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Supporting Information

Synthesis of Furandicarboxylic Acid Esters From Nonfood Feedstocks Without Concomitant Levulinic Acid Formation

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Supporting Information

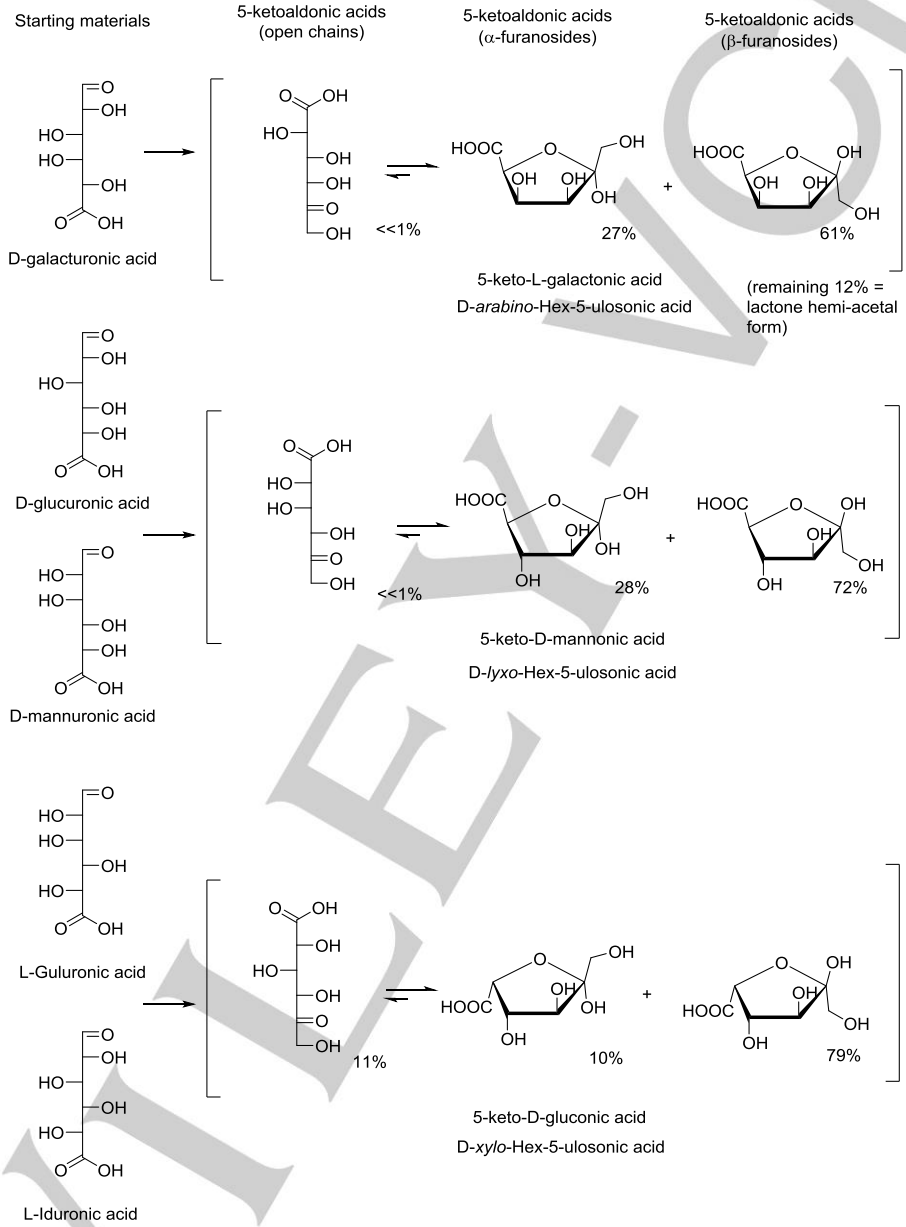

Figure S1. Five naturally occurring uronic acids and corresponding 5-keto-aldonic acids.

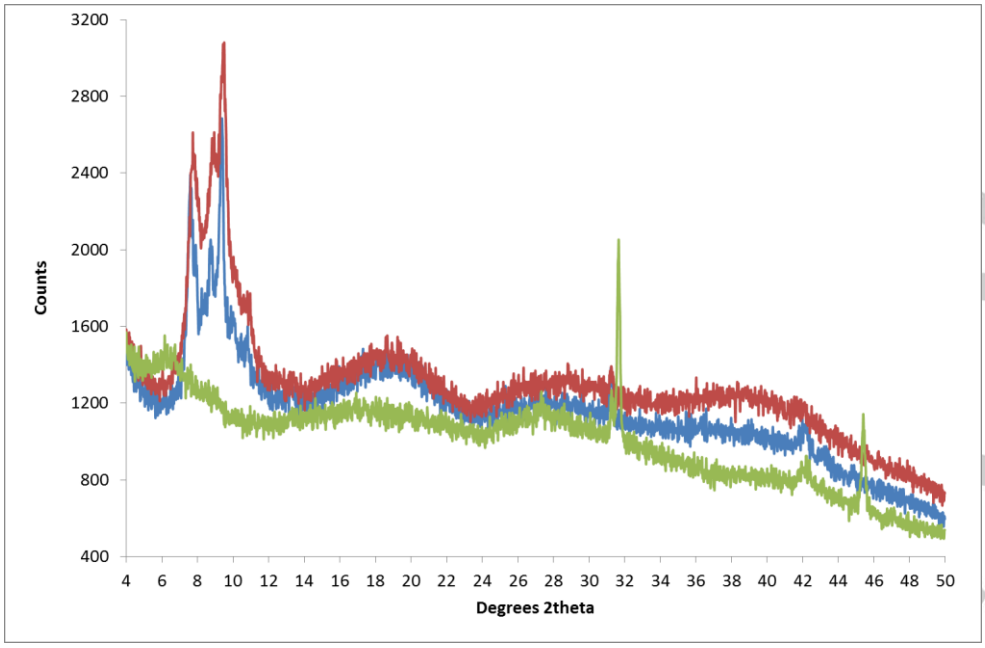

Figure S2. Wide-angle X-ray diffractograms of 5-keto-L-galactonic acid prepared from $Ca(OH)_2$ (blue) and $CaCl_2$ / NaOH (red), and 5-keto-D-mannonic acid (green).

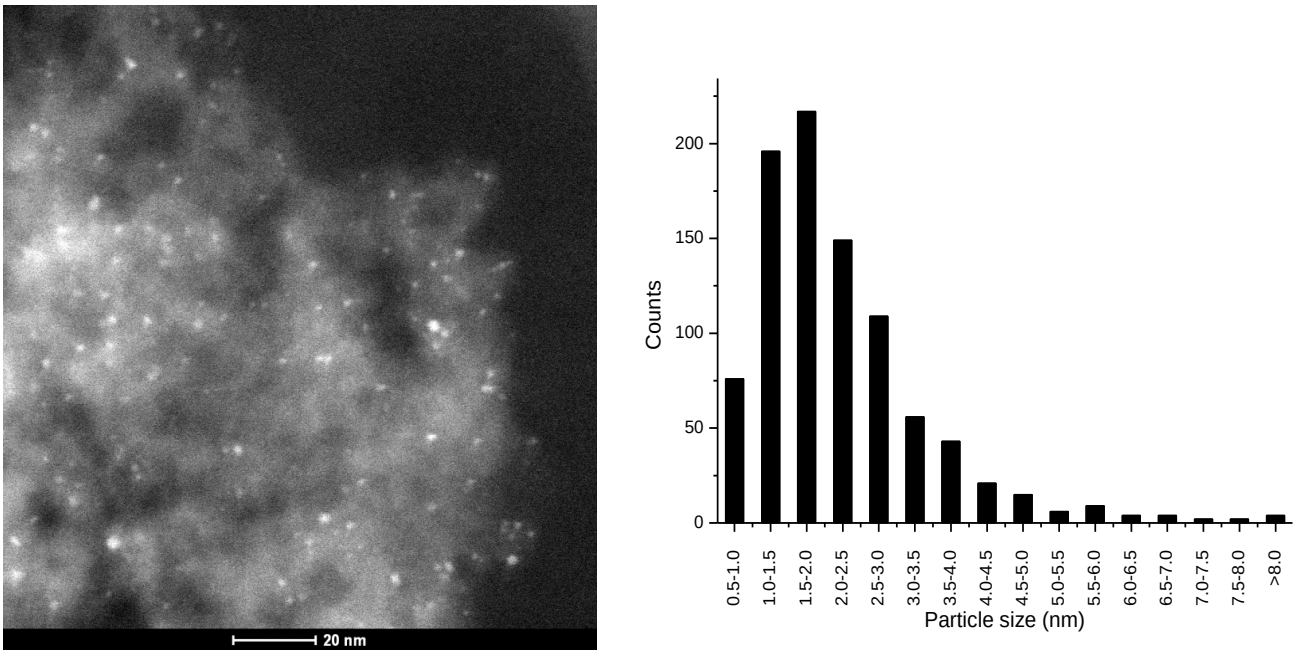

Figure S3. Representative HAADF image and particle size distribution of the 1.3 wt% Au/C catalyst.

Identification of side products

The general work-up procedure which is described in the main text involves an aqueous extraction step. Therefore, carbohydrate type products will most likely not be present in the organic layer but in the aqueous layer. Besides the carbohydrates, the aqueous phase also contains inorganic acids and salts, which makes analysis cumbersome. Therefore, for analytical purpose, a few reactions were performed using a non-aqueous work-up procedure, to determine the carbohydrate-type (side)products that are present in the reaction mixtures.

Product mixture from D-galacturonic acid in MeOH/HCl

A round bottom flask (100 mL) was equipped with a magnetic stirring bar and a reflux condenser with N_2-inlet. The flask was charged with D-galacturonic acid monohydrate (5.0 g, 23.6 mmol) and methanolic HCl (3N solution, 20 mL). The D-galacturonic acid dissolved rapidly, to give a clear colorless solution. The reaction mixture was heated to reflux (65 ˚C) for 24 h. The resulting clear yellow solution was allowed to cool to RT, and concentrated at 40 ˚C under vacuum using a rotary evaporator. The resulting light pink oil (6.095 g) was analyzed by ^{1}H-NMR in D_2O.

The NMR spectrum (Figure S4) shows a complex mixture consisting of methyl (methyl α-D-galactopyranosid)uronate (**1**), methyl (methyl β-D-galactopyranosid)uronate (**2**), methyl (methyl α-D-galactofuranosid)uronate (**3**), and methyl (methyl β-D-galactofuranosid)uronate (**4**) (as assigned and reported by Matsuhiro *et al.*[48]) as well as some residual methanol.

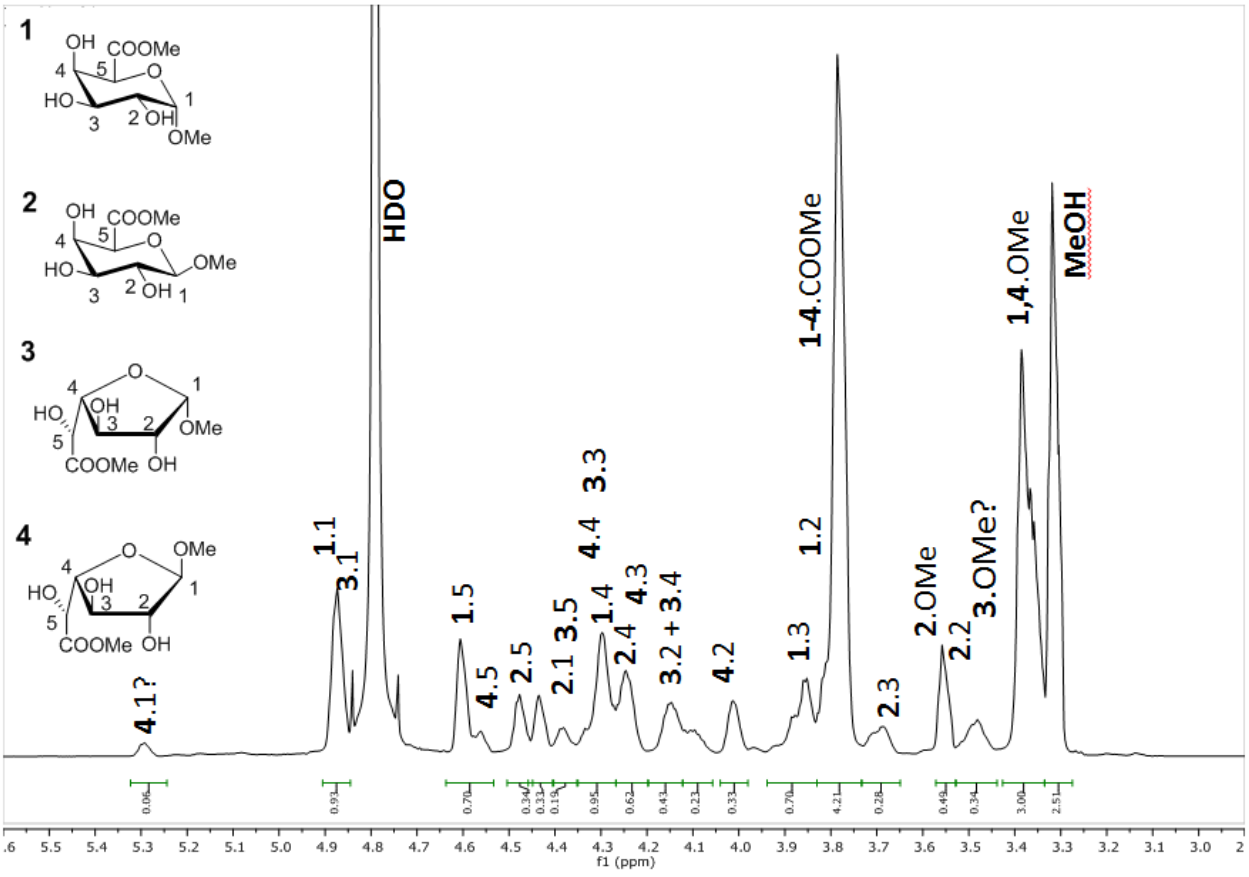

Figure S4. ^{1}H-NMR spectrum (D_2O) of the product mixture from D-galacturonic acid in MeOH/HCl. Reaction conditions: D-galacturonic acid monohydrate (5.0 g, 23.6 mmol) in methanolic HCl (3N solution, 20 mL), reflux, 24h.

Side products of the cyclodehydration of 5-keto-L-galactonic acid (CaOH-salt) in MeOH/HCl

A round bottom flask (100 mL) was equipped with a magnetic stirring bar and a reflux condenser with N_2-inlet. The flask was charged with 5-keto-L-galactonic acid CaOH-salt (3.0 g, 12 mmol) and methanolic HCl (3N solution, 30 mL). The reaction mixture was heated to reflux (65 ˚C) for 24 h. The resulting clear red-brown solution was allowed to cool to RT.

Initial attempts to concentrate the reaction mixture at 40 ˚C (rotary evaporator) failed, probably due to the formation of a conc. HCl/water mixture during evaporation. In contrast to the reaction with galacturonic acid in MeOH/HCl, concentrating led to very dark colored mixtures. Therefore, we allowed ourselves, for analytical purpose only, the use of lead(II) carbonate for the selective removal of HCl from the methanol (*Note:* Lead(II) carbonate is a very toxic compound that should never be used in an industrial process!).

Lead(II) carbonate was added to the reaction mixture until pH-paper showed a neutral solution. The solids were removed by filtration over a paper filter, followed by filtration over a micro-filter (45 µm). The brown filtrate was concentrated under vacuum at 40 ˚C using a rotary evaporator, to give 5.85 g of a clear brown oil.

To separate the crude product mixture in a furan-rich and a carbohydrate-rich fraction, the oil was transferred to a separatory funnel, and extracted with chloroform (poor solvent for carbohydrates, good solvent for furans). The remaining brown oil was completely soluble in methanol. Both clear brown solutions were concentrated: After evaporation (vacuum, 40 ˚C, rotary evaporator), the chloroform fraction gave 696 mg of a clear brown oil, and the methanol fraction gave 5.165 g of a clear brown oil.

The chloroform-soluble fraction was analyzed by ^{1}H-NMR in $CDCl_3$ and the methanol-soluble fraction was analyzed by ^{1}H-NMR in MeOD-D_4. The spectra are shown in Figure S5.

The chloroform-soluble fraction is rich in methyl 5-formyl-2-furoate (dimethyl acetal). There are no other furan-like signals present, indicating the absence of soluble furanic humins. Between 3 and 5 ppm, the carbohydrate region, a complex mixture of carbohydrate-like compounds, is visible (including methyl-esters and methylglycosides), as well as some more aliphatic signals at 2-2.5 ppm.

The methanol-soluble fraction shows only a small amount of methyl 5-formyl-2-furoate (dimethyl acetal). Again, there are no other furan-like signals present, indicating the absence of soluble furanic humins. In this sample, the carbohydrate region between 3 and 5 ppm contains most of the products. The mixture is however too complex to identify which carbohydrate compounds are present, based on NMR alone. Therefore, to get further insight in the type of products, HPLC-MS analysis was performed on both product fractions (Figures S6 and S7).

HPLC-MS analysis was performed according to a previously reported method[49] with the following slightly different settings: The spray temperature was set at 150 °C, the voltage was 5.00 kV and the spray was stabilized with a nitrogen sheath gas (60 arb/min). Capillary temperature was 280 °C. The isolation width of precursor ions was 2.0 mass units. Ions were obtained in the range of *m*/*z* 100–500. It should be noted that the systems runs under aqueous acidic conditions. This means that during the runs acetals or even ester functionalities could potentially hydrolyze under the applied conditions.

Figure S6 A shows the UV-signal, and Figure S6 B shows the total ion-count (TIC) of the chloroform-soluble sample. A broad range of compounds is visible in the TIC-signal, while the UV shows only the injection peak (at 6 min.) and some compounds around 13.6 min. After 55 min (not shown in Figure S6), Me-FFA is eluted, but this compound does not give a mass signal under the applied mild ionization

conditions. The low intensity of the UV-signal is in line with the expected carbohydrate structures, which have a low UV-adsorption. The broad TIC-signal indicates that many different compounds are present, since otherwise well-defined peaks should appear.

To get a better differentiation in the TIC signal, a selection in the mass ranges was made. Figures S6 C-E show selections of only one mass per figure: Figure S6 C shows only products with a molecular weight of 194 ($[M-H]^-$ = 192.5-193.5). This corresponds to the mass of 5-keto-aldonic acids (or uronic acids) without further functionality. Figure S6 D shows only products with a molecular weight of 208 ($[M-H]^-$ = 206.5-207.5), this corresponds to 5-keto-aldonic acids (or uronic acids) with one methyl-functionality (either a glycoside or methyl-ester). Figure S6 E shows only products with a molecular weight of 222 ($[M-H]^-$ = 220.5-221.5), which corresponds to 5-keto-aldonic acids (or uronic acids) with two methyl-functionalities (both ester and glycoside). Since noise signals are visible in the Figures C-E, it can be concluded that all the proposed compounds could be present, although in (very) low concentration. This is in line with the expectation that the carbohydrate concentration in the chloroform-soluble fraction is low, and this also corresponds to the NMR-spectrum, in which the Me-FFA dimethyl acetal is the main compound (Figure S4).

Figure S7 shows the methanol-soluble fraction, which should contain a higher concentration of carbohydrates (polar solvent, and already indicated by NMR). The UV-signal (Figure S7 A) and the TIC-signal (Figure S7 B) are comparable to the chloroform-soluble sample. However, in this sample the mass selection shows more distinct products: Figure S7 C shows only products with a molecular weight of 194 ($[M-H]^-$ = 192.5-193.5). This corresponds to the mass of 5-keto-aldonic acids (or uronic acids) without further functionality. Two more defined peaks are visible, at retention times of 7.9 and 8.4 min. These could be isomers of keto-aldonic acids or uronic acids, although the retention time does not match with galacturonic acid, which has a retention time of 8.2 min.

Figure S7 D shows only products with a molecular weight of 208 ($[M-H]^-$ = 206.5-207.5), this corresponds to 5-keto-aldonic acids (or uronic acids) with one methyl-functionality (either a glycoside or methyl-ester). Again, more well-defined peaks are visible compared to the chloroform-extractable fraction. The signal-noise ratio is also higher. Products with retention times of 8.11, 8.93,10.81 and 12.28 min. are present, indicating a mixture of various glycosides or methyl-esters.

Figure S7 E shows only products with a molecular weight of 222 ($[M-H]^-$ = 220.5-221.5), which corresponds to 5-keto-aldonic acids (or uronic acids) with two methyl-functionalities (both ester and glycoside). Here, again some distinct peaks (e.g. retention times 7.42, 8.18, 9.72, 10.24 min.) are present, although the intensity of the signal is lower, indicating low concentrations.

Based on the LC-MS measurements, it can be concluded that the product mixture contains a broad range of side products or intermediates, but that the structures are still carbohydrates. In principle these compounds could be available for other conversions. It should be noted that the aqueous acidic conditions which were used during the LC-MS analysis could have caused some hydrolysis of acid-labile functionalities like acetals and esters. This hydrolysis on the column leads to broadening in the product mixture, and potential overestimation of the number of products which is present in the mixture. Further identification of the carbohydrate-type side products falls beyond the scope of the current report, but will be the subject of future work.

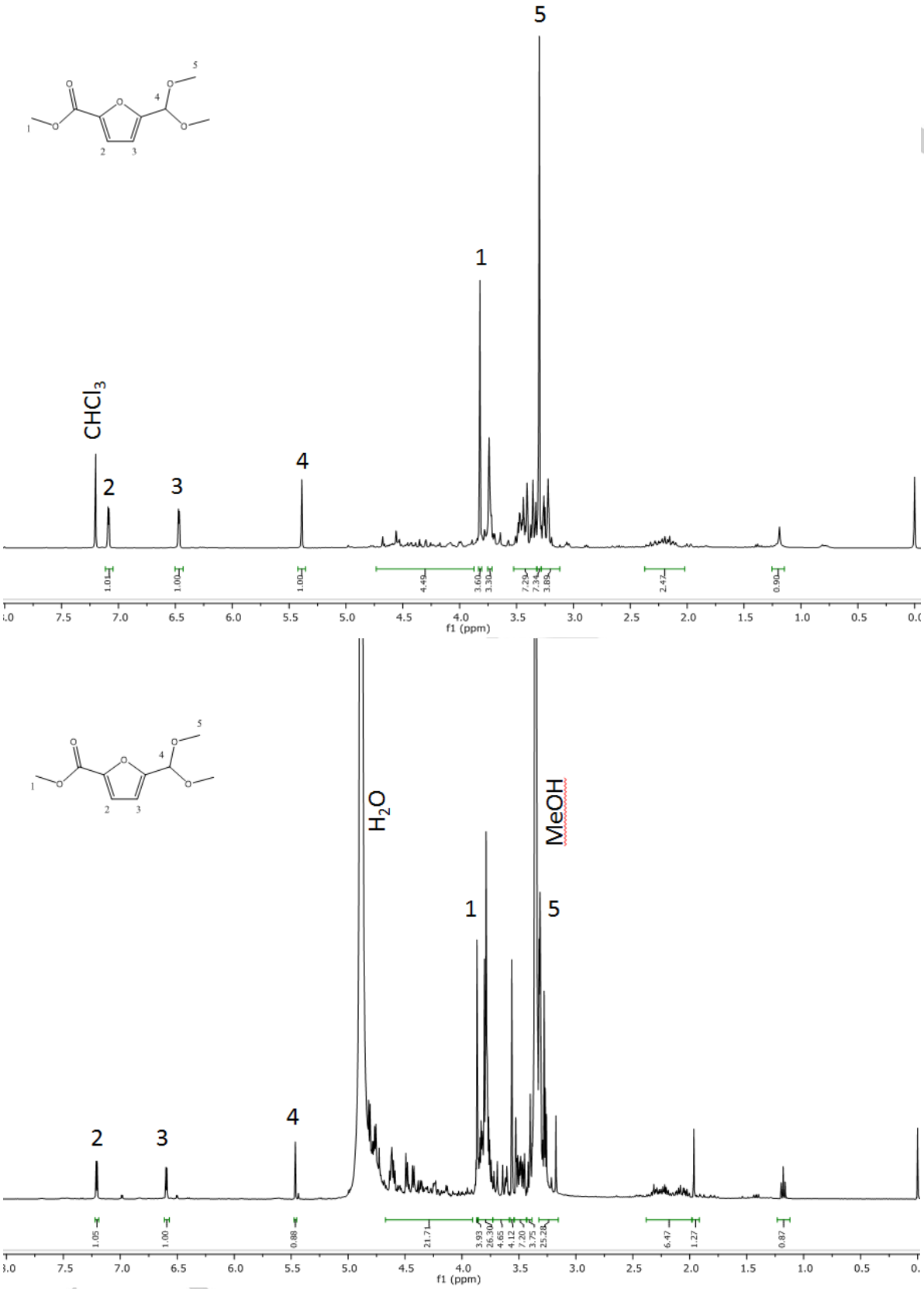

Figure S5. ^{1}H-NMR spectrum ($CDCl_3$) of the chloroform-soluble product mixture (top) and ^{1}H-NMR spectrum (MeOD-D_4) of the methanol-soluble product mixture (bottom) from the cyclodehydration of 5-keto-L-galactonic acid in MeOH/HCl.

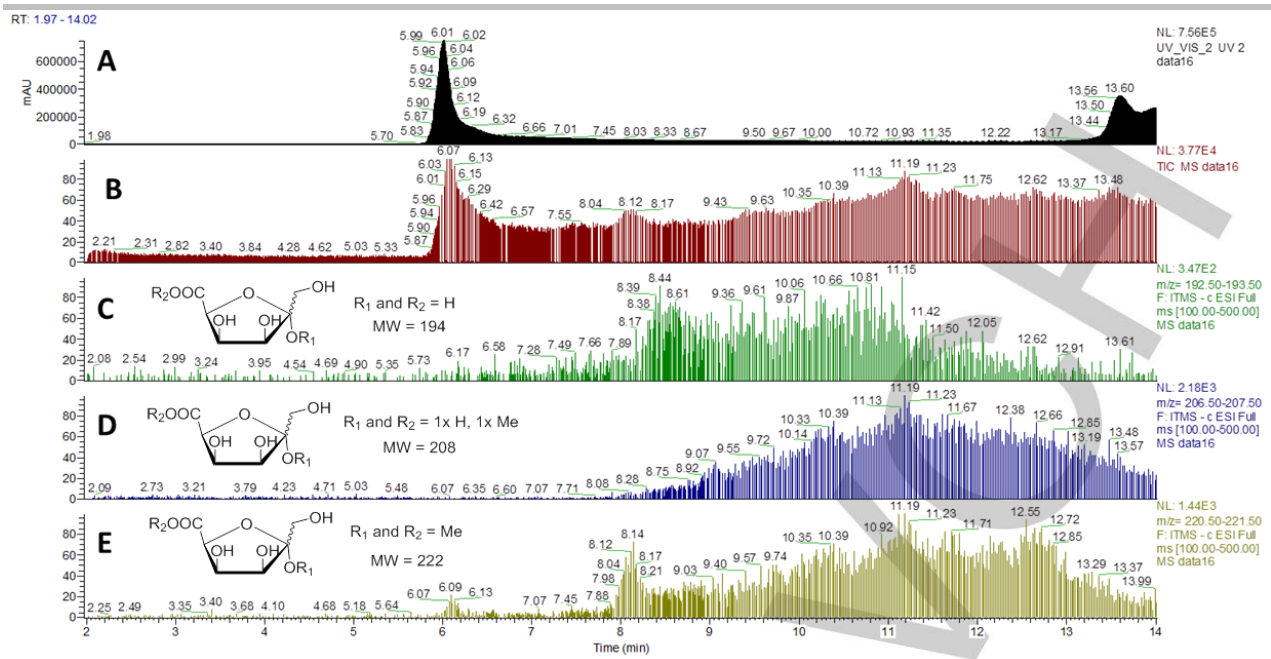

Figure S6. HPLC-MS chromatograms of the chloroform-soluble product mixture from the cyclodehydration of 5-keto-L-galactonic acid in MeOH/HCl. A) UV-VIS signal (at 6 min. the injection peak is visible); B) TIC signal; C) products with MW = 194 ($[M-H]^-$ = 192.5-193.5); D) products with MW = 208 ($[M-H]^-$ = 206.5-207.5); E) products with MW = 222 ($[M-H]^-$ = 220.5-221.5)

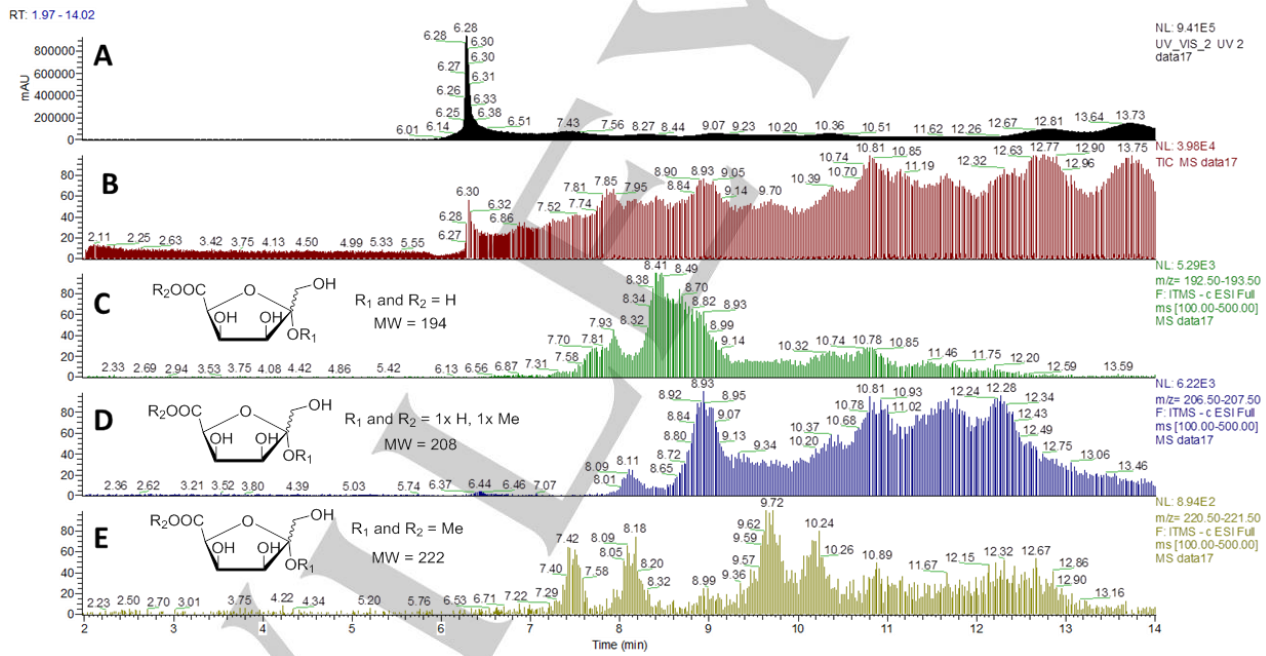

Figure S7. HPLC-MS chromatograms of the methanol-soluble product mixture from the cyclodehydration of 5-keto-L-galactonic acid in MeOH/HCl. A) UV-VIS signal (at 6 min. the injection peak is visible); B) TIC signal; C) products with MW = 194 ($[M-H]^-$ = 192.5-193.5); D) products with MW = 208 ($[M-H]^-$ = 206.5-207.5); E) products with MW = 222 ($[M-H]^-$ = 220.5-221.5).