

Isomerization of aldo-pentoses into keto-pentoses catalyzed by phosphates

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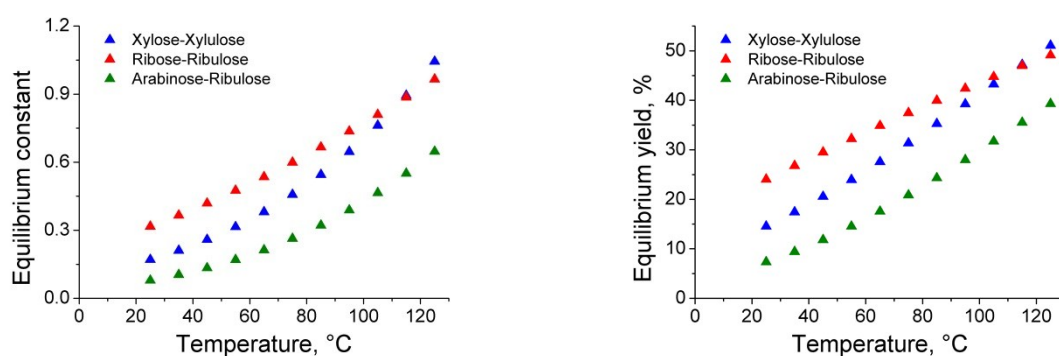
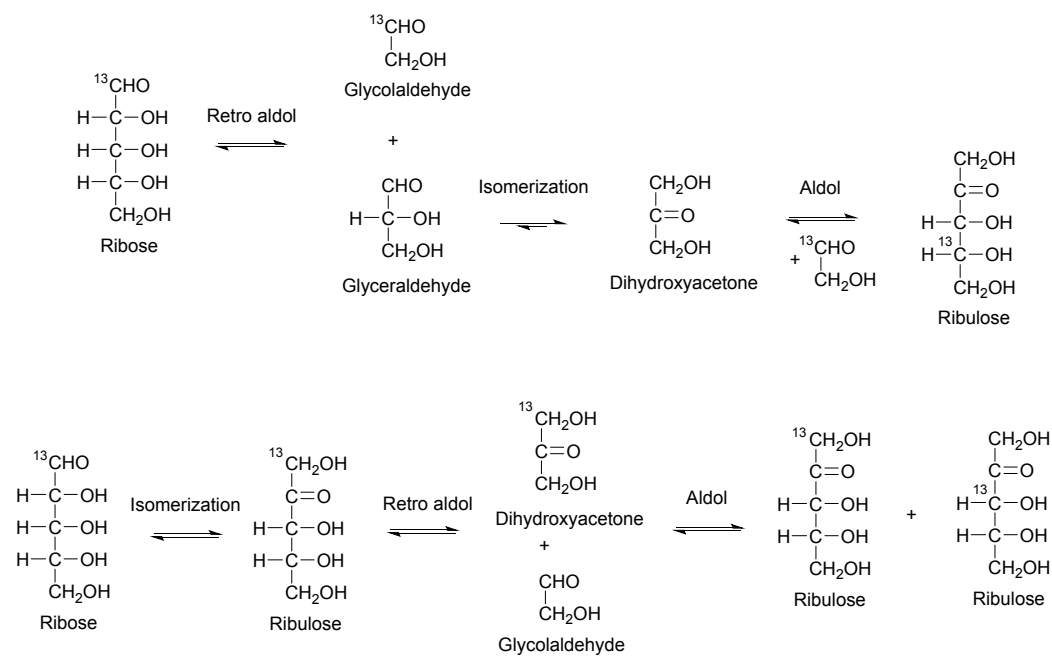


Fig. 1S Equilibrium constants of the isomerization reactions (left) and equilibrium yields (right) of keto-pentoses as functions of temperature according to the thermodynamic data reported by Tewari et al.^{1, 2}



Scheme 1S. Isotope label scrambling with D-(1-¹³C)-ribose as a substrate via consecutive retro aldol and aldol reactions. According to the previously published data, isomerization of glyceraldehyde into dihydroxyacetone (shown in the upper sequence of reactions) is highly favorable in the presence of NaH₂PO₄+Na₂HPO₄.³

Table 1S. Assignments of the resonance signals in the NMR spectra recorded after the isomerization of D-(1-¹³C)-ribose in the presence of NaH₂PO₄+Na₂HPO₄ (Fig. 2). F and P denote a furanose and a pyranose cyclic form, respectively.

Peak number	Chemical shift, ppm	Assignment of the resonance signal
1	103.6	C2-β-Xylulose
2	101.6	C1-βF-Ribose
3	97.4	C1-αP-Arabinose
4	96.9	C1-αF-Ribose
5	94.5	C1-βP-Ribose
6	94.2	C1-αP-Ribose
7	72.5	C5-α-Xylulose
8	71.3	C5-β-Ribulose
9	70.5	C5-β-Xylulose
10	67.0	C1-keto-Ribulose
11	66.6	C1-keto-Xylulose
12	63.7	C1-β-Xylulose
13	63.4	C1-α-Ribulose
14	63.2	C1-β-Ribulose
15	63.1	C1-α-Xylulose
M	49.5	Methanol (internal standard)

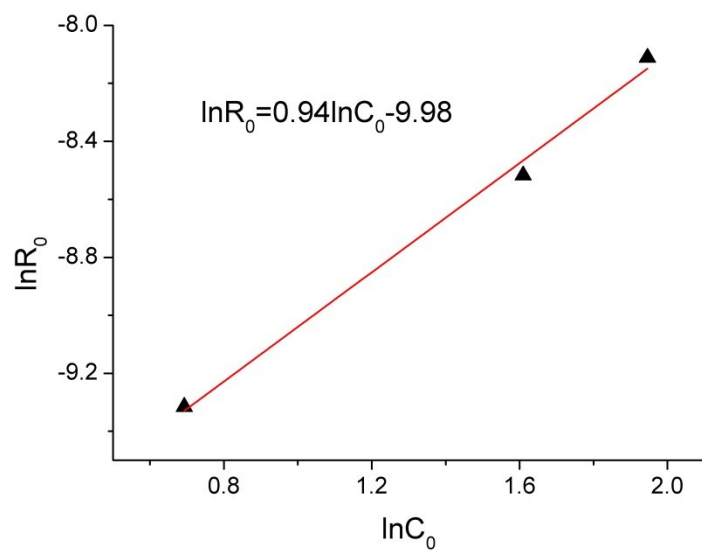
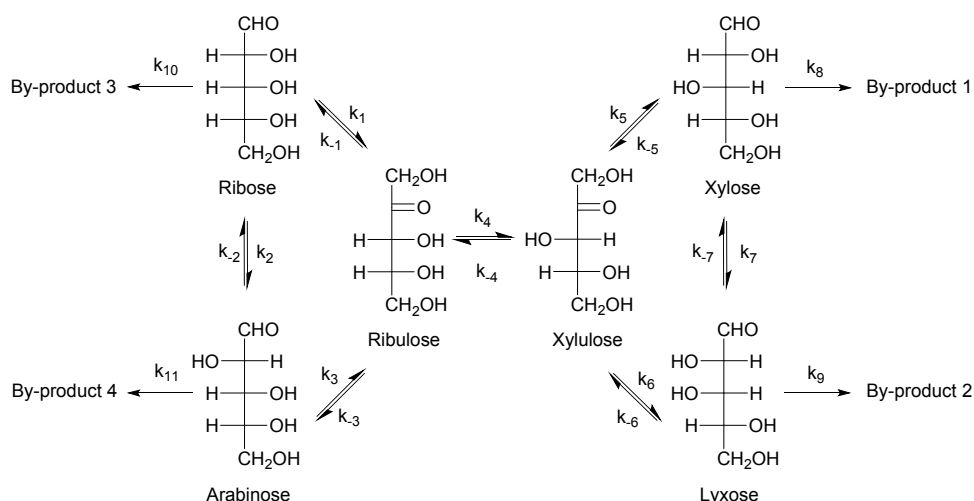


Fig. 2S. Linearized dependence of R_0 , the initial reaction rate of xylose isomerization, on C_0 , the initial concentration of xylose to determine the reaction order α : $\ln R_0 = \alpha \ln C_0 + \ln k$. Reaction conditions: 2, 5 or 7 wt.% aqueous solution of a substrate, 78°C, 750 rpm, 0.5M $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$.



Scheme 2S. Extended reaction network used for kinetic modeling

Based on this reaction network, we derive the following system of ordinary differential equations (ODEs):

$$\frac{d[\text{Ribose}]}{dt} = -(k_1 + k_2 + k_{10}) \cdot [\text{Ribose}] + k_{-1} \cdot [\text{Ribulose}] + k_{-2} \cdot [\text{Arabinose}] \quad (1S)$$

$$\frac{d[\text{Arabinose}]}{dt} = -(k_{-2} + k_3 + k_{11}) \cdot [\text{Arabinose}] + k_{-3} \cdot [\text{Ribulose}] + k_2 \cdot [\text{Ribose}] \quad (2S)$$

$$\frac{d[\text{Ribulose}]}{dt} = -(k_{-1} + k_{-3} + k_4) \cdot [\text{Ribulose}] + k_1 \cdot [\text{Ribose}] + k_{-4} \cdot [\text{Xylulose}] + k_3 \cdot [\text{Arabinose}] \quad (3S)$$

$$\frac{d[\text{Xylulose}]}{dt} = -(k_{-4} + k_5 + k_6) \cdot [\text{Xylulose}] + k_4 \cdot [\text{Ribulose}] + k_{-5} \cdot [\text{Xylose}] + k_{-6} \cdot [\text{Lyxose}] \quad (4S)$$

$$\frac{d[\text{Xylose}]}{dt} = -(k_{-5} + k_7 + k_8) \cdot [\text{Xylose}] + k_5 \cdot [\text{Xylulose}] + k_{-7} \cdot [\text{Lyxose}] \quad (5S)$$

$$\frac{d[\text{Lyxose}]}{dt} = -(k_{-6} + k_{-7} + k_9) \cdot [\text{Lyxose}] + k_6 \cdot [\text{Xylulose}] + k_7 \cdot [\text{Xylose}] \quad (6S)$$

$$\frac{d[\text{By-product 1}]}{dt} = k_8 \cdot [\text{Xylose}] \quad (7S)$$

$$\frac{d[\text{By-product 2}]}{dt} = k_9 \cdot [\text{Lyxose}] \quad (8S)$$

$$\frac{d[\text{By-product 3}]}{dt} = k_{10} \cdot [\text{Ribose}] \quad (9S)$$

$$\frac{d[\text{By-product 4}]}{dt} = k_{11} \cdot [\text{Arabinose}] \quad (10S)$$

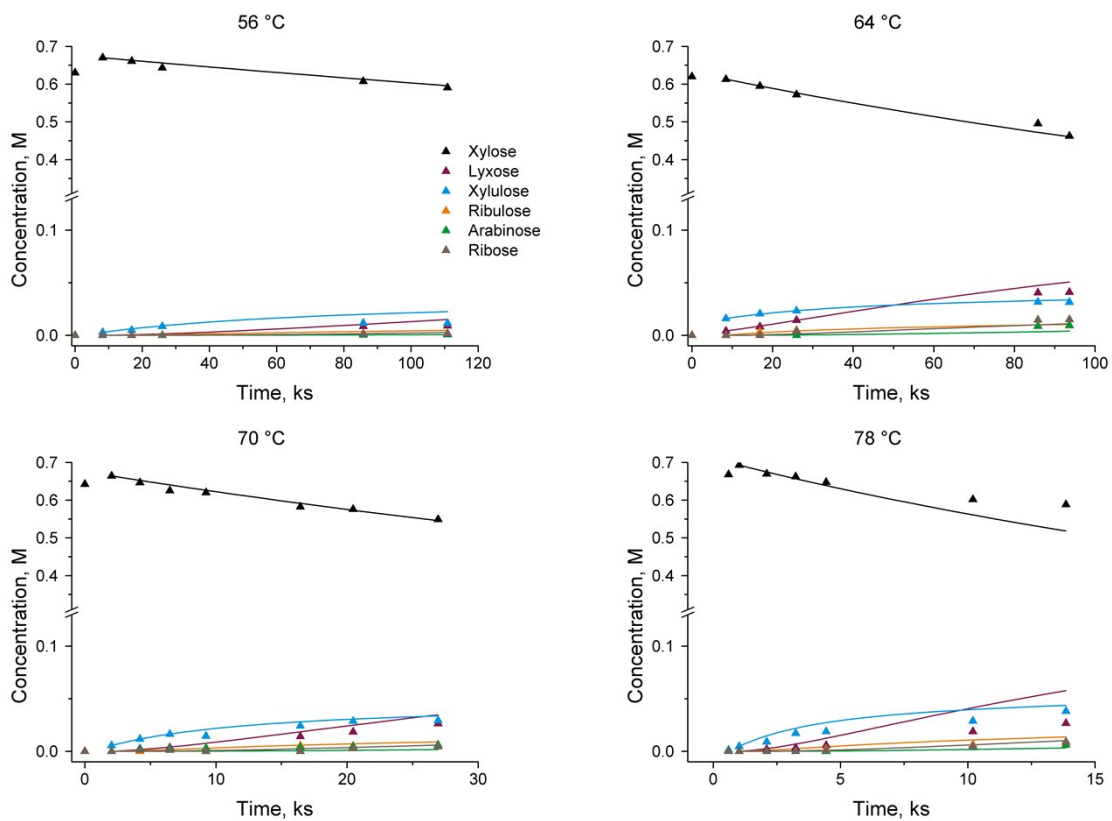


Fig. 3S. Model (solid line) and experimental data (markers) of xylose isomerization in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at different temperatures. Reaction conditions: 10wt. % of the substrate, 0.5M $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at pH 7.5, 750 rpm.

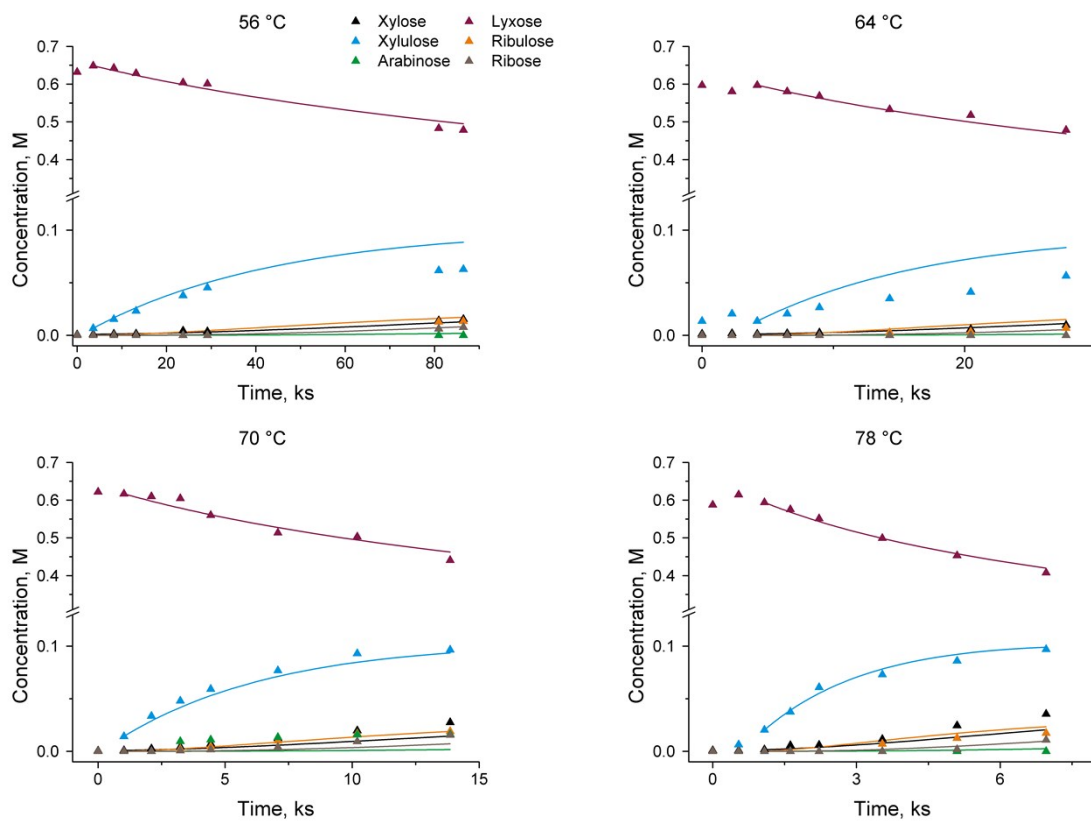


Fig. 4S. Model (solid line) and experimental data (markers) of lyxose isomerization in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at different temperatures. Reaction conditions: 10wt. % of the substrate, 0.5M $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at pH 7.5, 750 rpm.

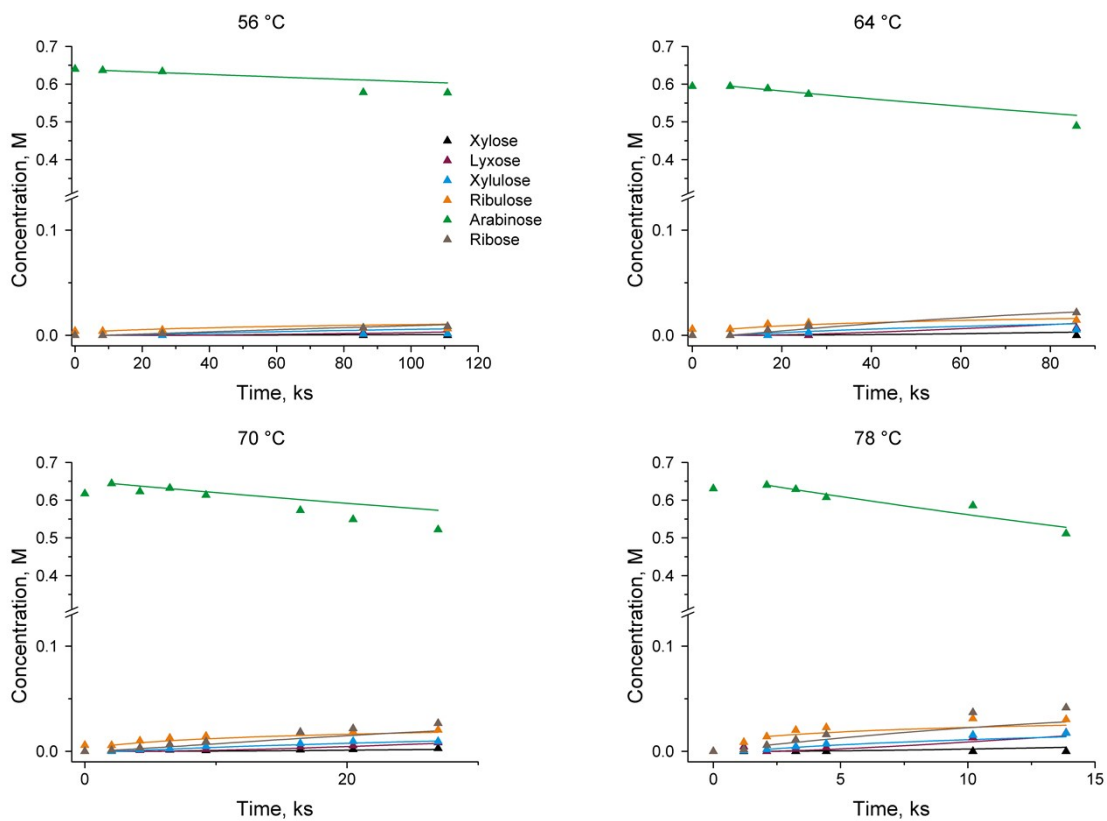


Fig. 5S. Model (solid line) and experimental data (markers) of arabinose isomerization in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at different temperatures. Reaction conditions: 10wt. % of the substrate, 0.5M $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at pH 7.5, 750 rpm.

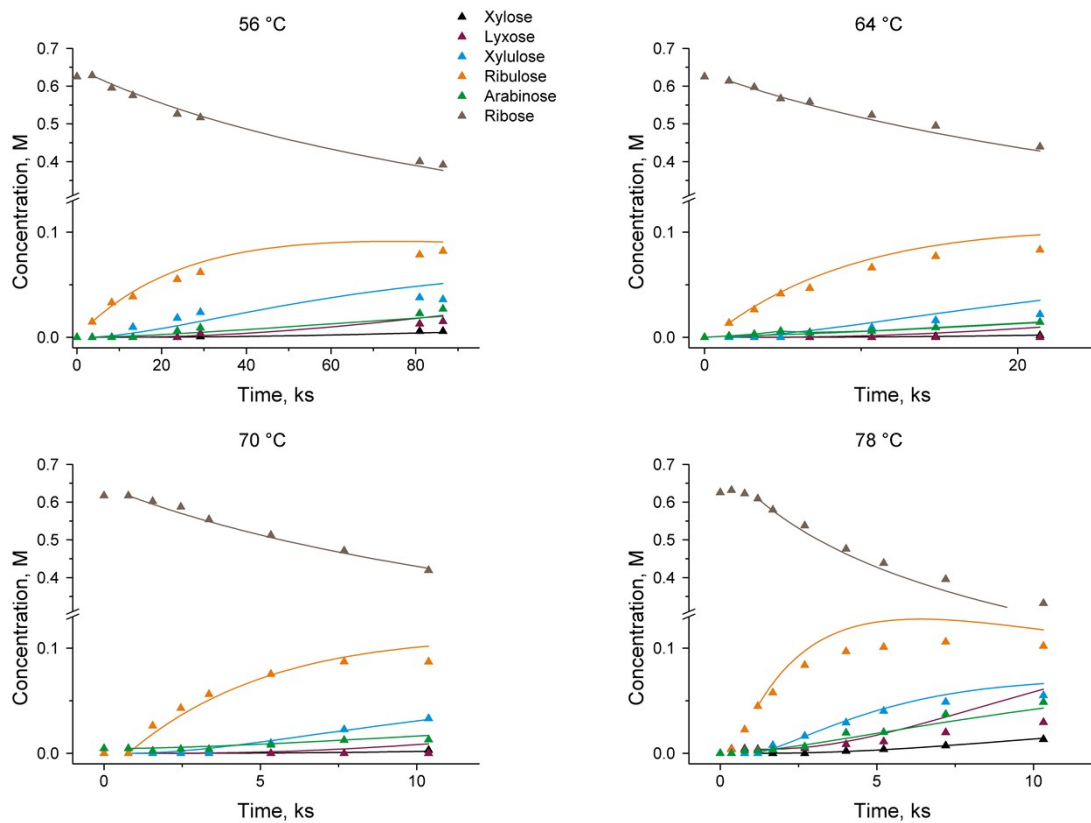


Fig. 6S. Model (solid line) and experimental data (markers) of ribose isomerization in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at different temperatures. Reaction conditions: 10wt. % of the substrate, 0.5M $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ at pH 7.5, 750 rpm.

Table 2S. Effective pre-exponential factors (k_0) and activation energies (E_a) obtained for the degradation of pentoses in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$.

Reaction	$\ln k_0$	E_a , kJ/mol
Xylose $\xrightarrow{k_8}$ By-products	25.6	110
Lyxose $\xrightarrow{k_9}$ By-products	33.7	131
Ribose $\xrightarrow{k_{10}}$ By-products	18.5	87
Arabinose $\xrightarrow{k_{11}}$ By-products	58.6	206

Table 3S. Comparison of the obtained values for the equilibrium constants (K) with the literature data

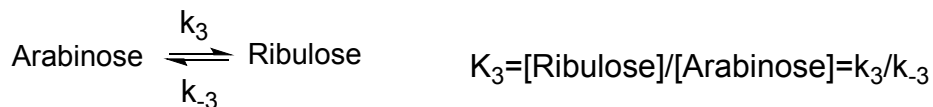
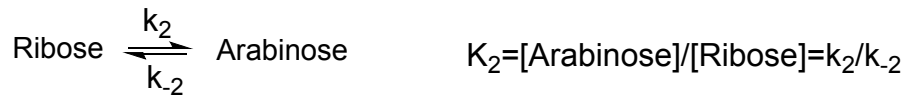
Reaction	Expression for K value ^a	K at 78°C obtained in this work	K at 78°C, literature data
Ribose \rightleftharpoons Ribulose	$K_1=k_1/k_{-1}$	0.66	0.62 ²
Ribose \rightleftharpoons Arabinose	$K_2=k_2/k_{-2}$	1.9	2.2 ²
Arabinose \rightleftharpoons Ribulose	$K_3=k_3/k_{-3}$	0.28	0.29 ²
Ribulose \rightleftharpoons Xylulose	$K_4=k_4/k_{-4}$	1.6	No data
Xylose \rightleftharpoons Xylulose	$K_5=k_{-5}/k_5$	0.45	0.45 ¹
Lyxose \rightleftharpoons Xylulose	$K_6=k_{-6}/k_6$	0.37	No data
Lyxose \rightleftharpoons Xylose	$K_7=k_{-7}/k_7$	1.44	1.4 ^{b 4}

^aExpressions were derived in accordance with the reaction network presented in Scheme 2S.

^bTemperature was not specified in the reference.

Estimating accuracy of rate constants

Interconversions of ribose-ribulose-arabinose and their equilibrium constants can be presented as follows:



A certain combination of the equilibrium constants would be equal to 1 because a microscopic reversibility determines the Gibbs energy of the cycles equal to zero:

$$Y = 1 = \frac{[\text{Ribulose}]}{[\text{Ribose}]} \cdot \frac{[\text{Arabinose}]}{[\text{Ribulose}]} \cdot \frac{[\text{Ribose}]}{[\text{Arabinose}]} = \frac{K_1}{K_3 \cdot K_2} = \frac{k_1}{k_{-1}} \cdot \frac{k_{-3}}{k_3} \cdot \frac{k_{-2}}{k_2} \quad (11S)$$

An absolute error of a function $Y(x_1, x_2, \dots, x_n)$ can be calculated as follows:

$$\Delta Y = \sum_{i=1}^n \left| \frac{\partial Y}{\partial x_i} \cdot \Delta x_i \right| \quad (12S)$$

In our case $Y(k_1, k_{-1}, k_2, k_{-2}, k_3, k_{-3}) = (k_1 \cdot k_{-3} \cdot k_{-2}) / (k_{-1} \cdot k_3 \cdot k_2)$, as indicated by the equation (11S). Assuming the same relative error for all the obtained rate constants, i.e. $\Delta k_i/k_i$ is independent of i , the following formula could be derived after differentiation of the Y function:

$$\frac{\Delta Y}{Y} = \sum_{i=1}^n \frac{\Delta k_i}{k_i} = 6 \frac{\Delta k_i}{k_i} \quad (13S)$$

As a result, a relative rate of determining the rate constants can be estimated as follows:

$$\frac{\Delta k_i}{k_i} = \left(\frac{\Delta Y}{Y} \right) / 6 \quad (14S)$$

Thus obtained values are provided in Table 4S. The same approach was used to calculate the relative errors of the rate constants of lyxose-xylulose-xylose interconversions.

Table 4S. Estimating relative errors of determining the rate constants ($\Delta k_i/k_i$)

Entry	Temperature, °C	$Y_{\text{calc}}^{\text{a}}$	$\Delta Y/Y, \%^{\text{b}}$	$\Delta k_i/k_i, \%$
Ribose-ribulose-arabinose, $Y=(k_1 \cdot k_3 \cdot k_2)/(k_1 \cdot k_3 \cdot k_2)$				
1	56	2.5	150	25
2	64	1.7	70	12
3	70	1.3	30	5
4	78	0.9	10	2
Lyxose-xylulose-xylose, $Y=(k_5 \cdot k_6 \cdot k_7)/(k_5 \cdot k_6 \cdot k_7)$				
5	56	1.4	40	7
6	64	1.5	50	8
7	70	1.6	60	10
8	78	1.8	80	13

^a Y_{calc} denotes Y value calculated according to the equation (11S) based on the determined rate constants;

^b Relative error of Y was determined as follows: $\Delta Y/Y=(|Y_{\text{calc}}-Y_{\text{true}}|/Y_{\text{true}}) \cdot 100\%$, where $Y_{\text{true}}=1$, since Gibbs energy of the cycles is equal to zero.

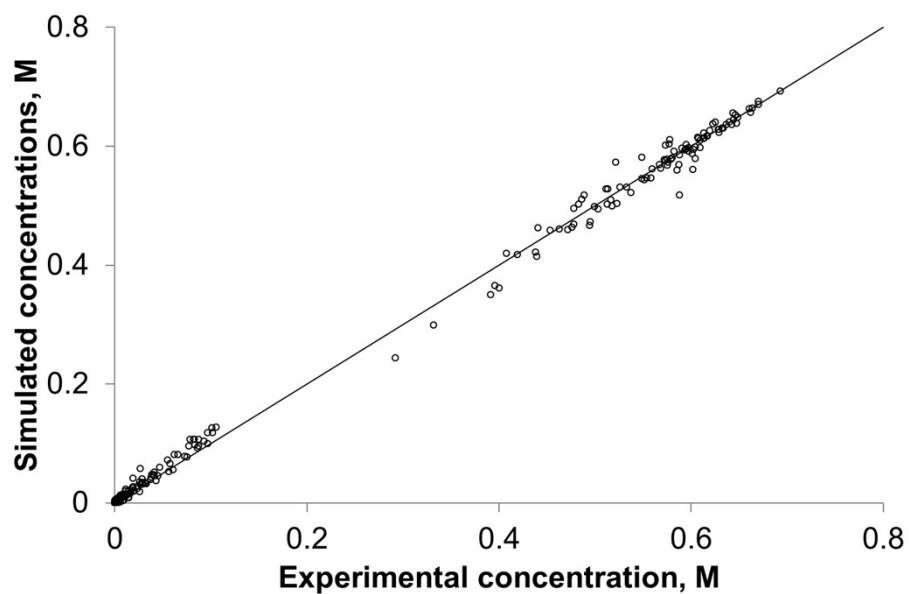
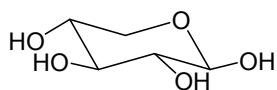
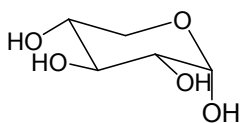


Fig. 75. Parity plot for the substrates and the products. The following data were used for the parity plot: concentrations of all the substrates (xylose, lyxose, arabinose, and ribose) at all the temperatures (56, 64, 70, and 78 °C) as well as concentrations of all the isomeric products upon isomerization of xylose at all the temperatures.

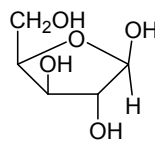
Xylose



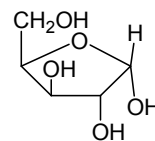
β -D-Xylopyranoside
63%



α -D-Xylopyranoside
35.5%

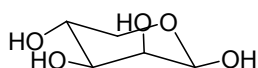


β -D-Xylofuranoside
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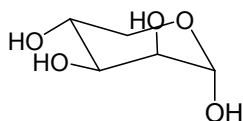


α -D-Xylofuranoside
<1%

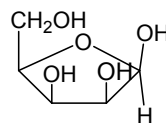
Lyxose



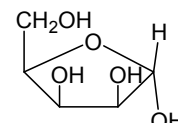
β -D-Lyxopyranoside
28%



α -D-Lyxopyranoside
70%

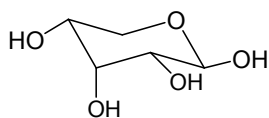


β -D-Lyxofuranoside
0.5%

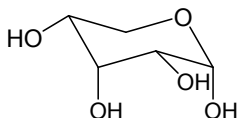


α -D-Lyxofuranoside
1.5%

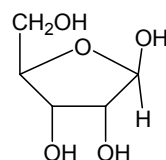
Ribose



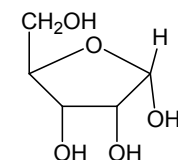
β -D-Ribopyranoside
58.5%



α -D-Ribopyranoside
21.5%

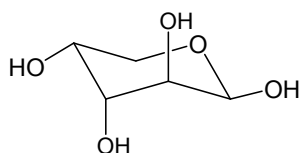


β -D-Ribofuranoside
13.6%

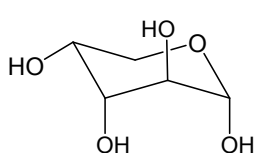


α -D-Ribofuranoside
6.5%

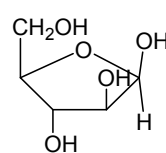
Arabinose



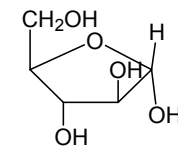
β -D-Arabinopyranoside
35.5%



α -D-Arabinopyranoside
60%



β -D-Arabinofuranoside
2%



α -D-Arabinofuranoside
2.5%

Fig. 8S. Cyclic forms of pentose present in aqueous solution⁵

Table 5S. Conformational free energies of the pyranosides in aqueous equilibrium solutions of D-aldopyranoses.

Aldose	Free energy, kcal mol ⁻¹		
	α form	β form	average ^a
Xylose	1.9	1.6	1.7
Lyxose	1.85	2.4	2.0
Ribose	3.1	2.3	2.6
Arabinose	1.95	2.2	2.05
Glucose	2.4	2.05	2.2

^aAverage free energy = (Average free energy of α form)·(Percentage of α form)+ (Average free energy of β form)·(Percentage of β form)

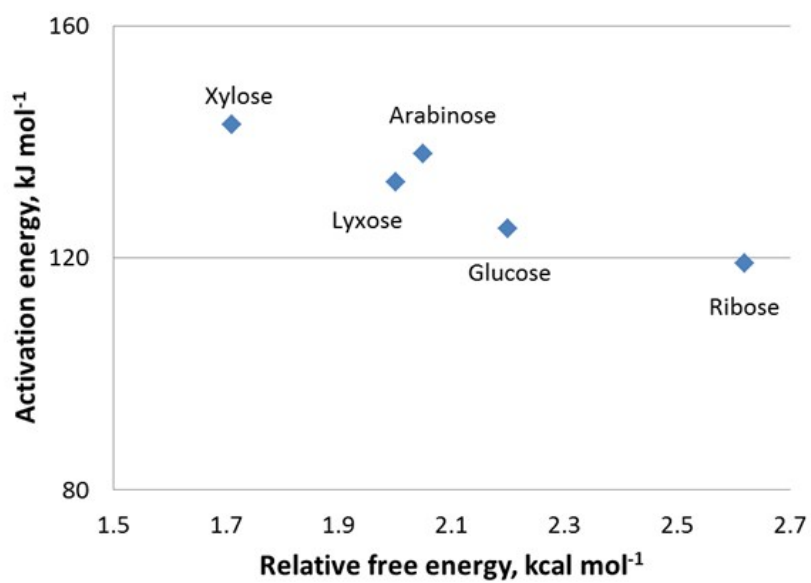


Fig. 9S. A correlation between activation energy of isomerization of the aldoses into the corresponding ketoses with relative free energy of the substrates.

Table 6S. Reaction rates contributing to the overall kinetics of the isomerization of the pentoses in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$. The reaction rates were calculated based on the results of kinetic modeling at 10% substrate conversion in accordance with the reaction network shown in Scheme S2. R denotes reaction rate.

Entry	T, °C	Conversion rate of a substrate aldo-pentose, mol L ⁻¹ s ⁻¹ ^a			Conversion rate of a keto-pentose, mol L ⁻¹ s ⁻¹ ^a			Formation rate of an epimeric aldo-pentose, mol L ⁻¹ s ⁻¹ ^b	
		Aldo-pentose to keto-pentose	Aldo-pentose to epimeric aldo-pentose	Aldo-pentose to by-product	Keto-pentose to epimeric aldo-pentose	Keto-pentose to C-3 epimeric keto-pentose	Keto-pentose to substrate aldo-pentose	From substrate aldo-pentose	From keto-pentose
Substrate: Xylose									
		Xylose to xylulose	Xylose to lyxose	Xylose to by-product 1	Xylulose to lyxose	Xylulose to ribulose	Xylulose to xylose	Lyxose formation based on xylose	Lyxose formation based on xylulose
		R = k ₅ [Xylose]	R = k ₇ [Xylose]	R = k ₈ [Xylose]	R = k ₆ [Xylulose]	R = k ₄ [Xylulose]	R = k ₅ [Xylulose]	R = k ₇ [Xylose]	R = k ₆ [Xylulose]
1	56	4.1·10 ⁻⁷ (58%)	1.1·10 ⁻⁸ (2%)	2.8·10 ⁻⁷ (40%)	2.2·10 ⁻⁷ (52%)	1.6·10 ⁻⁷ (37%)	4.6·10 ⁻⁸ (11%)	1.1·10 ⁻⁸ (5%)	2.2·10 ⁻⁷ (95%)
2	64	1.3·10 ⁻⁶ (65%)	3.6·10 ⁻⁸ (2%)	6.7·10 ⁻⁷ (33%)	8.7·10 ⁻⁷ (55%)	5.5·10 ⁻⁷ (34%)	1.8·10 ⁻⁷ (11%)	3.6·10 ⁻⁸ (4%)	8.7·10 ⁻⁷ (96%)
3	70	3.4·10 ⁻⁶ (69%)	9.9·10 ⁻⁸ (2%)	1.4·10 ⁻⁶ (29%)	1.9·10 ⁻⁶ (56%)	1.1·10 ⁻⁶ (33%)	3.9·10 ⁻⁷ (11%)	9.9·10 ⁻⁸ (5%)	1.9·10 ⁻⁶ (95%)
4	78	1.1·10 ⁻⁵ (74%)	3.3·10 ⁻⁷ (2%)	3.6·10 ⁻⁶ (24%)	6.1·10 ⁻⁶ (58%)	3.2·10 ⁻⁶ (30%)	1.2·10 ⁻⁶ (12%)	3.3·10 ⁻⁷ (5%)	6.1·10 ⁻⁶ (95%)
Substrate: Lyxose									
		Lyxose to xylulose	Lyxose to xylose	Lyxose to by-product 2	Xylulose to xylose	Xylulose to ribulose	Xylulose to lyxose	Xylose formation based on lyxose	Xylose formation based on xylulose
		R = k ₆ [Lyxose]	R = k ₇ [Lyxose]	R = k ₉ [Lyxose]	R = k ₅ [Xylulose]	R = k ₄ [Xylulose]	R = k ₆ [Xylulose]	R = k ₇ [Lyxose]	R = k ₅ [Xylulose]
5	56	2.1·10 ⁻⁶ (84%)	1.7·10 ⁻⁸ (1%)	3.9·10 ⁻⁷ (15%)	1.1·10 ⁻⁷ (11%)	3.9·10 ⁻⁷ (37%)	5.5·10 ⁻⁷ (52%)	1.7·10 ⁻⁸ (13%)	1.1·10 ⁻⁷ (87%)
6	64	6.1·10 ⁻⁶ (84%)	5.3·10 ⁻⁸ (1%)	1.1·10 ⁻⁶ (15%)	3.6·10 ⁻⁷ (11%)	1.1·10 ⁻⁶ (34%)	1.8·10 ⁻⁶ (55%)	5.3·10 ⁻⁸ (13%)	3.6·10 ⁻⁷ (87%)
7	70	1.5·10 ⁻⁵ (84%)	1.4·10 ⁻⁷ (1%)	2.6·10 ⁻⁶ (15%)	8.2·10 ⁻⁷ (11%)	2.4·10 ⁻⁶ (33%)	4.1·10 ⁻⁶ (56%)	1.4·10 ⁻⁷ (14%)	8.2·10 ⁻⁷ (86%)
8	78	4.1·10 ⁻⁵ (84%)	4.1·10 ⁻⁷ (1%)	7.2·10 ⁻⁶ (15%)	2.4·10 ⁻⁶ (11%)	6.5·10 ⁻⁶ (30%)	1.2·10 ⁻⁵ (58%)	4.1·10 ⁻⁷ (14%)	2.4·10 ⁻⁶ (86%)

^adifferential selectivities are given in parentheses; ^bpercentages of epimeric aldo-pentoses formed via a corresponding reaction pathway are given in parentheses.

Table 6S (Continuation). Reaction rates contributing to the overall kinetics of the isomerization of the pentoses in the presence of NaH₂PO₄+Na₂HPO₄. The reaction rates were calculated based on the results of kinetic modeling at 10% substrate conversion in accordance with the reaction network shown in Scheme S2. R denotes reaction rate.

Entry	T, °C	Conversion rate of a substrate aldo-pentose, mol L ⁻¹ s ⁻¹ ^a			Conversion rate of a keto-pentose, mol L ⁻¹ s ⁻¹ ^a			Formation rate of an epimeric aldo-pentose, mol L ⁻¹ s ⁻¹ ^b	
		Aldo-pentose to keto-pentose	Aldo-pentose to epimeric aldo-pentose	Aldo-pentose to by-product	Keto-pentose to epimeric aldo-pentose	Keto-pentose to C-3 epimeric keto-pentose	Keto-pentose to substrate aldo-pentose	From substrate aldo-pentose	From keto-pentose
Substrate: Ribose									
		Ribose to ribulose	Ribose to arabinose	Ribose to by-product 3	Ribulose to arabinose	Ribulose to xylulose	Ribulose to ribose	Arabinose formation based on ribose	Arabinose formation based on ribulose
		R = k ₁ [Ribose]	R = k ₂ [Ribose]	R = k ₁₀ [Ribose]	R = k ₃ [Ribulose]	R = k ₄ [Ribulose]	R = k ₁ [Ribulose]	R = k ₂ [Ribose]	R = k ₃ [Ribulose]
9	56	4.0·10 ⁻⁶ (78%)	5.1·10 ⁻⁸ (1%)	1.1·10 ⁻⁶ (21%)	1.4·10 ⁻⁷ (9%)	8.0·10 ⁻⁷ (52%)	5.9·10 ⁻⁷ (39%)	5.1·10 ⁻⁸ (27%)	1.4·10 ⁻⁷ (73%)
10	64	1.1·10 ⁻⁵ (82%)	1.7·10 ⁻⁷ (1%)	2.3·10 ⁻⁶ (17%)	3.8·10 ⁻⁷ (9%)	2.1·10 ⁻⁶ (50%)	1.7·10 ⁻⁶ (41%)	1.7·10 ⁻⁷ (30%)	3.8·10 ⁻⁷ (70%)
11	70	2.3·10 ⁻⁵ (84%)	3.9·10 ⁻⁷ (1%)	3.9·10 ⁻⁶ (14%)	6.5·10 ⁻⁷ (9%)	3.5·10 ⁻⁶ (49%)	3.0·10 ⁻⁶ (42%)	3.9·10 ⁻⁷ (38%)	6.5·10 ⁻⁷ (62%)
12	78	5.9·10 ⁻⁵ (87%)	1.2·10 ⁻⁶ (2%)	7.7·10 ⁻⁶ (11%)	2.9·10 ⁻⁶ (9%)	1.5·10 ⁻⁵ (47%)	1.4·10 ⁻⁵ (44%)	1.2·10 ⁻⁶ (29%)	2.9·10 ⁻⁶ (71%)
Substrate: Arabinose									
		Arabinose to ribulose	Arabinose to ribose	Arabinose to by-product 4	Ribulose to ribose	Ribulose to xylulose	Ribulose to arabinose	Ribose formation based on arabinose	Ribose formation based on ribulose
		R = k ₃ [Arabin.]	R = k ₂ [Arabin.]	R = k ₁₁ [Arabin.]	R = k ₁ [Ribulose]	R = k ₄ [Ribulose]	R = k ₃ [Ribulose]	R = k ₂ [Arabin.]	R = k ₁ [Ribulose]
13	56	2.6·10 ⁻⁷ (76%)	4.9·10 ⁻⁸ (14%)	3.5·10 ⁻⁸ (10%)	6.8·10 ⁻⁸ (39%)	9.1·10 ⁻⁸ (52%)	1.6·10 ⁻⁸ (9%)	4.9·10 ⁻⁸ (42%)	6.8·10 ⁻⁸ (58%)
14	64	7.3·10 ⁻⁷ (71%)	1.1·10 ⁻⁷ (11%)	1.8·10 ⁻⁷ (17%)	4.6·10 ⁻⁷ (41%)	5.6·10 ⁻⁷ (50%)	1.0·10 ⁻⁷ (9%)	1.1·10 ⁻⁷ (20%)	4.6·10 ⁻⁷ (80%)
15	70	1.9·10 ⁻⁶ (66%)	2.6·10 ⁻⁷ (9%)	6.9·10 ⁻⁷ (25%)	1.1·10 ⁻⁶ (42%)	1.3·10 ⁻⁶ (49%)	2.5·10 ⁻⁷ (9%)	2.6·10 ⁻⁷ (18%)	1.1·10 ⁻⁶ (82%)
16	78	5.6·10 ⁻⁶ (57%)	6.5·10 ⁻⁷ (7%)	3.6·10 ⁻⁶ (36%)	3.5·10 ⁻⁶ (44%)	3.7·10 ⁻⁶ (47%)	7.3·10 ⁻⁷ (9%)	6.5·10 ⁻⁷ (16%)	3.5·10 ⁻⁶ (84%)

^adifferential selectivities are given in parentheses; ^bpercentages of epimeric aldo-pentoses formed via a corresponding reaction pathway are given in parentheses.

Table 6S presents reaction rates and values of differential selectivities towards the products. By definition, differential selectivity is the ratio of the rate of desired product formation to the rate of reaction consumption.⁶ The differential selectivities were calculated as follows:

1. Differential selectivities for conversion of a substrate into a ketose, an epimeric aldopentose and by products

The calculations for xylose as a substrate were performed according to the following formula:

$$\begin{aligned}
 S_{\text{diff}}(\text{Xylose for xylulose}) &= \\
 &= \frac{R(\text{Xylose into xylulose})}{R(\text{Xylose into xylulose}) + R(\text{Xylose into lyxose}) + R(\text{Xylose into by-product 1})} = \\
 &= \frac{k_{-5}[\text{Xylose}]}{k_{-5}[\text{Xylose}] + k_7[\text{Xylose}] + k_8[\text{Xylose}]} = \frac{k_{-5}}{k_{-5} + k_7 + k_8} \quad (15S)
 \end{aligned}$$

Analogously differential selectivities can be expressed for all the products and all the substrates

$$S_{\text{diff}}(\text{Xylose for lyxose}) = \frac{k_7}{k_{-5} + k_7 + k_8} \quad (16S)$$

$$S_{\text{diff}}(\text{Xylose for by-product 1}) = \frac{k_8}{k_{-5} + k_7 + k_8} \quad (17S)$$

$$S_{\text{diff}}(\text{Lyxose for xylulose}) = \frac{k_{-6}}{k_{-6} + k_{-7} + k_9} \quad (18S)$$

$$S_{\text{diff}}(\text{Lyxose for xylose}) = \frac{k_{-7}}{k_{-6} + k_{-7} + k_9} \quad (19S)$$

$$S_{\text{diff}}(\text{Lyxose for by-product 2}) = \frac{k_9}{k_{-6} + k_{-7} + k_9} \quad (20S)$$

$$S_{\text{diff}}(\text{Ribose for ribulose}) = \frac{k_1}{k_1 + k_2 + k_{10}} \quad (21S)$$

$$S_{\text{diff}}(\text{Ribose for arabinose}) = \frac{k_2}{k_1 + k_2 + k_{10}} \quad (22S)$$

$$S_{\text{diff}}(\text{Ribose for by-product 3}) = \frac{k_{10}}{k_1 + k_2 + k_{10}} \quad (23S)$$

$$S_{\text{diff}}(\text{Arabinose for ribulose}) = \frac{k_3}{k_3 + k_{-2} + k_{11}} \quad (24S)$$

$$S_{\text{diff}}(\text{Arabinose for ribose}) = \frac{k_{-2}}{k_3 + k_{-2} + k_{11}} \quad (25S)$$

$$S_{\text{diff}}(\text{Arabinose for by-product 4}) = \frac{k_{11}}{k_3 + k_{-2} + k_{11}} \quad (26S)$$

2. Differential selectivities for conversion of a keto-pentose into a C-3 epimeric ketose and aldoses

$$S_{\text{diff}}(\text{Xylulose for ribulose}) = \frac{k_{-4}}{k_{-4} + k_5 + k_6} \quad (27S)$$

$$S_{\text{diff}}(\text{Xylulose for xylose}) = \frac{k_5}{k_{-4} + k_5 + k_6} \quad (28S)$$

$$S_{\text{diff}}(\text{Xylulose for lyxose}) = \frac{k_6}{k_{-4} + k_5 + k_6} \quad (29S)$$

$$S_{\text{diff}}(\text{Ribulose for xylulose}) = \frac{k_4}{k_4 + k_{-1} + k_{-3}} \quad (30S)$$

$$S_{\text{diff}}(\text{Ribulose for ribose}) = \frac{k_{-1}}{k_4 + k_{-1} + k_{-3}} \quad (31S)$$

$$S_{\text{diff}}(\text{Ribulose for arabinose}) = \frac{k_{-3}}{k_4 + k_{-1} + k_{-3}} \quad (32S)$$

3. Percentage of an epimeric aldo-pentose formed via direct epimerization of an aldo-pentose and isomerization of a ketose

Xylose as a substrate

$$\begin{aligned} \%(\text{Lyxose from xylose}) &= \frac{R(\text{Xylose into lyxose})}{R(\text{Xylose into lyxose}) + R(\text{Xylulose into lyxose})} = \\ &= \frac{k_7[\text{Xylose}]}{k_7[\text{Xylose}] + k_6[\text{Xylulose}]} \end{aligned} \quad (33S)$$

$$\%(\text{Lyxose from xylulose}) = \frac{k_6[\text{Xylulose}]}{k_7[\text{Xylose}] + k_6[\text{Xylulose}]} \quad (34S)$$

Lyxose as a substrate

$$\%(\text{Xylose from lyxose}) = \frac{k_{-7}[\text{Lyxose}]}{k_{-7}[\text{Lyxose}] + k_5[\text{Xylulose}]} \quad (35S)$$

$$\%(\text{Xylose from xylulose}) = \frac{k_5[\text{Xylulose}]}{k_{-7}[\text{Lyxose}] + k_5[\text{Xylulose}]} \quad (36S)$$

Arabinose as a substrate

$$\%(\text{Ribose from arabinose}) = \frac{k_{-2}[\text{Arabinose}]}{k_{-2}[\text{Arabinose}] + k_{-1}[\text{Ribulose}]} \quad (37S)$$

$$\%(\text{Ribose from ribulose}) = \frac{k_{-1}[\text{Ribulose}]}{k_{-2}[\text{Arabinose}] + k_{-1}[\text{Ribulose}]} \quad (38S)$$

Ribose as a substrate

$$\%(\text{Arabinose from ribose}) = \frac{k_2[\text{Ribose}]}{k_2[\text{Ribose}] + k_{-3}[\text{Ribulose}]} \quad (39S)$$

$$\%(\text{Arabinose from ribulose}) = \frac{k_{-3}[\text{Ribulose}]}{k_2[\text{Ribose}] + k_{-3}[\text{Ribulose}]} \quad (40S)$$

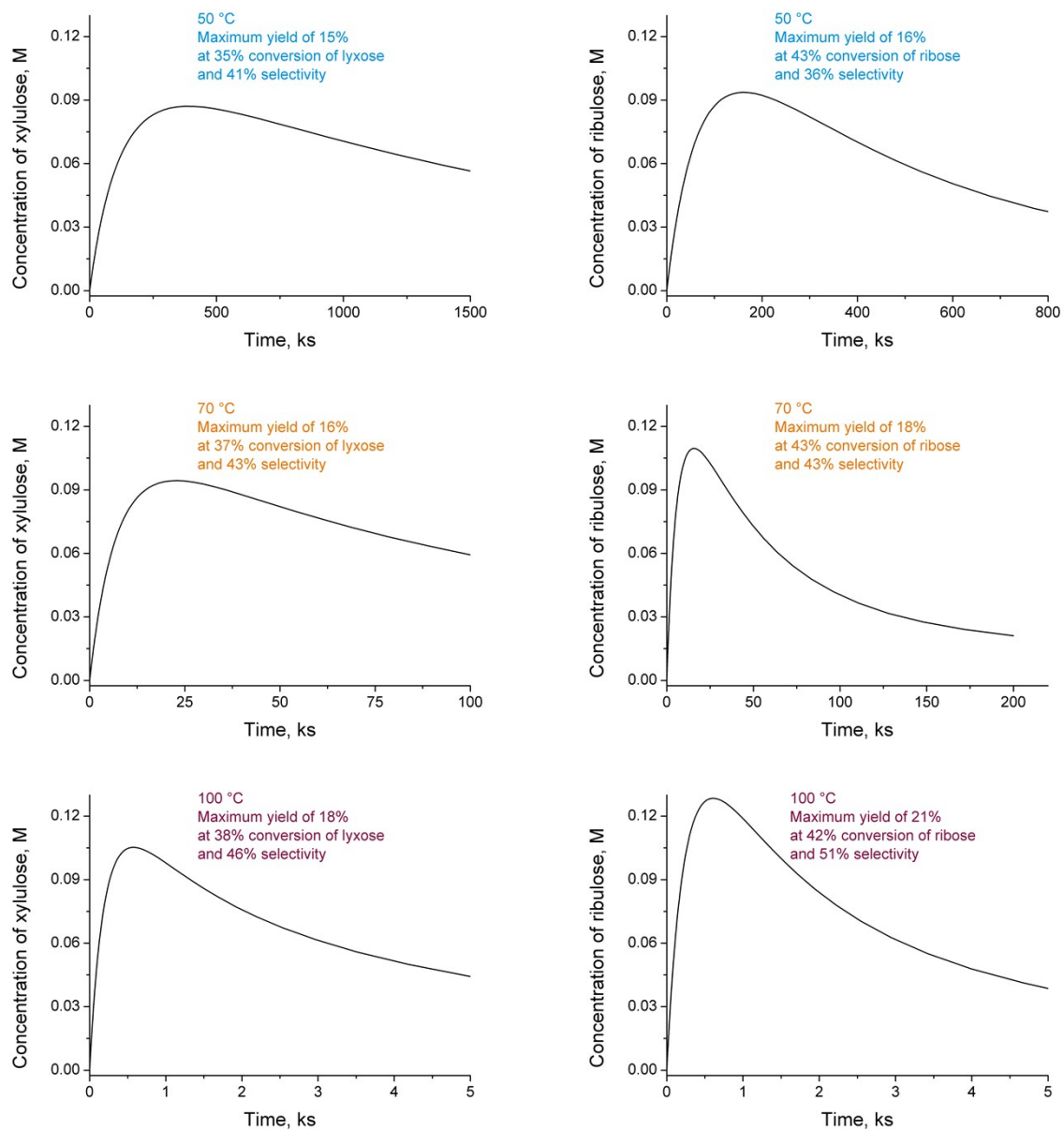


Fig. 10S. Concentration profiles of xylulose formation based on lyxose (left) and ribulose formation based on ribose (right) at various temperatures.

Calculation of amount of extracted monosaccharides and selectivity of extraction

In order to optimize the conditions of the anionic extraction, the solutions after reactions in the presence of $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$ were utilized. In addition to the substrate and the ketoses, the solutions contained minor amounts of other saccharides (Table 7S):

Table 7S. Concentrations of the saccharides in the solutions used for optimization of the extraction conditions.

Separation of aldose-ketose	[Lyxose], M	[Xylose], M	[Ribose], M	[Arabinose], M	[Ribulose], M	[Xylulose], M
Lyxose-xylulose	0.45	0.013	0.004	0	0.010	0.072
Ribose-ribulose	0.003	0.001	0.43	0.009	0.088	0.014

Percentages of the extracted components and selectivity of extraction shown in Table 3 were calculated as follows:

$$\text{Percentage of the extracted component\%} = \frac{c_i^0 - c_i}{c_i^0} \cdot 100\% \quad (41S)$$

$$\text{Selectivity, \%} = \frac{c_i^0 - c_i}{\sum_i c_i^0 - c_i} \cdot 100\% \quad (42S)$$

Where c_i^0 and c_i correspond to concentrations of the saccharides in aqueous phase before and after extraction, respectively.

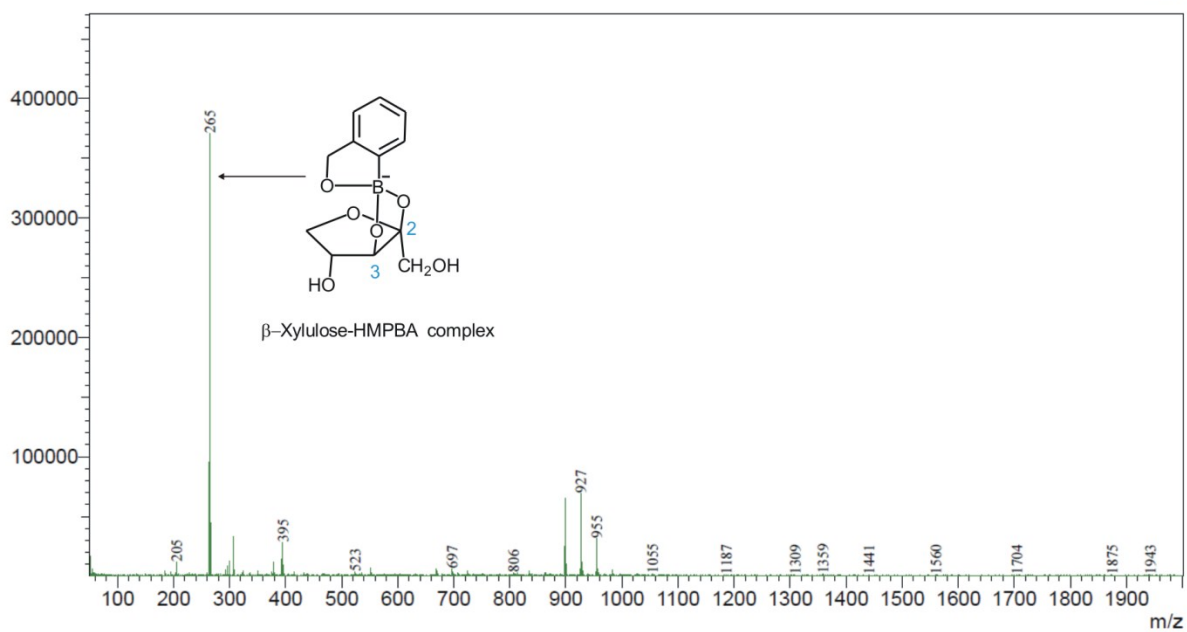
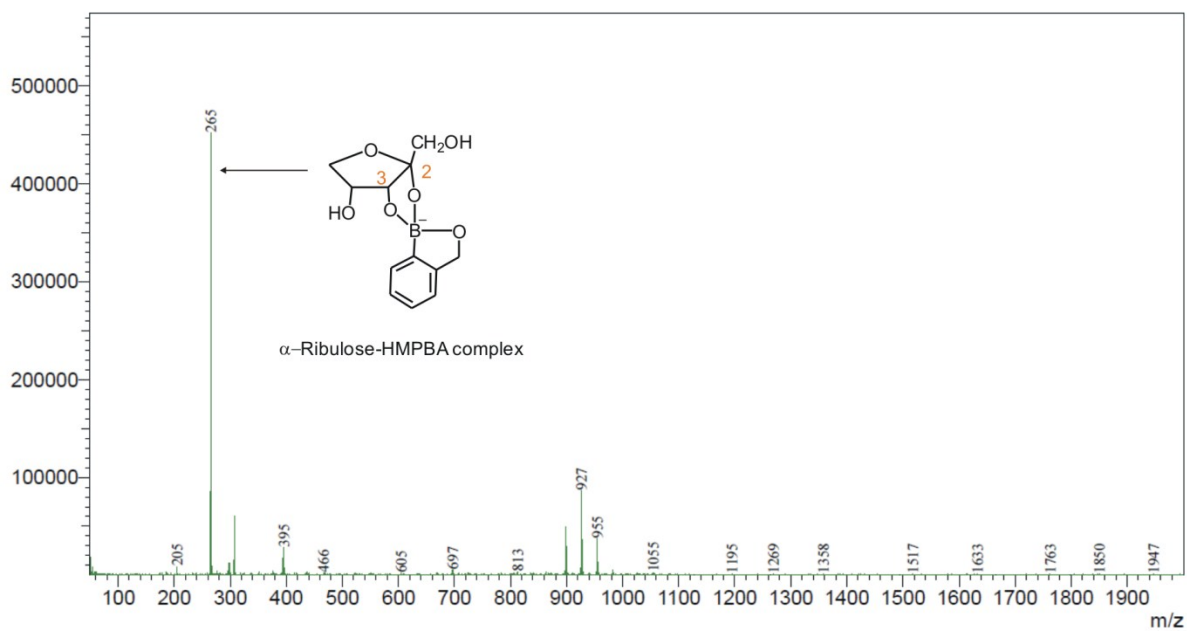


Fig. 11S Results of ESI-MS analysis in negative mode of the organic phase after anionic extraction of ribulose (up) and xylulose (down) with HMPBA.

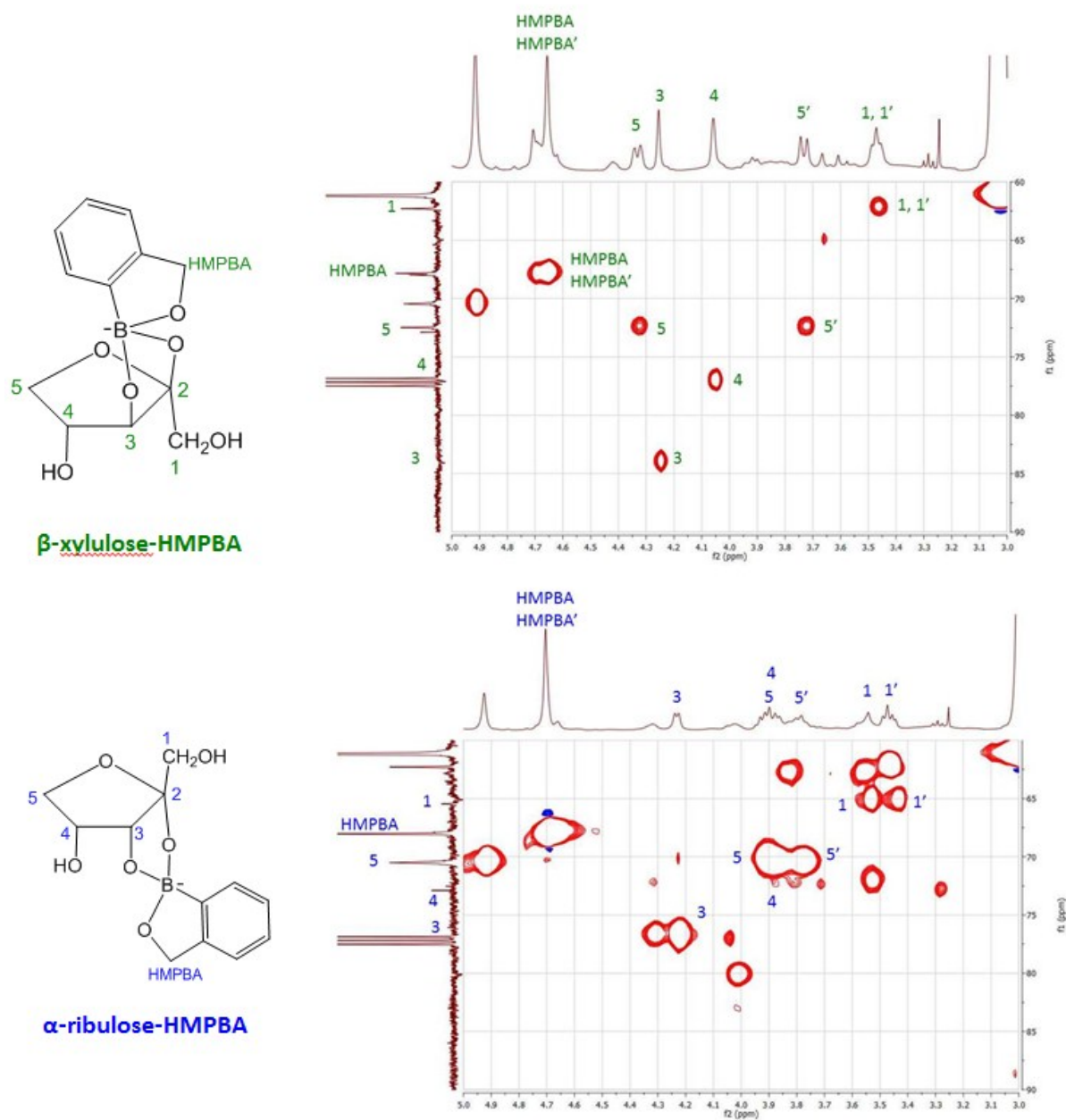


Fig. 12S. HSQC NMR spectra of the extracted complexes of keto-pentoses with HMBPA

Table 8S. Chemical shifts (in ppm) observed in ^{13}C NMR spectra for complexes between ribulose and HMPBA as well as xylulose and HMPBA (CDCl_3) and their comparison with α -ribulose and β -xylulose (D_2O).

	C1	C2 ^a	C3	C4	C5	CH ₂ -HMPBA ^b
β -Xylulose-HMPBA complex	62.3	-	84.1	77.2	72.5	61.8
β -Xylulose	64.5	104.4	77.7	76.4	71.3	-
$\Delta \delta^{13}\text{C}^c$	-2.2	-	6.4	0.8	1.2	-
α -Ribulose-HMPBA complex	65.1	-	77.2	72.1	70.6	68.0
α -Ribulose	64.3	104.0	71.9	71.6	72.9	-
$\Delta \delta^{13}\text{C}^c$	0.8	-	5.3	0.5	-2.3	-

^a ^{13}C NMR signals of the quaternary C2 atoms were not detected; ^b chemical shifts of the hydroxymethyl rest of HMPBA ligand; ^c ^{13}C chemical shift differences for a complex and a corresponding saccharide.

Table 9S. Results of extraction-assisted isomerization of lyxose into xylulose. Reaction conditions: isomerization over 0.5M NaH₂PO₄+Na₂HPO₄, 89 °C, 20 min, 750 rpm; extraction was conducted at room temperature for 1 h, 750 rpm using 0.1 M HMPBA and 0.1 M Aliquat® 336 in 1-octanol as an organic phase, reaction mixture after the isomerization was used as an aqueous phase.

Run	Isomerization							Extraction						Yield of xylulose, %
	Concentration of saccharides							Extracted amount, %			Selectivity of extraction, %			
	[Lyx] ₀ ^a M	[Xylu] ₀ ^a M	[Ribu] ₀ ^a M	[Lyx] _{fin} ^b M	[Xylu] _{fin} ^b M	[Ribu] _{fin} ^b M	Lyx conversion, %	Lyx	Xylu	Ribu	Lyx	Xylu	Ribu	
1	0.60	0	0	0.48	0.095	0.009	19	5	57	44	8	92	<1	16
2	0.57	0.02	0.002	0.48	0.092	0.011	16	4	51	56	7	93	<1	24
3	0.59	0.002	0.0009	0.47	0.092	0.008	21	3	48	54	6	94	<1	31
4	0.61	0.02	0.002	0.48	0.11	0.014	22	3	45	54	9	91	<1	37

^a[Lyx]₀, [Xylu]₀, and [Ribu]₀ are concentrations of lyxose, xylulose, and ribulose in the reaction mixture prior to the isomerization

^b[Lyx]_{fin}, [Xylu]_{fin}, and [Ribu]_{fin} are concentrations of lyxose, xylulose, and ribulose, in the reaction mixture after the isomerization

Calculation of conversion, selectivity, and yield for the reaction-assisted isomerization

Lyxose conversion was calculated as follows

$$\text{Lyxose conversion} = \frac{\sum_i ([\text{Lyx}]_{0,i} - [\text{Lyx}]_{\text{fin},i})}{\sum_i ([\text{Lyx}]_{0,i} - [\text{Lyx}]_{\text{extr},i-1})} \quad (43S)$$

Xylulose yield was calculated for the total amount of formed xylulose according to the formula:

$$\text{Xylulose yield} = \frac{\sum_i ([\text{Xylu}]_{\text{fin},i} - [\text{Xylu}]_{0,i})}{\sum_i ([\text{Lyx}]_{0,i} - [\text{Lyx}]_{\text{extr},i-1})} \quad (44S)$$

Used for Equations 43S and 44S parameter *i* denotes a number of run, whereas [Lyx]₀, [Xylu]₀, [Lyx]_{fin}, [Xylu]_{fin}, denote concentrations of lyxose and xylulose provided in Table 9S. [Lyx]_{extr}, and [Xylu]_{extr} denote concentrations of lyxose and xylulose in aqueous phase after extraction.

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