,5-DMTHF were more than 85% under all the experimental conditions for both 2*R*,5*R*-HDO and 2*S*,5*S*-HDO dehydration at 523 K, indicating that sterically hindered *cis*-2,5-DMTHF, which was thermodynamically less stable than *trans*-2,5-DMTHF, was produced preferentially from 2*R*,5*R*-HDO or 2*S*,5*S*-HDO in high-temperature liquid water. We confirmed that the isomerization reaction between *cis*-2,5-DMTHF and *trans*-2,5-DMTHF did not proceed in high-temperature liquid water with high-pressure carbon dioxide at 523 K for 5 h. The high *cis* selectivities of 2,5-DMTHF from the 2*R*,5*R*-HDO and 2*S*,5*S*-HDO dehydration demonstrated that 2,5-HDO dehydration proceeded via an S_N2 substitution of a protonated hydroxyl group as shown in Scheme 1. At first, hydroxyl group at C2 or C5 position was protonated, and then oxygen atom in a non-protonated hydroxyl group attacked the carbon atom with a protonated hydroxyl group and simultaneously water molecule was eliminated (Scheme 1). The 2*R*,5*R*-HDO or 2*S*,5*S*-HDO dehydration by concentrated sulfuric acid

Scheme 1. Reaction Pathway of (2*R*,5*R*)-(−)-2,5-hexanediol and (2*S*,5*S*)-(+)-2,5-hexanediol Dehydration



at 293 K was reported to produce a mixture of *cis*-2,5-DMTHF (ca. 50%) and *trans*-2,5-DMTHF (ca. 50%).[12,13] The strong affinity of concentrated sulfuric acid for water is sufficient to eliminate a water molecule from protonated 2,5-HDO to form the carbocation, and the 2,5-HDO dehydration proceeds via S_N1 mechanism by concentrated sulfuric acid.

In summary, we successfully demonstrated that the combination of high-temperature liquid water and high-pressure carbon dioxide was beneficial in providing protons for the stereoselective intramolecular dehydration of chiral 2,5-hexanediol. This technique can be extended to other acid-catalyzed reactions, which will lead to an environmentally benign technology for the conversion of biomass derivatives to valuable chemicals.

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REFERENCES

(1) Ragauskas, A. J.; Williams, C. K.; Davison, B. H.; Britovsek, G.; Cairney, J.; Eckert, C. A.; Frederick, J., W. J.; Hallett, J. P.; Leak, D. J.; Liotta, C. L.; Mielenz, J. R.; Murphy, R.; Templer, R.; Tschaplinski, T. *Science* **2006,** *311*, 484–489.

(2) Huber, G. W.; Iborra, S.; Corma, A. *Chem. Rev.* **2006,** *106*, 4044–4098.

(3) Corma, A.; Iborra, S.; Velty, A. *Chem. Rev.* **2007,** *107*, 2411–2502.

(4) Roman-Leshkov, Y.; Barrett, C. J.; Liu, Z. Y.; Dumesic, J. A. *Nature* **2007**, *447*, 982–985.

(5) *Top value added chemicals from biomass*; Technical report, 2004; Pacific Northwest National Laboratory and National Renewable Energy Laboratory: Richland, WA, 2004.

(6) Tong, X.; Ma, Y.; Li, Y. *Appl. Catal., A* **2010,** *385*, 1–13.

(7) Hunter, S. E.; Ehrenberger, C. E.; Savage, P. E. *J. Org. Chem.* **2006**, *71*, 6229–6239.

(8) Hunter, S. E.; Savage, P. E. *Ind. Eng. Chem. Res.* **2003,** *42*, 290–294.

(9) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Bando, K. K.; Shirai, M. *Green Chem.* **2009,** *11*, 48–52.

(10) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Rode, C. V.; Shirai, M. *Chem. Lett.* **2008,** *37*, 926–927.

(11) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Shirai, M. *Top. Catal.* **2010,** *53*, 487–491.

(12) Mihailovic, M. L.; Gojkovic, S.; Cekovic, Z. *J. Chem. Soc., Perkin Trans. 1* **1972,** 2460–2464.

(13) Molnar, A.; Felfoldi, K.; Bartok, M. *Tetrahedron* **1981,** *37*, 2149–2151.

(14) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Osada, M.; Shirai, M. *Energy Fuels* **2008,** *22*, 1485–1492.

(15) Hunter, S. E.; Savage, P. E. *AIChE J.* **2008,** *54*, 516–528.