DOI: 10.1002/cssc.201402965

Xylose Isomerization with Zeolites in a Two-Step Alcohol–Water Process

Marta Paniagua,[a] Shunmugavel Saravanamurugan,[b] Mayra Melian-Rodriguez,[b] Juan A. Melero,[a] and Anders Riisager*[b]

Isomerization of xylose to xylulose was efficiently catalyzed by large-pore zeolites in a two-step methanol–water process that enhanced the product yield significantly. The reaction pathway involves xylose isomerization to xylulose, which, in part, subsequently reacts with methanol to form methyl xyluloside (step 1) followed by hydrolysis after water addition to form additional xylulose (step 2). NMR spectroscopy studies performed with ^{13}C-labeled xylose confirmed the proposed reaction pathway. The most active catalyst examined was zeolite Y, which proved more active than zeolite beta, ZSM-5, and mordenite. The yield of xylulose obtained over H-USY (Si/Al = 6) after 1 h of reaction at 100 °C was 39%. After water hydrolysis in the second reaction step, the yield increased to 47%. Results obtained from pyridine adsorption studies confirm that H-USY (6) is a catalyst that combines Brønsted and Lewis acid sites, and isomerizes xylose in alcohol media to form xylulose at low temperature. The applied zeolites are commercially available; do not contain any auxiliary tetravalent metals, for example, tin, titanium, or zirconium; isomerize xylose efficiently; are easy to regenerate; and are prone to recycling.

Introduction

Biofuels and biochemicals are progressively pursued as alternatives for fossil-based products due to diminishing availability, uneven localization, and increasing price of currently used petroleum resources.[1–5] Lignocellulosic biomass is a promising feedstock because it is the cheapest, most abundant, and fastest growing form of terrestrial biomass as well as the only inedible and sustainable source of carbon.[6,7] The major components of lignocellulosic biomass are cellulose (40–50 wt%), hemicellulose (25–40 wt%), and lignin (10–25 wt%). Hemicellulose is an easily hydrolysable amorphous polymer composed of five different sugars—D-xylose, L-arabinose, D-galactose, D-glucose, and D-mannose—of which xylose is the most common.[8]

Catalytic dehydration of xylose to produce furfural offers an attractive transformation process. Furfural is presently the most common industrial chemical derived from lignocellulosic biomass, and serves as a potential platform for biofuels for which it can be used as a feedstock to make gasoline, diesel, or jet fuel.[9,10] Direct xylose dehydration into furfural has a relatively high activation barrier of 124 kJ mol^{-1} and is therefore carried out at high temperatures (> 150 °C) in aqueous medium.[11] However, under these conditions, furfural is very reactive, and insoluble carbonaceous polymers (i.e., humins) with lower activation energy of formation ($\approx$70 kJ mol^{-1}) often decrease the yield.[12] The conversion of xylose into furfural can alternatively be carried out in two steps: isomerization of xylose to form xylulose followed by dehydration to furfural over homo- and heterogeneous catalytic systems at moderate temperatures.[13,14] Previously, it was found that xylose did not form furfural in water with Amberlyst-15 or hydrochloric acid at low temperatures.[11] In contrast, xylulose conversion was 66% and a furfural yield of 24% was found under identical conditions; this suggested that xylulose dehydration proceeded readily through Brønsted acid catalysis. Hence, the efficient formation of xylulose from xylose is a key step for efficient furfural production.

The isomerization of xylose to xylulose is assumed to occur through an intramolecular 1,2-hydride shift, similar to the conversion of glucose to fructose,[15] and can be carried out with the enzyme glucose/xylose isomerase (GI). The equilibrium mixture of xylose (73%) and xylulose (27%) has been achieved with immobilized GI at 70 °C and at pH 7.[16] However, GI possesses some technical deficiencies that affect its industrial suitability, for example, inactivation above 60 °C, narrow pH operation optima, Ca^{2+}-ion inhibition (needed for action of amylase if liquefaction, saccharification, and isomerization are carried out simultaneously), prerequisite for a Co^{2+}-ion promoter, and suboptimal concentrations of the product.[17] To circumvent some of these issues, chemocatalytic routes have been studied as an alternative to GI.

Takagaki et al. used hydrotalcite as a basic catalyst and DMF as the solvent for isomerization–dehydration to form furfural

---

[a] *Dr. M. Paniagua,+ Prof. J. A. Melero*
Chemical and Environmental Engineering Group, ESCET
Universidad Rey Juan Carlos, C/Tulipán s/n, E-28933
Móstoles, Madrid (Spain)

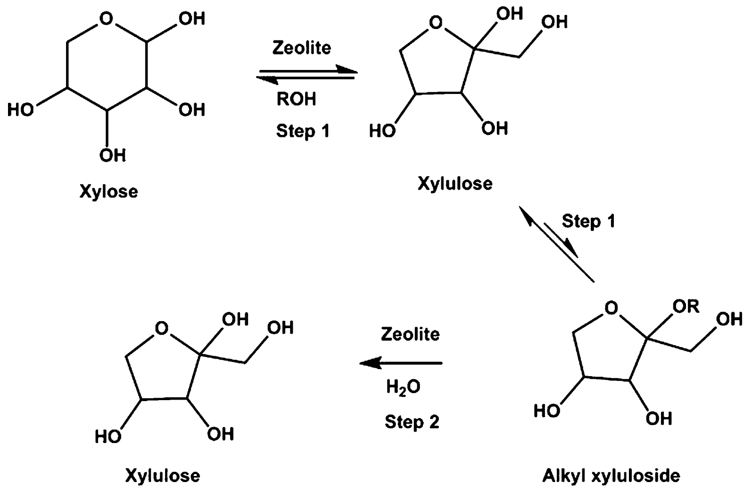
[b] *Dr. S. Saravanamurugan,+ M. Melian-Rodriguez, Prof. A. Riisager*
Centre for Catalysis and Sustainable Chemistry
Department of Chemistry, Technical University of Denmark
2800 Kgs. Lyngby (Denmark)
Fax: (+45) 45883136
E-mail: ar@kemi.dtu.dk

[+] *These authors contributed equally to this work.*

Supporting Information for this article is available on the WWW under http://dx.doi.org/10.1002/cssc.201402965.

from xylose,[13] whereas Binder et al. examined chromium halide in *N*,*N*-dimethylacetamide (DMA).[14] Despite the improved yield of furfural at low temperatures, both studies employed high-boiling organic solvents that increased the cost of the separation of products from the solvent. Alternative studies have focused on xylose isomerization to form xylulose in aqueous medium by using zeolite catalysts.[11,18,19] Hence, Lew et al. found that both Sn-MFI and Sn-BEA zeolites isomerized xylose,[18] and after reaction for 210 min at 90 °C moderate yields of 19 and 24 % of xylulose, respectively, were obtained, although the conversion of xylose was almost twice as high for the latter catalyst.[18] Also, Choudhary et al. reported a maximum yield to xylulose of 27 % by using Sn-beta zeolite, with a corresponding yield to lyxose of 11 % at a xylose conversion of 60 % in 7 min at 110 °C and 15 min at 100 °C, respectively.[11]

We have very recently demonstrated that large-pore zeolites Y and beta afforded efficient isomerization of aldohexose glucose to ketohexose fructose in alcohol (especially methanol) and aqueous media by following a two-step, batch protocol.[20] Notably, the yields obtained in the process were even higher than those reported with biological catalysts. These promising results have encouraged us to examine whether the strategy is also applicable to the isomerization of aldopentoses contained in hemicellulose to the corresponding ketopentoses. Thus, herein, the protocol is successfully introduced for xylose isomerization to form xylulose (Scheme 1).



Scheme 1. A plausible reaction pathway for the formation of xylulose from xylose through the isomerization of xylose and etherification to give an alkyl xyluloside in alcohol (step 1) followed by hydrolysis (step 2).

Results and Discussion

Screening of various zeolites

Xylose can be converted into methyl xylulosides in methanol in the presence of acids.[21] To produce xylulose, a subsequent hydrolysis step is needed. The isomerization of xylose to xylulose was studied with several types of commercial zeolites at 100 °C with 1 h of reaction time (step 1), followed by water addition and another hour of reaction (step 2), to obtain xylulose from the generated methyl xyluloside (Scheme 1 and Table 1).

Table 1. Product distribution obtained for xylose conversion over commercial zeolite catalysts after the first and second reaction steps.[a]

Zeolite	Si/Al ratio	Step	Product distribution [mol %]				B/L ratio[c]
			xylose	xylulose	lyxose	methyl xyluloside	
H-Y	2.6	1	66	23	trace	<1	0.49
		2	65	25	trace	<1	
H-USY	6	1	31	39	trace	13	1.07
		2	31	47	trace	4	
	30	1	92	4	trace	5	0.95
		2	87	4	trace	4	
H-Beta	12.5	1	46	31	trace	11	0.76
		2	45	39	trace	5	
	19	1	71	16	trace	8	0.33
		2	71	20	trace	5	
	150	1	>99	trace	trace	–	
		2	>99	trace	trace	–	
H-USY[b]	6	1	trace	29	25	8	
		2	trace	37	26	2	

[a] Reaction conditions: Step 1: catalyst (75 mg), xylose (125 mg), methanol (4 g), 1 h, 100 °C; Step 2: water (4 g), 1 h, 100 °C. [b] Lyxose was used as a substrate. [c] Ratio of Brønsted to Lewis acid sites based on pyridine adsorption studies.

When H-USY (6) and H-Beta (12.5) were used as catalysts for the two-step reaction, good yields of 47 and 39 % of xylulose, respectively, were obtained after the second reaction step with 4 g of water, as shown in Table 1. Concurrently, the yields of methyl xyluloside were 13 and 11 % over H-USY (6) and H-beta (12.5), respectively, after the first step, and dropped down to 4 and 5 % after the second step, respectively; these results corroborated that methyl xyluloside hydrolyzed to form xylulose. Moreover, a trace amount of lyxose, which is the epimer of xylose, was observed by HPLC analysis (Figure S1 in the Supporting Information), whereas furfural, which is the dehydration product of xylose, was not found. These values closely resemble the results obtained in the isomerization of glucose to fructose with the same zeolites in methanol and aqueous media.[20]

The influence of different zeolites on the yield of xylulose was evaluated by comparing the reaction time required to obtain similar xylose conversions (69–83 %) after the first reaction step (Table 2). The results in Table 2 confirm that H-USY (6) was the most active of the tested catalysts, giving a yield of 33 % xylulose after 3 h of reaction, whereas H-USY (30) required a significantly longer reaction time of 44 h to reach a comparable xylulose yield of 36 %. Although the numbers of acid sites were higher for H-Y (2.6) than the rest of the catalysts used, it needed a longer reaction time (24 h) to attain a 29 % yield of xylulose. Moreover, H-Beta (19) and H-USY (30) yielded 21 and 19 % of methyl xyluloside, respectively, along with xylulose after a prolonged reaction time; this implies that these zeolites somehow stabilize methyl xyluloside. However, further studies are required to obtain a better understanding

Table 2. The activity of zeolites at similar xylose conversions after the first reaction step.[a]

Zeolite	Si/Al ratio	Reaction time [h]	Xylose conversion [%]	Yield [%] xylulose	Yield [%] methyl xyluloside
H-USY	6	3	76	33	13
H-Beta	12.5	6	72	29	12
	19	24	79	30	21
H-Y	2.6	24	83	29	9
H-USY	30	44	69	36	19

[a] Reaction conditions: catalyst (75 mg), xylose (125 mg), methanol (4 g), 100 °C.

of this stabilization. Additionally, the activity of the zeolites was compared at low conversion of xylose (below 15%) and the obtained results proved that H-USY (6) and H-Beta (12.5) were the active catalysts among the zeolites employed, yielding more xylulose (9%) than the other zeolites (Table S1 in the Supporting Information).

To obtain further information about the relationship between methyl xyluloside formation and xylulose yield, a time-course study was performed for the conversion of xylose with the preferred H-USY (6) catalyst. Figure 1 shows a normalized relative distribution of the reactant and products obtained at 100 °C as a function of reaction time. After 3 h of reaction, a thermodynamic equilibrium of xylose/xylulose/methyl xyluloside corresponding to 28:53:19% was apparently reached, which remained unchanged after 6 h of reaction. In this 3–6 h time interval, 38% yield of xylulose was formed and 20% yield of xylose remained unconverted (Table S2 in the Supporting Information). When the reaction time was prolonged to 24 h, the xylulose yield dropped to 19% as the formation of (unidentified) byproducts increased.

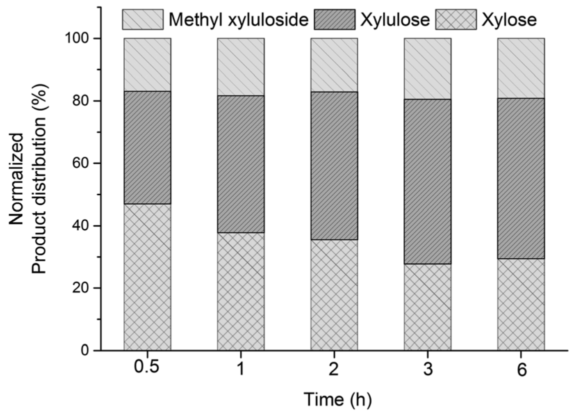


Figure 1. Equilibrium study between xylose, xylulose, and methyl xyluloside after the first reaction step (reaction conditions: 75 mg of H-USY (6), 125 mg of xylose, 4 g of methanol, 100 °C).

From the equilibrium study between xylose, xylulose, and methyl xyluloside, the two thermodynamic equilibrium constants involved were calculated to be K_1 = [xylulose]/[xylose] = 53:28 = 1.89 and K_2 = [methyl xyluloside]/[xylulose] = 19:53 = 0.36. The value of K_2 was constant after 1 h of reaction, whereas K_1 levelled out after 2 h of reaction (Table S2 in the Supporting Information); this implied that the formation of xylulose from xylose was faster than the formation of methyl xyluloside from xylulose. Moreover, standard Gibbs free reaction energies were calculated for the reactions by using the equation $\Delta_r G^o = -RT(\ln K)$, resulting in $-1.98\ \mathrm{kJ\,mol^{-1}}$ for the formation of xylulose from xylose and $+3.18\ \mathrm{kJ\,mol^{-1}}$ for the formation of methyl xyluloside from xylulose.

To substantiate the proposed reaction pathway (Scheme 1), the conversion of lyxose (epimer of xylose, isomer of xylulose) was also studied over H-USY (6) under identical reaction conditions to those used for xylose. After the first reaction step, xylulose (29%) and methyl xyluloside (8%) were the major products formed and a trace amount of xylose was also observed (Table 1). These results established that the three isomers—xylose, xylulose, and lyxose—could be interconverted to a small extent in alcohol media, as also previously found for the corresponding C6 sugars (glucose, fructose, and mannose).[20] When water was added to the reaction mixture in the second reaction step, the relative amount of xylulose formed (from 29 to 37%) was comparable to that obtained with xylose (from 39 to 47%). However, lyxose was apparently more reactive than xylose because 26% remained unconverted compared with 31% for xylose. From results of HPLC analysis, it was further inferred that the amount of byproducts (unidentified) did indeed prevail for the lyxose experiment; thus confirming that xylose had a lower tendency to form unwanted products than lyxose.

Furthermore, ^{13}C-labeled xylose was also used as a substrate for isomerization to form xylose. In the experiment, D-[2-^{13}C]-xylose (20 mg) was dissolved in CD_3OD (1.74 g) in presence of H-USY (6) (13 mg) and the reaction was run at 100 °C for 1 h, after which time the reaction mixture was subjected to NMR spectroscopic analysis (^{13}C chemical shifts are reported relative to the solvent CD_3OD, $\delta = 47.8$ ppm; Figure S2 in the Supporting Information). After the first reaction step, two major signals assigned to α- and β-methyl xyluloside were observed at $\delta =$ 105.0 and 109.0 ppm, respectively, along with a minor signal at $\delta = 103.3$ ppm. After the second hydrolysis step, the intensity of the low-field signals were significantly reduced, whereas the intensity of the signal at 103.3 ppm increased and a new signal appeared at $\delta = 106.4$ ppm. In accordance with the proposed reaction pathway, these signals are ascribed to xylulose (β- and α-xylulose), and the chemical shift values are close to the values reported for xylulose in D_2O.[21]

It is known that alkaline catalysts are able to perform sugar isomerization reactions.[13,22–24] Hence, zeolite Na-Y (2.6) was also tested in the current two-step xylose isomerization protocol. As expected, the alkaline catalyst was found to isomerize xylose to some degree, but was incapable of catalyzing the etherification of xylose to form methyl xyluloside. Accordingly, the maximum yield of xylulose produced over Na-Y (2.6) was around 3%, with 6% conversion of xylose. Different kinds of sulfonic acid functionalized SBA-15 catalysts were also tested in the xylose isomerization reaction. However, these catalysts were also unable to isomerize xylose to form xylulose under the applied reaction conditions, as also observed previously for glucose isomerization in which no fructose formed.[25] In combination, these results confirmed that Lewis acidity was necessary to carry out xylose isomerization in alcohol.

Effect of zeolite acidity

The role of acidity for the zeolites used was elucidated in our previous work by temperature-programmed desorption of ammonia (NH_3-TPD) analysis with glucose isomerization. In accordance with this analysis, the highest yields of xylulose were obtained with H-USY (6), which had a ratio of medium (type 1, $T_{desorb} = 100–270\,^{\circ}C$) to strong (type 2, $T_{desorb} = 270–500\,^{\circ}C$) acid sites of 1:0.81 and with H-Beta (12.5) at a ratio of 1:0.52.[20,26,27] Above or below the mentioned acid site ratios, or for zeolites with a lower number of total acid sites, a lower yield of xylulose was obtained (Table S3 in the Supporting Information).

When the H-USY catalysts were subjected to ^{27}Al MAS-NMR spectroscopic analysis, the presence of tetrahedral aluminum (major signal, $\delta_3 \approx 60$ ppm), a very small amount of pentacoordinated or tetrahedrally distorted aluminum (minor signal, $\delta_2 \approx 20–40$ ppm), and octahedrally coordinated aluminum (major signal, $\delta_1 \approx 0$ ppm) were observed, as also reported in previous studies with zeolite USY.[28,29] Assuming that most of the Brønsted and Lewis acidity is generated from tetra- (δ_3) and octahedral (δ_1) aluminum species, respectively, the Brønsted/Lewis acid site ratios of H-USY (6) and H-USY (30) were measured to be 1:0.795 and 1:0.361, respectively. However, it has previously been reported that Lewis acid sites also can be generated from aluminum present in a non-tetrahedral environment.[29] Accordingly, it is not apparent that Lewis and Brønsted acid sites can be directly related from Al magic angle spinning (MAS) NMR spectroscopic analysis.

To gain more insight and to further substantiate the presence of acid sites in the zeolite, selected zeolites were subjected to pyridine adsorption studies to correlate the role and the influence of the ratio of Brønsted to Lewis acid sites (B/L) on the product distributions found. It is known that the isomerization of xylose to form xylulose can take place in the presence of Lewis acid sites,[30] since it is important for the first reaction step, as shown in Scheme 1. From the results given in Table 1, it can be inferred that the B/L ratios of the zeolites correlate with the yield of xylulose as follows: H-USY (6) > H-Beta (12.5) > H-Y (2.6) > H-Beta (19). Moreover, we found that H-USY (6) with a B/L ratio of 1.07 had a relatively large acidity of 650 μequiv. H^+ per g, which might be important for improving the yield of xylulose by facilitating both an initial high conversion of xylulose into alkyl xyluloside and subsequent hydrolysis. In comparison, H-USY (30), with a similar B/L ratio of 0.95, but only 290 μequiv. H^+ per g, that is, more than twofold lower than that of H-USY (6), yielded only 4% of xylulose after the reaction steps (Figure S3 in the Supporting Information). In agreement with the present study, West et al. determined that H-USY (6) contained a larger fraction of weaker Lewis acid sites compared to H-USY (30) by FTIR using pyridine as probe molecule.[30] Based on observations from the acid sites measurements, we speculate that weak Lewis acid sites could be responsible for the isomerization of xylose to form xylulose, whereas medium/strong Brønsted acid sites could be responsible for the etherification of xylulose and hydrolysis of methyl xyluloside. Consequently, the activity correlates both with the total number of acid sites and B/L ratio; a tertiary role of acid site strength also seems to be important.

Effect of reaction parameters

Prolonged reaction time and increased temperature promoted the conversion of xylose. Hu et al., however, showed that methyl xylulosides degraded slightly in methanol at 130 °C under a prolonged reaction time to produce 2-(dimethoxymethyl)furan and furfural, and that 150 °C resulted in significant degradation of the methyl xylulosides.[31] As shown in Figure 2, increases in the conversion of xylose and in xylulose production were also found with increased temperature over H-USY (6) in the current study. However, it was preferential to perform the reaction at low temperature to avoid sugar degradation, that is, the carbon mass balance decreased at higher temperature. Based on these results, additional experiments were conducted at low temperature and longer reaction times, and it was confirmed that similar results (41% of xylulose) could be obtained at 60 °C and 24 h of reaction.

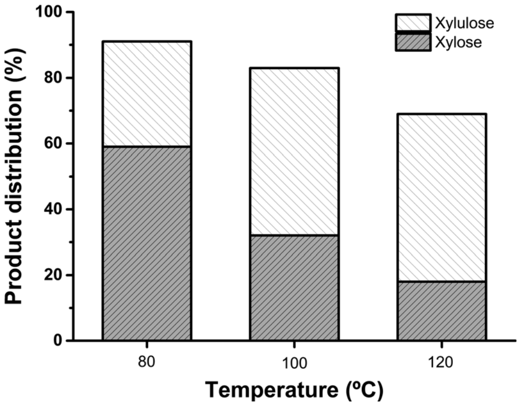


Figure 2. Influence of reaction temperature on the conversion of xylose into xylulose after the second reaction step (reaction conditions: Step 1: 75 mg of H-USY (6), 125 mg of xylose, 4 g of methanol, 1 h; Step 2: 4 g of water, 1 h).

When the isomerization reaction was carried out in pure aqueous media, no xylulose production was observed. This result highlights the important role of the alcohol (methanol) in shifting the reaction towards methyl xyluloside formation. Hence, the catalysts studied were not able to isomerize sugars in water. Changing the solvent from methanol to ethanol led to the formation of the corresponding ethyl xyluloside (Figure 3). Like for methanol, an increased amount of xylulose was observed after the addition of water in the second reaction step with ethanol. However, xylulose etherification with ethanol seemed to be more difficult to accomplish, probably due to steric impediments. Therefore, less xylulose and more byproducts were detected in comparison with methanol.

The initial xylose concentration may influence the isomerization rate, and thus, the productivity of the conversion process.

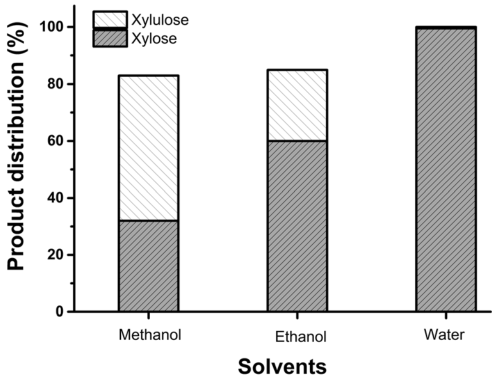


Figure 3. Comparison of different solvents for the conversion of xylose into xylulose after the second reaction step (reaction conditions: Step 1: 75 mg of H-USY (6), 125 mg of xylose, 4 g of solvent, 1 h, 100 °C; Step 2: 4 g of water, 1 h, 100 °C).

Therefore, experiments were also carried out over H-USY (6) with an increased initial concentration of xylose. Notably, in all of these experiments, the catalyst was added after ensuring complete dissolution of xylose in methanol. The results in Figure 4 show a progressive decrease in the obtained yield of xylulose: at 3 wt% of the initial xylose concentration, the xylulose yield reached 51%, whereas at 16.7 wt% only 26% yield was reached after 1 h of reaction. Because the overall yield of xylose and xylulose remained constant, this tendency was probably related to a rate difference caused by the larger amount of water formed during etherification at a higher xylose concentration. Accordingly, it was possible to increase the xylulose yield from 36 to 42% with 9.1 wt% of the initial xylose concentration by prolonging the reaction time to 2 h for both the first and second reaction steps.

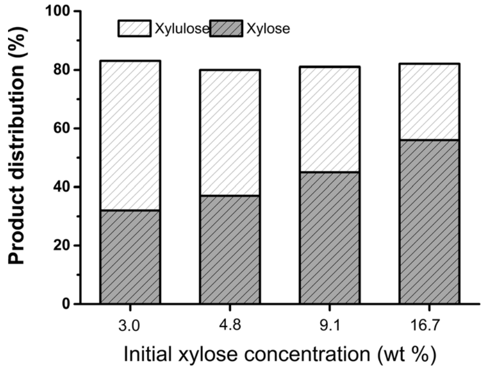


Figure 4. Effect of the initial xylose concentration for the conversion of xylose after the second reaction step (reaction conditions: Step 1: 75 mg of H-USY (6), 4 g of methanol, 1 h, 100 °C; Step 2: 4 g of water, 1 h, 100 °C).

The influence of the amount of H-USY (6) catalyst loading on the product yield and distribution was also examined, and the results are compiled in Table 3 and Table S4 in the Supporting Information. As expected, the yield of xylulose decreased after the second step, if the amount of catalyst loading was lowered and the other reaction conditions were unaltered. However, by individual adjustment of the reaction times of the two consecutive reaction steps, it proved possible to maintain a fairly good yield of 36% of xylulose, even when using a low amount of catalyst of 5 mg, corresponding to $m_{\text{xylose}}/m_{\text{cat.}}=25$.

Table 3. Influence of H-USY (6) catalyst loading on product distribution obtained for xylose conversion after the first and second reaction steps.[a]

$m_{\text{cat.}}$ [mg]	$m_{\text{xylose}}/m_{\text{cat.}}$	Step	Reaction time [h]	Product distribution [%]	
				xylose	xylulose
5	25	1	1	80	7
			24	46	27
		2	1	42	36
20	6.3	1	1	65	13
			5	43	29
		2	1	39	37
30	4.2	1	1	49	18
			3	43	31
		2	2	39	41
50	2.5	1	1	38	31
		2	2	37	44
75	1.7	1	1	31	39
		2	1	31	47

[a] Reaction conditions: Step 1: xylose (125 mg), methanol (4 g), 100 °C; Step 2: water (4 g), 100 °C.

Catalyst recycling

Catalyst reusability was finally evaluated for the preferred H-USY (6) catalyst. Figure 5 depicts the results of three consecutive catalytic runs performed by reusing the catalyst under optimal reaction conditions with $m_{\text{xylose}}/m_{\text{cat.}}=4.2$. After each catalytic run, the catalyst was regenerated by calcination at 550 °C for 6 h before being used again in the next reaction.

The results in Figure 5 indicate a slight loss of catalyst performance after the third reaction run, resulting in a decrease in the xylulose yield from 48 to 32%, which suggests that H-USY (6) might have lost active sites. However, performing the recycling experiments with a lower xylose/catalyst mass ratio of 1.7 enabled a constant xylulose yield of 40–50% to be maintained throughout five consecutive runs (Tables S5 and S6 in the Sup-

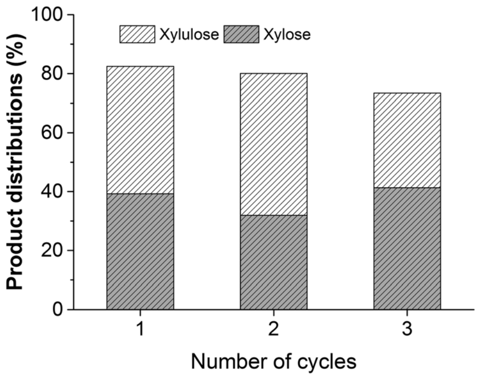


Figure 5. Reuse of H-USY (6) for xylose conversion after the second reaction step (reaction conditions: Step 1: mass ratio xylose/catalyst = 4.2, 4 g of methanol, 3 h, 100 °C; Step 2: 4 g of water, 1 h, 100 °C).

porting Information). The catalyst was recovered by simple filtration before being washed thoroughly with methanol and dried overnight at 140 °C (not calcined) before reuse. Importantly, unconverted xylose was also preserved; thus making regeneration of the catalyst by calcination unnecessary (e.g., to remove deposited humins). After the fifth reaction run, the catalyst was calcined at 550 °C for 6 h and then subjected to analysis by nitrogen sorption. The formal BET area and pore volume of H-USY (6) before use was 708 $m^2 g^{-1}$ and 0.2436 $cm^3 g^{-1}$, respectively. After the fifth reaction run, these values were essentially unchanged (701 $m^2 g^{-1}$ and 0.2442 $cm^3 g^{-1}$), which corroborated that the structural integrity of the zeolite was indeed maintained after five cycles. Hence, the reusability study indicates that the catalyst is capable of being reused, and thus, is potentially applicable for long-term use on a technical scale.

Conclusions

This study demonstrated that large-pore zeolites were excellent heterogeneous catalysts for the isomerization of xylose and subsequent etherification with methanol. Accordingly, a two-step reaction pathway recently proposed for the isomerization of glucose to form fructose (hexose isomerization)[20] was also applicable to produce xylulose from xylose (pentose isomerization). The best result was obtained by using zeolite H-USY containing an optimal level of Brønsted and Lewis acidity (Si/Al ratio of 6). Moreover, excellent catalyst reutilization was exhibited by H-USY (6), which maintained the same initial activity in five consecutive runs without any intermediate regeneration treatment, such as calcination. A catalyst such as H-USY (6), which combines Brønsted and Lewis acid sites, is a highly promising catalyst, since it facilitates sugar isomerization, an etherification step and final hydrolysis to yield the xylulose compound at low temperatures, while maintaining low reactivity towards the formation of undesired byproducts.

Experimental Section

Materials

D-Xylose (99%) was acquired from Sigma. D-Lyxose (99%), methanol (99.9%), ethanol (99.9%), 1-propanol (99.7%), and CD_3OD were obtained from Sigma–Aldrich. D-Xylulose (1.0 M aqueous solution) and D-[2-^{13}C]-xylose were purchased from Omicron Biochemicals.
All commercially available zeolites used herein were purchased from Zeolyst International as pure materials in the NH_4 form without binders. The zeolites were calcined at 550 °C in air for 6 h prior to use to produce the acidic forms.

Catalyst characterization

^{13}C NMR spectra were recorded on a Bruker AM360 NMR spectrometer in CD_3OD and water at 25 °C, and signal positions are reported relative to the solvent (CD_3OD: $\delta = 48.27$ ppm). ^{27}Al MAS-NMR spectroscopic analyses were conducted at room temperature at a magnetic field strength of 9.4 T on a Varian Infinity AS400 NMR spectrometer operating at 104.16 MHz. MAS NMR spectra were obtained by using a 4 mm T3HX Varian MAS probe with spinning rates of 12000 rpm. Solid-state 1D single-pulse ^{27}Al MAS NMR spectra were recorded with a 3.5 μs pulse, a recycle delay of 1 s, and 5000 transients.

The number of acid sites present in the zeolites was measured by NH_3-TPD by using AutoChem II 2920 apparatus from Micromeritics. About 100 mg of sample was placed in a quartz reactor and degassed at 500 °C for 1 h in helium (50 mL min^{-1}), after which time ammonia (50 mL min^{-1}) was administrated to the sample at 100 °C for 2 h. The sample was concurrently flushed with helium (50 mL min^{-1}) to remove any physisorbed ammonia before chemisorbed ammonia was desorbed by temperature ramping (10 °C min^{-1}) from 100 to 500 °C. The number of acid sites was calculated as the area under the desorption curve.

BET areas were calculated by performing nitrogen adsorption and desorption measurements at the temperature of liquid nitrogen by using a Micromeritics ASAP 2020 instrument. The samples were degassed under vacuum at 200 °C prior to measurements being taken.

Pyridine adsorption studies were carried out by means of diffuse reflectance IR Fourier transform (DRIFT) spectra obtained by using a Nicolet Avatar 370 MCT spectrometer with a Smart Collector accessory, mid/near-IR source, and mercury cadmium telluride (MCT-A) photon detector at the temperature of liquid nitrogen. Ex situ pyridine adsorption was performed by exposure of samples diluted with KBr powder (10 wt% in KBr) to pyridine vapor in a desiccator overnight. Excess physisorbed pyridine was removed in a vacuum oven. Thereafter, samples were loaded into the environmental cell and subjected to additional drying under vacuum at 110 °C for 10 min prior to measurements being taken to remove moisture physisorbed during air exposure. Finally, spectra were recorded at 25 °C in vacuum. The acid strength was estimated as the ratio between the FTIR intensities of Brønsted ($\tilde{\nu} = 1542$ cm^{-1}) and Lewis acid sites ($\tilde{\nu} = 1447$ cm^{-1}) in the DRIFT spectra.

Reaction procedure

The isomerization reactions were carried out in Ace pressure tubes by following a two-step procedure, as shown in Scheme 1. For the first reaction step, zeolite catalyst (75 mg (11–75 μmol of acid sites based on NH_3-TPD studies[20])), sugar (125 mg, 0.83 mmol, 3 wt% with regard to methanol), and alcohol (4 g) were added and mixed in the pressure tube by magnetic stirring (for experiments with higher sugar concentration, xylose was dissolved completely in methanol before adding the catalyst). The tube was then placed in a preheated, thermally controlled oil bath and the reaction temperature adjusted to a reaction temperature of 40–120 °C while being magnetically stirred (600 rpm). After a desired reaction time, the tube was removed from the oil bath and rapidly cooled. In the second reaction step, water (4 mL) was added to the reaction mixture and the tube was reheated in an oil bath under stirring at 100 °C for 1 h before finally being cooled for analysis.

Analysis of reaction products

Reaction samples were analyzed by HPLC and quantified from standards. Xylose ($R_f = 9.76$ min) was analyzed on a HPLC Agilent 1200 Series instrument equipped with an Aminex HPX-87H column (Bio-Rad) by using 0.005 M aqueous sulfuric acid as the eluent at a flow rate of 0.6 mL min^{-1} and a column temperature of 60 °C. Xylulose ($R_f = 14.4$ min) and lyxose ($R_f = 14.84$ min) were analyzed on a HPLC Agilent 1200 Series instrument equipped with a Rezex

RCM-Monosaccharide Ca^{2+} column (Phenomenex) by using MiliQ water as the mobile phase at a flow rate of 0.6 mL min^{-1} and a column temperature of 80 °C. Both HPLC instruments were equipped with a refractive index detector. A combination of columns was required for analysis because xylulose, lyxose, and their corresponding alkyl derivatives eluted at the same retention time when using the Aminex column, whereas xylose and methyl xyluloside eluted at similar retention times with the Monosaccharide column. The quantification of methyl xyluloside from HPLC was difficult because a reference was not commercially available, but identification was established by ^{13}C NMR spectroscopic analysis.

Catalytic results are reported in terms of molar product distribution, that is, the molar amount of each product present in the reaction mixture divided by the total molar amount of starting sugar.

Acknowledgements

M.P. and J.A.M. are thankful for financial support from the "Ministerio de Ciencia e Innovación" of Spain through the project CTQ2011-28216, and from the Regional Government of Madrid through the project S2013-MAE-2882. S.S., M.M.-R., and A.R thank the Danish Council for Independent Research-Technology and Production Sciences (project no. 10-081991), The Catalysis for Sustainable Energy initiative funded by the Danish Ministry of Science, Technology and Innovation, as well as Haldor Topsøe A/S for financial support of the work. Dr. Jinesh Cherukkattu Manayil of EBRI, Aston University, is acknowledged for the acid site measurements.

Keywords: alcohols · heterogeneous catalysis · isomerization · NMR spectroscopy · zeolites

[1] G. W. Huber, S. Iborra, A. Corma, *Chem. Rev.* **2006**, *106*, 4044.
[2] M. E. Himmel, S.-Y. Ding, D. K. Johnson, W. S. Adney, M. R. Nimlos, J. W. Brady, T. D. Foust, *Science* **2007**, *315*, 804.
[3] J. N. Chheda, G. W. Huber, J. A. Dumesic, *Angew. Chem. Int. Ed.* **2007**, *46*, 7164; *Angew. Chem.* **2007**, *119*, 7298.
[4] M. S. Holm, S. Saravanamurugan, E. Taarning, *Science* **2010**, *328*, 602.
[5] S. Saravanamurugan, O. N. Van Buu, A. Riisager, *ChemSusChem* **2011**, *4*, 723.
[6] Y.-C. Lin, G. W. Huber, *Energy Environ. Sci.* **2009**, *2*, 68.
[7] A. Corma, S. Iborra, A. Velty, *Chem. Rev.* **2007**, *107*, 2411.
[8] D. M. Alonso, J. Q. Bond, J. A. Dumesic, *Green Chem.* **2010**, *12*, 1493.
[9] S. Dutta, S. De, B. Saha, M. I. Alam, *Catal. Sci. Technol.* **2012**, *2*, 2025.
[10] G. W. Huber, J. N. Chheda, C. J. Barrett, J. A. Dumesic, *Science* **2005**, *308*, 1446.
[11] V. Choudhary, A. B. Pinar, S. I. Sandler, D. G. Vlachos, R. F. Lobo, *ACS Catal.* **2011**, *1*, 1724.
[12] R. Weingarten, G. A. Tompsett, W. C. Conner, Jr., G. W. Huber, *J. Catal.* **2011**, *279*, 174.
[13] A. Takagaki, M. Ohara, S. Nishimura, K. Ebitani, *Chem. Lett.* **2010**, *39*, 838.
[14] J. B. Binder, J. J. Blank, A. V. Cefali, R. T. Raines, *ChemSusChem* **2010**, *3*, 1268.
[15] Y. Román-Leshkov, M. Moliner, J. A. Labinger, M. E. Davis, *Angew. Chem. Int. Ed.* **2010**, *49*, 8954; *Angew. Chem.* **2010**, *122*, 9138.
[16] J. T. Pronk, A. W. Bakker, H. E. van Damt, A. J. J. Straathot, W. A. Scheffers, J. P. van Dijken, *Enzyme Microb. Technol.* **1988**, *10*, 537.
[17] S. H. Bhosale, M. B. Rao, V. V. Deshpande, *Microbiol. Rev.* **1996**, *60*, 280.
[18] C. M. Lew, N. Rajabbeigi, M. Tsapatsis, *Microporous Mesoporous Mater.* **2012**, *153*, 55.
[19] M. S. Holm, S. Saravanamurugan, Y. J. Pagán-Torres, A. Riisager, J. A. Dumesic, E. Taarning, *Green Chem.* **2012**, *14*, 702.
[20] S. Saravanamurugan, M. Paniagua, J. A. Melero, A. Riisager, *J. Am. Chem. Soc.* **2013**, *135*, 5246.
[21] T. Vuorinen, A. S. Seerianni, *Carbohydr. Res.* **1991**, *209*, 13.
[22] C. Moreau, R. Durand, A. Roux, D. Tichit, *Appl. Catal. A* **2000**, *193*, 257.
[23] S. Lima, A. S. Dias, Z. Lin, P. Brandão, P. Ferreira, M. Pillinger, J. Rocha, V. Calvino-Casilda, A. A. Valente, *Appl. Catal. A* **2008**, *339*, 21.
[24] R. O. L. Souza, D. P. Fabiano, C. Feche, F. Rataboul, D. Cardoso, N. Essayem, *Catal. Today* **2012**, *195*, 114.
[25] S. Saravanamurugan, A. Riisager, *Catal. Commun.* **2012**, *17*, 71.
[26] S. Saravanamurugan, A. Riisager, Patent Application No. WO2014020153A1..
[27] S. Saravanamurugan, A. Riisager, *ChemCatChem* **2013**, *5*, 1754.
[28] A. Corma, V. Fornes, A. Martinez, J. Sanz, *ACS Symp. Ser.* **1988**, *375*, 17.
[29] P. J. Kunkeler, B. J. Zuurdeeg, J. C. van der Waal, J. A. van Bokhoven, D. C. Koningsberger, H. van Bekkam, *J. Catal.* **1998**, *180*, 234.
[30] R. M. West, M. S. Holm, S. Saravanamurugan, J. Xiong, Z. Beversdorf, E. Taarning, C. H. Christensen, *J. Catal.* **2010**, *269*, 122.
[31] X. Hu, C. Lievens, C.-Z. Li, *ChemSusChem* **2012**, *5*, 1427.

Received: September 8, 2014
Revised: December 5, 2014