Supporting Information

Synthesis and anionic polymerization of isosorbide mono-epoxides for linear biobased polyethers

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1. Materials and Characterization Methods

General. All reagents and solvents were obtained from commercial sources and were used without further purification if not mentioned otherwise.

Reactions were monitored by thin-layer chromatography (TLC), and TLC plates were visualized either by UV detection or by staining with $KMnO_4$, vanilla, or phosphomolybdic acid solution. Purification of reaction products was done by flash chromatography using silica gel 60 (0.040−0.063 mm, 230−400 mesh).

Structural Characterization. The structure of the monomers and polymers was characterized by NMR spectroscopy using a Bruker 400 MHz spectrometer with the samples dissolved in chloroform-*d*. The ^{1}H NMR and ^{13}C NMR spectra were recorded at 400.1 MHz and or 100.6 MHz, respectively. The chemical shifts for the ^{1}H and ^{13}C NMR spectra are given in ppm and are calibrated using residual solvent signals (for ^{1}H, $CDCl_3$: $\delta = 7.26$ ppm, for ^{13}C, $CDCl_3$: $\delta = 77.0$ ppm). The following abbreviations are used for multiplicities: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; b, broadened. The formation of polymers (**P8** and **P9**) from the corresponding isosorbide epoxides (**8** and **9**) was determined by the disappearance of the proton signals of the epoxy groups between the 3.2−2.5 ppm region in comparison with the characteristic peaks of the polymers in ^{1}H NMR spectra.

For HRMS analysis of monomers, a Thermo Electron LTQ Orbitrap XL analyzer was used.

An FTIR (ATR) spectrophotometer Shimadzu IRAffinity-1 was used for IR analysis.

The molecular weights of the polymers were determined by size-exclusion chromatography (SEC) in THF. The SEC setup included three Shodex columns coupled in series (KF-805, -804, and -802.5) situated in a Shimadzu CTO-20A prominence column oven, a Shimadzu RID-20A refractive index detector, with Shimadzu LabSolution software. All samples were run at 40 °C in THF and at an elution rate of 1 mL/min. Calibration was done by using poly(ethylene oxide) standards (M_n = 3 860, 12 600, 49 640, and 96 100 g mol^{-1}).

Thermal Characterization. Thermogravimetric analysis (TGA) was performed using a TA Instruments TGA Q500 apparatus to determine the thermal stability of the polymers under a N_2 atmosphere. The temperature was increased from 40 to 600 °C at a heating rate of 10 °C min^{-1}. The peak temperatures (T_p) at the highest mass-loss rates of the polymers were determined from the derivative thermogravimetric (DTG) curves. Differential scanning calorimetry (DSC) analysis was carried out by using a TA Instruments DSC Q2000 differential scanning calorimeter. Dried samples were transferred to aluminium pans, which were hermetically sealed. The samples were first heated to 150 °C, then cooled to –50 °C, and finally heated to 150 °C. The scan rate was 10 °C/min during the temperature program. The T_g's of the polymers were evaluated from the second heating scans by identifying the inflection points.

Solubility. Small samples (about 5 mg) of isosorbide polyethers (**P8** or **P9**) were mixed with a range of selected solvents (1 mL). The mixture was stirred for 24 h at room temperature. The results of the dissolution tests were divided into two categories, soluble (+) and insoluble (–), based on visual inspection. If the samples were found to be completely dissolved, they were considered as soluble; if not, they were considered as insoluble.

2. Synthesis of Organic Compounds

2.1. Synthesis of isosorbide mono-epoxides 6, 7, 8, and 9

2-methoxy-5-allyl-isosorbide (4)

The solution of 5-allyl-isosorbide **2** (22.54 g, 121 mmol) in THF (150 mL) was cooled on an ice-bath and potassium *tert*-butoxide (*t*-BuOK, 1.2 eq., 145 mmol, 17.13 g, reagent purity 95%) was added in three portions. The ice-bath was removed, and reaction mixture was stirred for 4 h at rt. Next, the flask was cooled down on an ice bath again and MeI (1.2 eq, 20.64 g, 9.05 mL, 145 mmol) was added dropwise. After stirring for 12 h at rt, the reaction mixture was poured into ice-cold water (200 mL) and extracted with EtOAc (3 x 200 mL). After drying ($MgSO_4$) and concentration using rotary evaporator, the crude material was purified by flash chromatography on silica gel using increasing amounts of EtOAc (20 to 70%) in petroleum ether (PE) to yield 2-methoxy-5-allyl-isosorbide **4** as a colourless oil (22.50 g, 93%).

TLC: $R_f = 0.53$ (60% EtOAc/PE), $R_f = 0.64$ (70% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 5.92 (ddt, J = 17.1, 10.4, 2x5.7 Hz, 1H), 5.28 (ddd, J = 17.1, 2.8, 1.5 Hz, 1H), 5.18 (ddd, J = 10.4, 2.8, 1.1 Hz, 1H), 4.58 (dd, J = 4.4, 4.3 Hz, 1H), 4.47 (dd, J = 4.3, 0.8 Hz, 1H), 4.18 (dddd, J = 12.5, 5.7, 1.5, 1.1 Hz, 1H), 4.06–3.98 (m, 2H), 3.94 (dm, J = 3.0 Hz, 2H), 3.90 (dd, J = 8.5, 6.7 Hz, 1H), 3.83 (m, 1H), 3.58 (dd, J = 8.5, 8.1 Hz, 1H), 3.35 (s, 3H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 134.56, 117.65, 85.96, 85.88, 80.23, 79.48, 73.02, 71.62, 69.94, 57.11 ppm.

2-methoxy-5-epoxy-isosorbide (8)

Meta-chloroperoxybenzoic acid (*m*-CPBA, 1.34 eq., 18.86 g, 84.2 mmol, reagent purity 77%) was dissolved in CH_2Cl_2 (280 mL) and cooled down on an ice-bath followed by the addition of 2-methoxy-5-allyl-isosorbide **4** (12.55 g, 62.75 mmol). The ice-bath was removed, and the reaction mixture was stirred for 12 h at rt. During the reaction, the resulting *m*-chlorobenzoic acid precipitated as white crystals. These crystals were filtered off using a glass filter. The organic layer was concentrated to around 100 mL and cooled in a refrigerator for 24 h. The formed solids (additional *m*-chlorobenzoic acid) were filtered off and water (150 mL) was added to the filtrate. Organic phase was separated, and the water phase extracted with CH_2Cl_2 (3 x 100 mL). Combined organic phase was washed with sat. aq. $NaHCO_3$ until neutral and dried over $MgSO_4$. After concentration, the product was purified by flash chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (30 to 90%) to yield 2-methoxy-5-epoxy-isosorbide **8** as a colourless oil (10.97 g, 81%).

TLC: $R_f = 0.36$ (70% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 2924, 1462, 1115, 1092, 1076, 853, 760.

HRMS (ESI): calcd for $C_{10}H_{16}O_5Na$ $[M + Na]^+$ 239.0890, found 239.0889.

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.60 (ddd, J = 10.3, 4.7, 4.4 Hz, 1H), 4.46 (d, J = 4.4 Hz, 1H), 4.07 (m, 1H), 4.01–3.76 (m, 5H), 3.62–3.28 (m, 2H), 3.32 (m, 3H), 3.15 (m, 1H), 2.76 (ddm, J = 4.9, 4.3, 2.9 Hz, 1H), 2.56 (ddd, J = 21.1, 4.9, 2.7 Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 85.85, 85.80, 85.78, 85.76, 80.71, 80.43, 80.36, 80.13, 72.99, 72.96, 71.78, 71.05, 70.14, 69.85, 57.09, 50.82, 50.65, 44.19, 44.07 ppm.

5-epoxy-isosorbide (6)

To an ice-cool stirred solution of *m*-CPBA (1.2 eq., 20.5 g, 91.44 mmol, reagent purity 77%) in CH_2Cl_2 (170 mL), 5-allyl-isosorbide **2** (14.17 g, 76.2 mmol) dissolved in CH_2Cl_2 (80 mL) was added. The mixture was stirred at rt for 20 h and concentrated to about 120 mL. *m*-Chlorobenzoic acid was precipitated upon keeping the crude reaction mixture in a refrigerator for 24 h. Solid material was removed by filtration and water (100 mL) was added to the filtrate. The water phase was extracted with CH_2Cl_2 (3 x 120 mL). The extract was washed with sat. aq. $NaHCO_3$ until neutral, dried over $MgSO_4$ and concentrated under reduced pressure. Purification by column chromatography on silica gel (increasing amounts of EtOAc in petroleum ether, 30 to 100%) afforded the 5-epoxy-isosorbide **6** as a colourless oil (12.52 g, 81%).

TLC: $R_f = 0.27$ (70% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 3422, 2943, 1130, 1072, 1022, 837, 748, 667.

HRMS (ESI): calcd for $C_9H_{14}O_5Na$ $[M + Na]^+$ 225.0733, found 225.0734.

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.68 (ddd, J = 10.5, 4.6, 4.4 Hz, 1H), 4.41 (m, 1H), 4.28 (m, 1H), 4.10 (dddd, J = 16.2, 7.3, 6.8, 4.6 Hz, 1H), 4.04–3.81 (m, 4H), 3.63–3.33 (m, 2H), 3.18 (m, 1H), 2.79 (ddd, J = 4.9, 4.0, 1.1 Hz, 1H), 2.59 (ddd, J = 16.9, 4.9, 2.8 Hz, 1H), 2.53 (bs, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 88.48, 88.47, 80.85, 80.51, 80.29, 80.08, 76.69, 76.64, 75.87, 71.81, 71.20, 70.39, 70.11, 50.92, 50.79, 44.26, 44.13 ppm.

2-allyl-5-methoxy-isosorbide (5)

To a solution of 2-allyl-isosorbide **3** (9.50 g, 51 mmol), aqueous KOH (50%, 8.60 mL) and tetrabutylammonium bromide (TBAB, 0.50 g, 1.55 mmol) in CH_2Cl_2 (120 mL) MeI (1.15 eq, 8.35 g, 3.66 mL, 59 mmol) was added. The reaction mixture was stirred at room temperature for 6 h, thereafter diluted with water (30 mL). Organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (3 x 60 mL). Combined organic fraction was washed with water (30 mL), dried ($MgSO_4$), and concentrated. Crude product was purified by flash chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (20 to 70%) to obtain 2-allyl-5-methoxy-isosorbide **5** as a colourless oil (8.76 g, 86%).

TLC: $R_f = 0.45$ (60% EtOAc/PE).

The NMR spectra were found identical to those previously reported.[1]

2-epoxy-5-methoxy-isosorbide (9)

m-CPBA (1.2 eq., 9.55 g, 42.6 mmol, reagent purity 77%) was added to CH_2Cl_2 (120 mL) and the solution was cooled down on ice bath. The solution of 2-allyl-5-methoxy-isosorbide **5** (7.1 g, 35.5 mmol) in CH_2Cl_2 (50 mL) was added dropwise and the mixture stirred at rt for 25 hours.

The volume of the reaction mixture was reduced to about 80 mL on a rotary evaporator and stored in a refrigerator for 24 h to promote the precipitation of *m*-chlorobenzoic acid. Solids were filtered off and water (80 mL) was added to the filtrate. Organic phase was separated, and water phase extracted with CH_2Cl_2 (3 x 50 mL). Combined organic phase was washed with sat. aq. $NaHCO_3$ until neutral, dried over $MgSO_4$ and concentrated under reduced pressure. Purification by column chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (30 to 90%) afforded 2-epoxy-5-methoxy-isosorbide **9** as a colourless oil (6.46 g, 84%).

TLC: $R_f = 0.35$ (70% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 2932, 1462, 1134, 1092, 1069, 849, 752.

HRMS (ESI): calcd for $C_{10}H_{16}O_5Na$ $[M + Na]^+$ 239.0890, found 239.0888.

^1H NMR (400.1 MHz, $CDCl_3$) δ 4.62 (ddm, *J* = 8.5, 4.3 Hz, 1H), 4.49 (dd, *J* = 11.6, 4.3 Hz, 1H), 3.99 (m, 1H), 3.97–3.85 (m, 4H), 3.77 (ddd, *J* = 11.5, 5.4, 2.8 Hz, 1H), 3.52 (m, 1H), 3.42 (s, 3H), 3.38 (ddd, *J* = 19.2, 11.5, 6.2 Hz, 1H), 3.09 (m, 1H), 2.75 (ddd, *J* = 4.8, 4.2, 3.2 Hz, 1H), 2.56 (ddd, *J* = 5.4, 4.8, 2.7 Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 86.21, 86.14, 84.89, 84.86, 81.69, 81.68, 79.90, 73.41, 73.20, 70.44, 70.24, 69.66, 58.17, 50.55, 50.53, 44.25, 44.24 ppm.

2-epoxy-isosorbide (7)

m-CPBA (1.2 eq., 14.10 g, 62.8 mmol, reagent purity 77%) was dissolved in CH_2Cl_2 (150 mL) and cooled on an ice bath. 2-Allyl-isosorbide **3** (9.73 g, 52.3 mmol) in CH_2Cl_2 (60 mL) was added. Ice bath was removed, and the reaction mixture was stirred at rt for 20 h. About half of the solvent was evaporated and the reaction mixture stored in a refrigerator for 24 h. The precipitated *m*-chlorobenzoic acid was removed by filtration. Water (100 mL) was added to the filtrate. Organic phase was separated, and the water layer was extracted with CH_2Cl_2 (3 x 80 mL). The extract was washed with sat. aq. $NaHCO_3$, dried over $MgSO_4$ and evaporated under reduced pressure. The crude material was purified by column chromatography on silica gel (increasing amounts of EtOAc in petroleum ether, 30 to 100%) to afford the 2-epoxy-isosorbide **7** as a white solid product (8.22 g, 78%).

TLC: $R_f = 0.25$ (70% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 3433, 2936, 1111, 1076, 1049, 849, 752, 667.

HRMS (ESI): calcd for $C_9H_{14}O_5Na$ $[M + Na]^+$ 225.0733, found 225.0734.

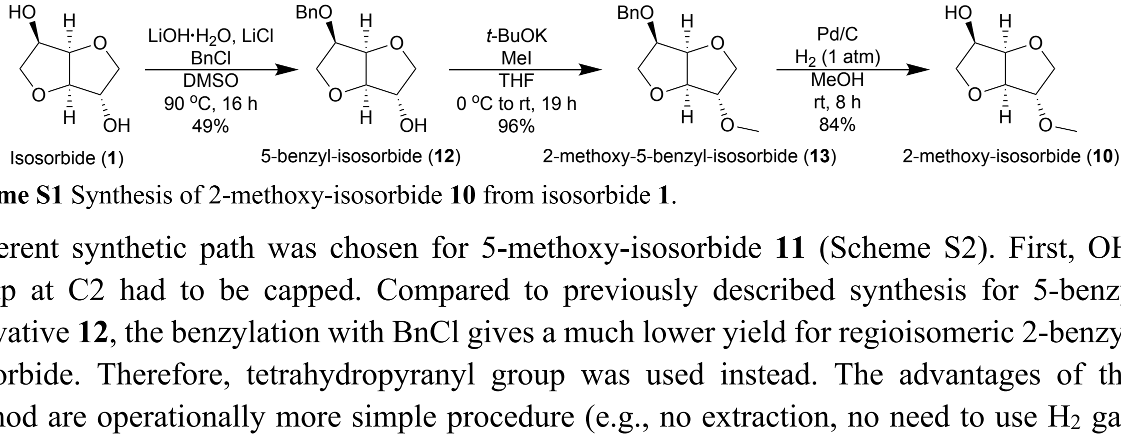
^1H NMR (400.1 MHz, $CDCl_3$) δ 4.59 (ddm, *J* = 4.7, 3.3 Hz, 1H), 4.46 (dd, *J* = 10.3, 4.7 Hz, 1H), 4.25 (m, 1H), 4.08–3.98 (m, 2H), 3.87 (ddd, *J* = 10.3, 6.6, 3.8 Hz, 1H), 3.85–3.78 (m, 2H), 3.53 (dd, *J* = 9.4, 5.8 Hz, 1H), 3.41 (ddd, *J* = 11.2, 5.8, 5.1 Hz, 1H), 3.13 (m, 1H), 2.79 (ddd, *J* = 5.0, 4.2, 1.7 Hz, 1H), 2.72 (d, *J* = 6.8 Hz, 1H), 2.59 (ddd, *J* = 5.0, 2.8, 1.1 Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 85.89, 85.82, 84.76, 84.71, 81.79, 81.77, 73.55, 73.54, 73.45, 73.22, 72.24, 72.23, 70.43, 70.42, 50.59, 50.56, 44.27 ppm.

2.2. Synthesis of 2-methoxy-isosorbide (10) and 5-methoxy-isosorbide (11), and epoxides (*S*)-8, (*R*)-8, (*S*)-9, and (*R*)-9

For the synthesis of methoxy-capped (*R*)- and (*S*)-mono-epoxides of isosorbide (**(*S*)-8**, **(*R*)-8**, **(*S*)-9**, and **(*R*)-9**), the 2-methoxy- and 5-methoxy-isosorbide derivatives (**10** and **11**, respectively) were prepared first. Initially, we tested direct mono-methylation of isosorbide, however these attempts had limited success. Efficient mono-methylation method of isosorbide has not been reported by other authors either and longer synthetic sequences have been implemented.[1-4] As the direct mono-methylation was not the main focus of this study, we also opted for a more established approach.

For the synthesis of 2-methoxy-isosorbide (**10**), we used benzylation, followed by methylation and debenzylation, as is outlined in Scheme S1. According to the literature, benzyl chloride (BnCl) with LiOH and LiCl in DMSO at 90 °C gives preference towards 5-*endo*-OH addition.[2] Thus, 5-benzyl-isosorbide (**12**) was obtained in 49% yield. Following methylation with MeI using *t*-BuOK in THF afforded 2-methoxy-5-benzyl-isosorbide (**13**) in 96% yield. Finally, the 2-methoxy derivative (**10**) was obtained by the benzyl-group removal with Pd/C and H_2 in MeOH at ambient temperature in 84% yield.

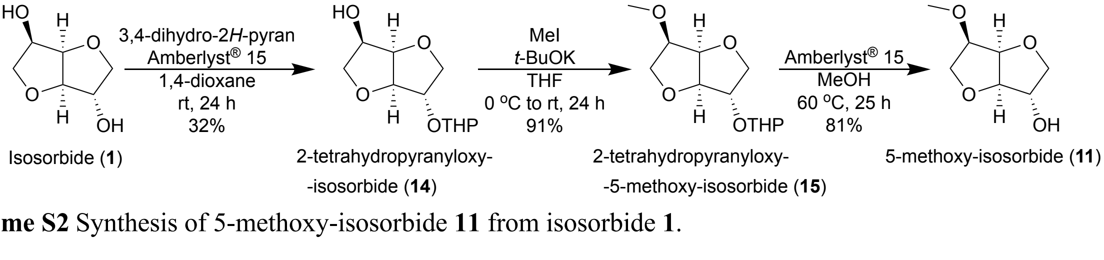


Isosorbide (**1**) 5-benzyl-isosorbide (**12**) 2-methoxy-5-benzyl-isosorbide (**13**) 2-methoxy-isosorbide (**10**)

Scheme S1 Synthesis of 2-methoxy-isosorbide **10** from isosorbide **1**.

Different synthetic path was chosen for 5-methoxy-isosorbide **11** (Scheme S2). First, OH-group at C2 had to be capped. Compared to previously described synthesis for 5-benzyl derivative **12**, the benzylation with BnCl gives a much lower yield for regioisomeric 2-benzyl-isosorbide. Therefore, tetrahydropyranyl group was used instead. The advantages of this method are operationally more simple procedure (e.g., no extraction, no need to use H_2 gas) and the use of only inexpensive reagents. Hence, 3,4-dihydro-2*H*-pyran and Amberlyst® 15 in 1,4-dioxane at rt afforded 2-tetrahydropyranyloxy-isosorbide (**14**) in 32% yield. Additionally, regioisomeric 5-tetrahydropyranyloxy-isosorbide (30%) and the dialkylated derivative 2,5-ditetrahydropyranyloxy-isosorbide (30%) also formed during the reaction but were easily separated by column chromatography. Next, 2-tetrahydropyranyloxy-5-benzyl-isosorbide (**15**) was obtained from **14** in 91% yield using MeI and *t*-BuOK in THF at rt. Subsequently, reaction of **15** with Amberlyst® 15 in MeOH at 60 °C afforded 5-methoxy-isosorbide (**11**) in 81% yield.

The methoxy-capped isosorbide derivatives **10** and **11** were further used for the synthesis of isosorbide mono-epoxides **(*S*)-8** and **(*R*)-8**, and **(*S*)-9** and **(*R*)-9**, respectively.



Isosorbide (**1**) 2-tetrahydropyranyloxy--isosorbide (**14**) 2-tetrahydropyranyloxy--5-methoxy-isosorbide (**15**) 5-methoxy-isosorbide (**11**)

Scheme S2 Synthesis of 5-methoxy-isosorbide **11** from isosorbide **1**.

5-benzyl-isosorbide (12)

Isosorbide **1** (16.30 g, 112 mmol), $LiOH·H_2O$ (1 eq., 4.70 g, 112 mmol) and LiCl (1 eq., 4.75 g, 112 mmol) were dissolved in DMSO (60 mL). The reaction mixture was heated to 90 °C and benzyl bromide (1 eq., 19.20 g, 112 mmol) was added dropwise. The reaction mixture was stirred for 16 h, cooled down to rt, acidified to pH 1 using 1 N aq. HCl and extracted with EtOAc (3 x 200 mL). The combined organic phase was washed with sat. aq. $NaHCO_3$ (60 mL) and brine (sat. aq. NaCl, 60 mL). After drying over $MgSO_4$, the crude product was concentrated under reduced pressure. Purification by column chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (30 to 100%) afforded 5-benzyl-isosorbide **12** as a colorless oil (12.78 g, 49%).

TLC: $R_f = 0.30$ (60% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 7.39–7.27 (m, 5H), 4.76 (d, J = 11.9 Hz, 1H), 4.69 (dd, J = 4.6, 4.4 Hz, 1H), 4.56 (d, J = 11.9 Hz, 1H), 4.40 (dm, J = 4.4 Hz, 1H), 4.29 (m, 1H), 4.06 (ddd, J = 7.6, 6.8, 4.6 Hz, 1H), 4.02–3.90 (m, 2H), 3.85 (dd, J = 8.8, 6.8 Hz, 1H), 3.60 (J = 8.8, 7.6 Hz, 1H), 2.35 (bs, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 137.64, 128.43, 127.92, 127.88, 88.29, 80.06, 79.13, 76.66, 75.82, 72.42, 70.17 ppm.

The NMR data is consistent with previous literature reports.[2, 3, 5]

2-methoxy-5-benzyl-isosorbide (13)

t-BuOK (1.3 eq., 7.88 g) was added to the ice-cold solution of 5-benzyl-isosorbide **12** (12.70 g, 54 mmol) in THF (100 mL) in three portions. The reaction mixture was stirred for 3 h at 0 °C, and MeI (1.5 eq., 11.50 g, 5.04 mL, 81 mmol) was added. The reaction was allowed to warm up to rt and stirred for additional 16 h. The solution was then poured into water (100 mL) and extracted with EtOAc (3 x 100 mL). The combined organic layer was washed with water (60 mL) and brine (60 mL), dried over $MgSO_4$, filtered, and evaporated. Purification by column column chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (20 to 80%) yielded 2-methoxy-5-benzyl-isosorbide **13** as a colourless oil (12.94 g, 96%).

TLC: $R_f = 0.50$ (70% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 7.39–7.27 (m, 5H), 4.77 (d, J = 11.8 Hz, 1H), 4.64 (dd, J = 4.6, 4.4 Hz, 1H), 4.56 (d, J = 11.8 Hz, 1H), 4.48 (dm, J = 4.4 Hz, 1H), 4.05 (ddd, J = 7.7, 6.7, 4.6 Hz, 1H), 4.02–3.95 (m, 2H), 3.89–3.82 (m, 2H), 3.63 (dd, J = 8.2, 7.7 Hz, 1H), 3.37 (s, 3H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 137.80, 128.49, 128.00, 127.92, 85.95, 85.88, 80.29, 79.18, 73.06, 72.45, 70.11, 57.17 ppm.

The NMR data is consistent with a previous literature report.[3]

2-methoxy-isosorbide (10)

2-Methoxy-5-benzyl-isosorbide **13** (12.90 g, 51.6 mmol) was dissolved in MeOH (100 mL). The air inside the flask was replaced by argon and the Pd/C catalyst was added. The reaction flask was equipped with H_2 balloon. First the H_2 was bubbled through the reaction mixture for some minutes and then stirred under H_2 atmosphere at rt for 8 h until the TLC monitoring indicated the complete consumption of the starting material. The reaction mixture was passed through a celite and the catalyst was washed with MeOH. The filtrate was concentrated in vacuo and the crude oily product was chromatographed on silica gel with increasing amounts of MeOH in CH_2Cl_2 (0 to 15%) to give 2-methoxy-isosorbide **10** as a colourless oil (6.89 g, 84%).

TLC: $R_f = 0.38$ (10% MeOH/CH_2Cl_2).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.58 (dd, $J = 5.1, 4.6$ Hz, 1H), 4.45 (dm, $J = 4.6$ Hz, 1H), 4.26 (ddd, $J = 11.4, 6.9, 5.8$ Hz, 1H), 4.03 (dm, $J = 9.9$ Hz, 1H), 3.90 (dm, $J = 4.0$ Hz, 1H), 3.87–3.80 (m, 2H), 3.55 (dd, $J = 9.5, 5.8$ Hz, 1H), 3.37 (s, 3H), 2.73 (d, $J = 6.9$ Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 85.58, 85.41, 81.67, 73.51, 72.93, 72.18, 57.13 ppm.

The NMR data is consistent with previous literature reports.[2–4]

2-methoxy-(*R*)-(-)-5-epoxy-isosorbide ((*R*)-8)

2-Methoxy-isosorbide **10** (1.495 g, 9.34 mmol) was mixed with aq. solution of NaOH (2.24 g, 28.03 mmol, 3 eq., 50% solution) and Bu_4NHSO_4 (32 mg, 0.01 eq. 0.09 mmol). (*R*)-(-)-epichlorohydrin (2.56 g, 26.80 mmol, 2.87 eq.) was added at rt and the mixture was stirred at 40 °C for 4 h. The product solution was decanted from a thick sticky material. Then the obtained aq. solution was washed with EtOAc (4 x 15 mL). Organic phases were combined, dried over $MgSO_4$ and the solvent with an excess of epichlorohydrin were distilled off under reduced pressure. The residue was subjected to column chromatography on silica gel (increasing amounts of EtOAc in petroleum ether, 30 to 100%) to obtain 2-methoxy-(*R*)-(-)-5-epoxy-isosorbide **(*R*)-8** as a colurless oil (1.309 g, 69%).

TLC: $R_f = 0.33$ (60% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.62 (dd, $J = 4.6, 4.3$ Hz, 1H), 4.46 (d, $J = 4.3$ Hz, 1H), 4.05 (ddd, $J = 7.6, 6.8, 4.6$ Hz, 1H), 4.01–3.85 (m, 3H), 3.84–3.78 (m, 2H), 3.61–3.53 (m, 2H), 3.33 (s, 3H), 3.16 (m, 1H), 2.76 (dd, $J = 4.9, 4.3$ Hz, 1H), 2.60 (dd, $J = 4.9, 2.7$ Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 85.80, 85.75, 80.64, 80.30, 72.89, 70.97, 69.79, 57.00, 50.57, 44.11 ppm.

2-methoxy-(*S*)-(+)-5-epoxy-isosorbide ((*S*)-8)

(*S*)-(+)-epichlorohydrin (2.71 g, 2.5 eq., 28.35 mmol) was added to the mixture of 2-methoxy-isosorbide **10** (1.814 g, 11.34 mmol), aq. solution of NaOH (2.72 g of 50% solution, 3 eq.) and Bu_4NHSO_4 (38.5 mg, 0.01 eq., 0.11 mmol) at rt. Resulting viscous mixture was stirred for 4 h at 40 °C and thereafter for 16 h at rt. The product together with an excess of epichlorohydrin was decanted from the viscous precipitate and the product solution was washed with EtOAc (4 x 20 mL). Combined organic layer was dried over $MgSO_4$, concentrated under reduced pressure, and the residue was purified on silica gel column using increasing amounts of EtOAc (30 to 100%) in petroleum ether to afford 1.634 g (71%) of 2-methoxy-(*S*)-(+)-5-epoxy-isosorbide **(*S*)-8** as a colourless oil.

TLC: $R_f = 0.33$ (60% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.63 (dd, *J* = 4.6, 4.4 Hz, 1H), 4.50 (d, *J* = 4.4 Hz, 1H), 4.12 (ddd, *J* = 7.4, 6.7, 4.6 Hz, 1H), 4.01 (dd, *J* = 11.6, 2.7 Hz, 1H), 3.99–3.91 (m, 3H), 3.86 (m, 1H), 3.63 (dd, *J* = 8.6, 7.9 Hz, 1H), 3.41–3.33 (m, 4H), 3.18 (m, 1H), 2.80 (dd, *J* = 4.9, 4.2 Hz, 1H), 2.58 (dd, *J* = 4.9, 2.7 Hz, 1H) ppm.
^{13}C NMR (100.6 MHz, $CDCl_3$) δ 85.89, 85.85, 80.51, 80.21, 73.07, 71.85, 70.23, 57.17, 50.90, 44.15 ppm.

2-tetrahydropyranyloxy-isosorbide (14)

To a solution of isosorbide (40.0 g, 274 mmol) in 1,4-dioxane (300 mL), Amberlyst® 15 (2.6 g) and 3.4-dihydro-*2H*-pyran (1.0 eq., 23.0 g, 274 mmol) were added. The reaction mixture was stirred at rt for 24 h. After filtrating off the catalyst, the crude mixture was concentrated and the crude product was purified by chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (30 to 90%) to yield 2-tetrahydropyranyloxy-isosorbide **14** as a colourless oil (20.22 g, 32%).
TLC: R_f = 0.37 (60% EtOAc/PE).
^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.67 (ddd, *J* = 18.2, 4.3, 2.7 Hz, 1H), 4.62–4.38 (m, 2H), 4.32 (m, 1H), 4.25 (m, 1H), 4.03 (m, 1H), 3.96–3.76 (m, 3H), 3.56–3.44 (m, 2H), 2.71 (bs, 1H), 1.87–1.74 (m, 1H), 1.73–1.40 (m, 5H) ppm.
^{13}C NMR (100.6 MHz, $CDCl_3$) δ 98.44, 98.05, 86.85, 86.27, 81.81, 81.58, 81.07, 81.03, 74.50, 73.39, 73.37, 73.17, 72.44, 72.23, 62.83, 62.81, 30.75, 30.71, 25.26, 19.54, 19.52 ppm.

2-tetrahydropyranyloxy-5-methoxy-isosorbide (15)

To an ice-cold solution of 2-tetrahydropyranyloxy-isosorbide **14** (15.77 g., 69 mmol) in THF (300 mL), *t*-BuOK (1.4 eq., 10.77 g, 96 mmol) was added in three portions. The mixture was stirred for 4 h at 0 °C followed by the addition of MeI (1.4 eq., 13.62 g, 5.97 mL, 96 mmol). The reaction mixture was allowed to warm up and the stirring was continued at rt for 20 h. Then the reaction mixture was poured into water (200 mL), extracted with EtOAc (3 x 200 mL), washed with water (50 mL) and brine (50 ml). After drying over $MgSO_4$ and concentration in vacuum, the residue was purified by column chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (20 to 70%) to yield 2-tetrahydropyranyloxy-5-methoxy-isosorbide **15** as a colourless oil (15.14 g, 91%).
TLC: R_f = 0.43 (60% EtOAc/PE).
^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.74–4.45 (m, 3H), 4.30 (m, 1H), 4.04–3.88 (m, 4H), 3.88–3.78 (m, 1H), 3.60–3.49 (m, 2H), 3.48–3.43 (m, 3H), 1.88–1.75 (m, 1H), 1.74–1.41 (m, 5H) ppm.
^{13}C NMR (100.6 MHz, $CDCl_3$) δ 98.32, 98.16, 87.22, 86.73, 82.03, 81.80, 81.32, 81.20, 79.88, 79.74, 74.59, 73.40, 69.62, 69.59, 62.92, 62.71, 58.20, 58.16, 30.78, 30.77, 25.30, 19.62, 19.50 ppm.

***Alternative synthesis of* 2-tetrahydropyranyloxy-5-methoxy-isosorbide (15)**:

To 2-tetrahydropyranyloxy-isosorbide **14** (6.22 g, 27.0 mmol) in CH_2Cl_2 (60 mL) was added aqueous KOH (50%, 4.60 mL) and TBAB (270 mg, 0.84 mmol). The reaction mixture was cooled down on ice-bath and then MeI (1.2 eq., 4.60 g, 2.02 mL) was added. After stirring at rt for 6 h the reaction mixture was diluted with water (60 mL) and extracted with CH_2Cl_2 (3 x 80 mL). Combined organic fraction was washed with water (50 mL), dried over $MgSO_4$, and concentrated. Crude product was purified by column chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (20 to 70%) to yield 2-tetrahydropyranyloxy-5-methoxy-isosorbide **15** as colourless oil (6.22 g, 90%).

5-methoxy-isosorbide (11)

The 2-tetrahydropyranyloxy-5-methoxy-isosorbide **15** (15.1 g, 61.9 mmol) was stirred in MeOH (200 mL) in the presence of Amberlyst® 15 (2.0 g) at 60 °C for 25 h. After filtrating off the catalyst, the crude mixture was concentrated and the crude product was purified by chromatography on silica gel using increasing amounts of EtOAc in petroleum ether (30 to 100%) to yield 5-methoxy-isosorbide **11** as a colourless oil (7.99 g, 81%).

TLC: $R_f = 0.29$ (60% EtOAc/PE).

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.72 (dd, J = 4.2, 4.0 Hz, 1H), 4.44 (dm, J = 4.2 Hz, 1H), 4.30 (m, 1H), 3.98–3.88 (m, 4H), 3.55 (dd, J = 11.1, 10.5 Hz, 1H), 3.46 (s, 3H), 2.36 (bs, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 88.40, 81.80, 79.79, 76.73, 75.90, 69.95, 58.28 ppm.

The NMR data is consistent with previous literature reports.[2, 4, 6]

(*R*)-(-)-2-epoxy-5-methoxy-isosorbide ((*R*)-9)

To a stirred mixture of 5-methoxy-isosorbide **11** (1.28 g, 7.98 mmol), NaOH (3 eq., 0.96 g, 23.94 mmol) and water (1 mL), *R*-(-)-epichlorohydrin (2.5 eq., 1.90 g, 19.95 mmol), and TBAB (5 mol%, 130 mg, 0.4 mmol) were sequentially added. The mixture was stirred at 40 °C for 6 h. After completion of the reaction, it was diluted with ice-cooled water (15 mL) and the resulting mixture was extracted with EtOAc (3 x 20 mL). The extract was washed with water (2 x 10 mL), brine (15 mL), dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. The crude material was purified by column chromatography using increased amounts of EtOAc in petroleum ether (30 to 100%) to afford the (*R*)-2-epoxy-5-methoxy-isosorbide **(*R*)-9** as a colourless oil (1.12 g, 70%).

TLC: $R_f = 0.30$ (60% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 2947, 1462, 1134, 1088, 1072, 849, 756.

^{1}H NMR (400.1 MHz, $CDCl_3$) δ 4.66 (dm, J = 4.3 Hz, 1H), 4.51 (d, J = 4.3 Hz, 1H), 4.03 (m, 1H), 4.02–3.88 (m, 4H), 3.80 (dd, J = 11.6, 2.8 Hz, 1H), 3.57 (m, 1H), 3.49–3.42 (dd, J = 11.6, 5.8 Hz, 1H), 3.46 (s, 3H), 3.13 (m, 1H), 2.79 (dd, J = 4.9, 4.1 Hz, 1H), 2.61 (dd, J = 4.9, 2.7 Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, $CDCl_3$) δ 86.19, 84.94, 81.71, 79.93, 73.44, 70.26, 69.70, 58.20, 50.56, 44.29 ppm.

$[\alpha]^{20}_D$ +89.5 (c 1.1, $CHCl_3$)

(*S*)-(+)-2-epoxy-5-methoxy-isosorbide ((*S*)-9)

Epoxide **(*S*)-9** as a colourless oil (1.26 g, 69%) was obtained from 5-methoxy-isosorbide **11** (1.45 g, 9.0 mmol) and *S*-(+)-epichlorohydrin (2.5 eq., 2.15 g, 22.5 mmol) using similar procedure as for epoxide **(*R*)-9**.

TLC: $R_f = 0.31$ (60% EtOAc/PE).

IR (ATR) ν_{max} (cm^{-1}): 2932, 1462, 1215, 1091, 1072, 853, 752.

^{1}H NMR (400.1 MHz, CDCl$_3$) δ 4.65 (dm, *J* = 4.3 Hz, 1H), 4.53 (d, *J* = 4.3 Hz, 1H), 4.01 (m, 1H), 3.99–3.87 (m, 4H), 3.80 (dd, *J* = 11.5, 2.8 Hz, 1H), 3.59–3.51 (m, 1H), 3.44 (s, 3H), 3.39 (dd, *J* = 11.5, 6.1 Hz, 1H), 3.12 (m, 1H), 2.78 (dd, *J* = 4.9, 4.2 Hz, 1H), 2.58 (dd, *J* = 4.9, 2.7 Hz, 1H) ppm.

^{13}C NMR (100.6 MHz, CDCl$_3$) δ 86.24, 84.88, 81.71, 79.92, 73.21, 70.45, 69.69, 58.18, 50.56, 44.28 ppm.

$[\alpha]^{20}_D$ +74.1 (*c* 1.1, CHCl$_3$)

3. Synthesis of Polyethers

General procedure for anionic ring-opening polymerization of isosorbide mono-epoxides. Isosorbide epoxide (**8** or **9**) was dried carefully prior to the polymerization. The flask with epoxide was degassed with argon three times and the epoxide was dissolved in freshly distilled toluene. The reaction flask was flamed with a hot-gun, equipped with a magnetic stirrer bar, fitted with a rubber septum, degassed with argon three times, and then cooled down to –30 °C on acetonitrile/liquid N_2 bath. The epoxide in toluene was transferred to the reaction flask at –30 °C. $NOct_4Br$ in toluene followed by *i*-Bu_3Al in toluene (C = 1.1 M) were added via a syringe under argon at –30 °C. The temperature of the mixture was slowly increased to room temperature (20 °C) and the polymerization was allowed to proceed for 24 h at this temperature. Then a small amount of MeOH was added to stop the reaction. The polymer conversion was determined by ^1H NMR spectrum. The polymer was precipitated into the excess of Et_2O and stirred for 2 h. Et_2O was decanted, new portion of Et_2O was added, and this procedure was repeated twice. Finally, after Et_2O was decanted, the polymer was dissolved in $CHCl_3$, collected into a small flask and dried under reduced pressure. After drying both polymers were transparent, sticky substances.

Polymer P8

IR (ATR) ν_{max} (cm^{-1}): 2932, 1462, 1115, 1088, 1080, 756.

^1H NMR (400 MHz, $CDCl_3$) δ 4.59 (m, 1H), 4.47 (d, J = 4.4 Hz, 1H), 4.03 (m, 1H), 3.96–3.85 (m, 3H), 3.82 (1 H), 3.81–3.65 (m, 1H), 3.64–3.43 (m, 5 H), 3.36 (bs, 3H) ppm.

Polymer P9

IR (ATR) ν_{max} (cm^{-1}): 2936, 1474, 1126, 1087, 1072, 760.

^1H NMR (400 MHz, $CDCl_3$) δ 4.64 (m, 1H), 4.50 (m, 1H), 4.02–3.88 (m, 5H), 3.67–3.48 (m, 6H), 3.46 (bs, 3H) ppm.

Table S1 Solubility of isosorbide polyethers **P8** and **P9** at 21 °C.

	solvent[a]								
polymer	**H_2O δ= 48 (s)**	**MeOH δ= 30 (s)**	***n*-BuOH δ= 23 (s)**	**DMSO δ= 25 (m)**	**THF δ= 19 (m)**	**Et_2O δ= 15 (m)**	**ACN δ= 24 (p)**	**$CHCl_3$ δ= 19 (p)**	**toluene δ= 18 (p)**
P8	–	+	–	+	+	–	–	+	+
P9	–	+	–	+	+	–	–	+	+

[a]The symbols ”+” and “–” indicate solubility and insolubility, respectively. Solubility parameters (δ, $MPa^{1/2}$) were obtained from the *Polymer Handbook* (J. Brandrup, E. H. Immergut, E. A. Grulke, A. Abe, D. Bloch. *Polymer Handbook, 4th ed.*, John Wiley and Sons, New York, 1999), and the letters s, m, and p denote strongly, moderately, and poorly hydrogen-bond-forming solvents, respectively.

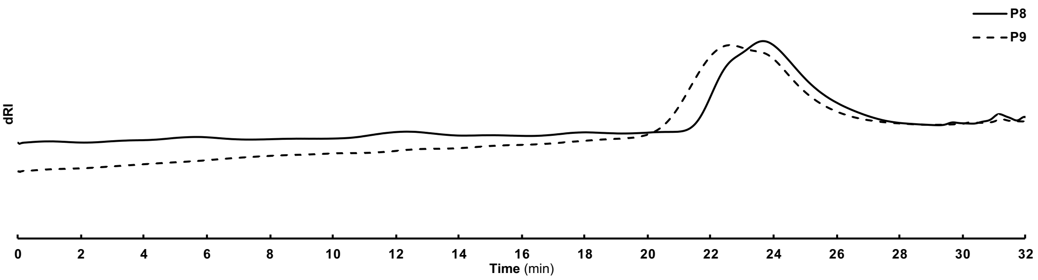


Fig. S1 SEC curves of polymers **P8** and **P9** in THF with differential refractive index (dRI) detector.

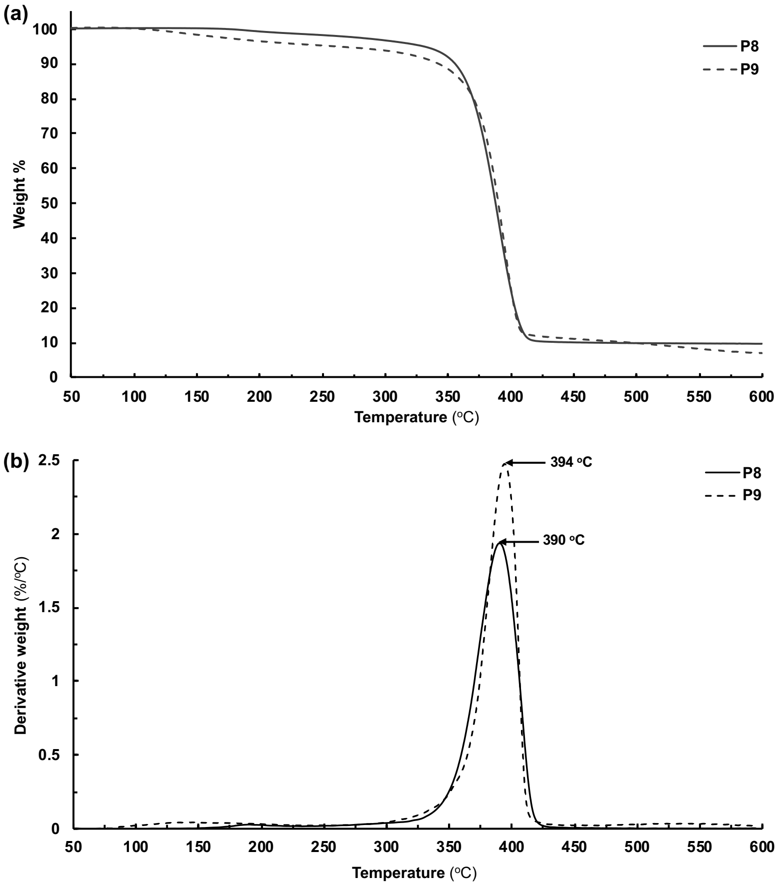


Fig. S2 TGA (a) and DTG (b) profiles of polymer **P8** and **P9**. The T_p values are indicated at the respective peak. Notably, sample **P9** showed a small weight loss (approx. 3%) at 100–200 °C connected with the evaporation of a trace amount of water.

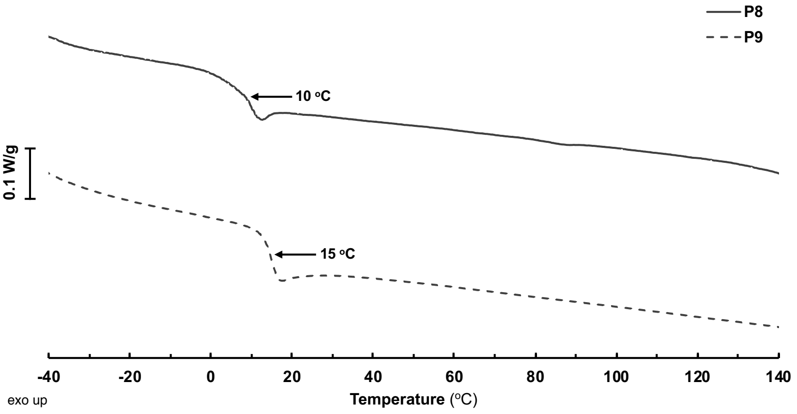


Fig. S3 DSC heating curves of polymers **P8** and **P9**, T_g values are indicated at the transitions.

4. ^{1}H and ^{13}C NMR Spectra

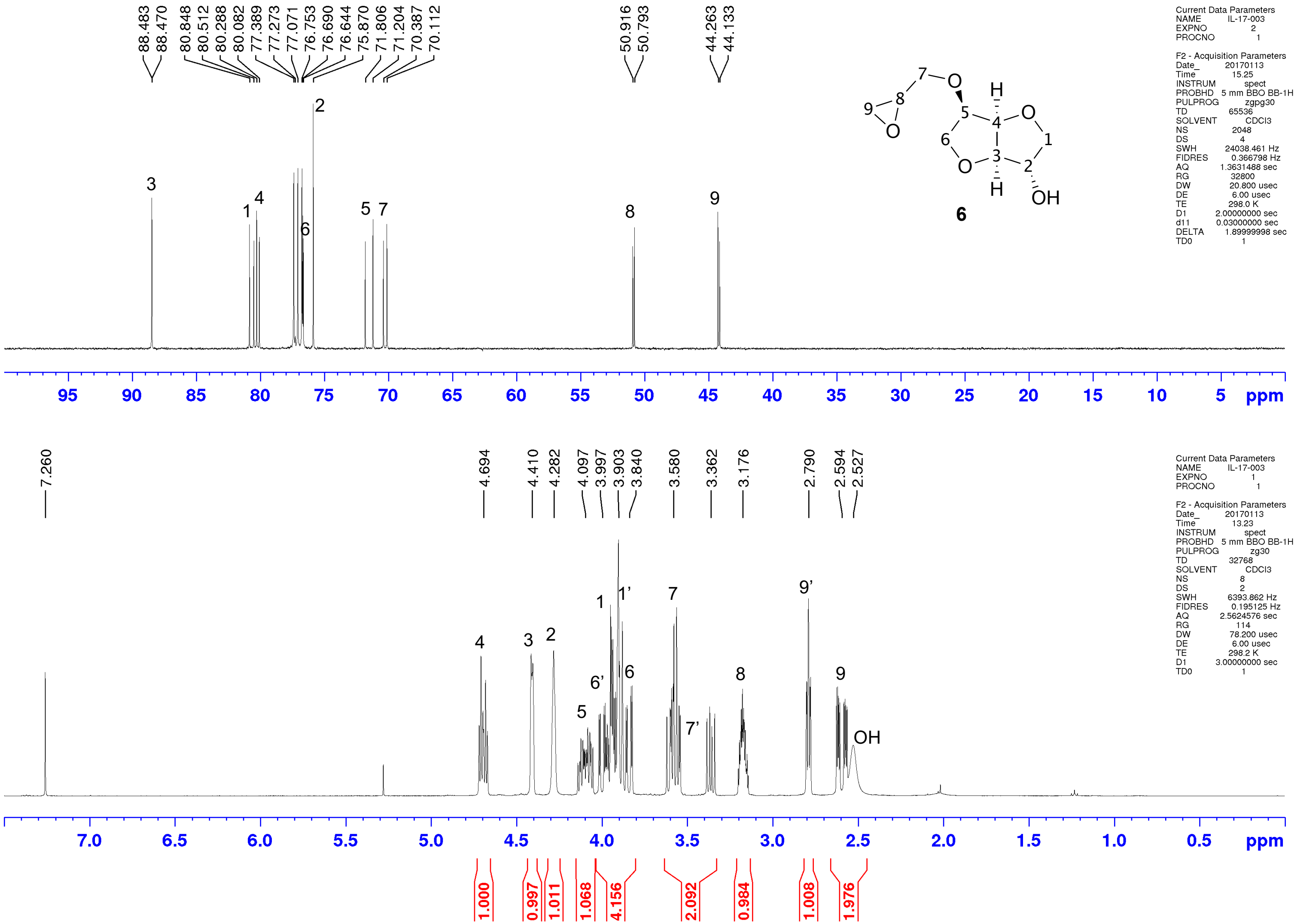


Fig. S4 ^{1}H and ^{13}C NMR spectra of 5-epoxy-isosorbide (**6**).

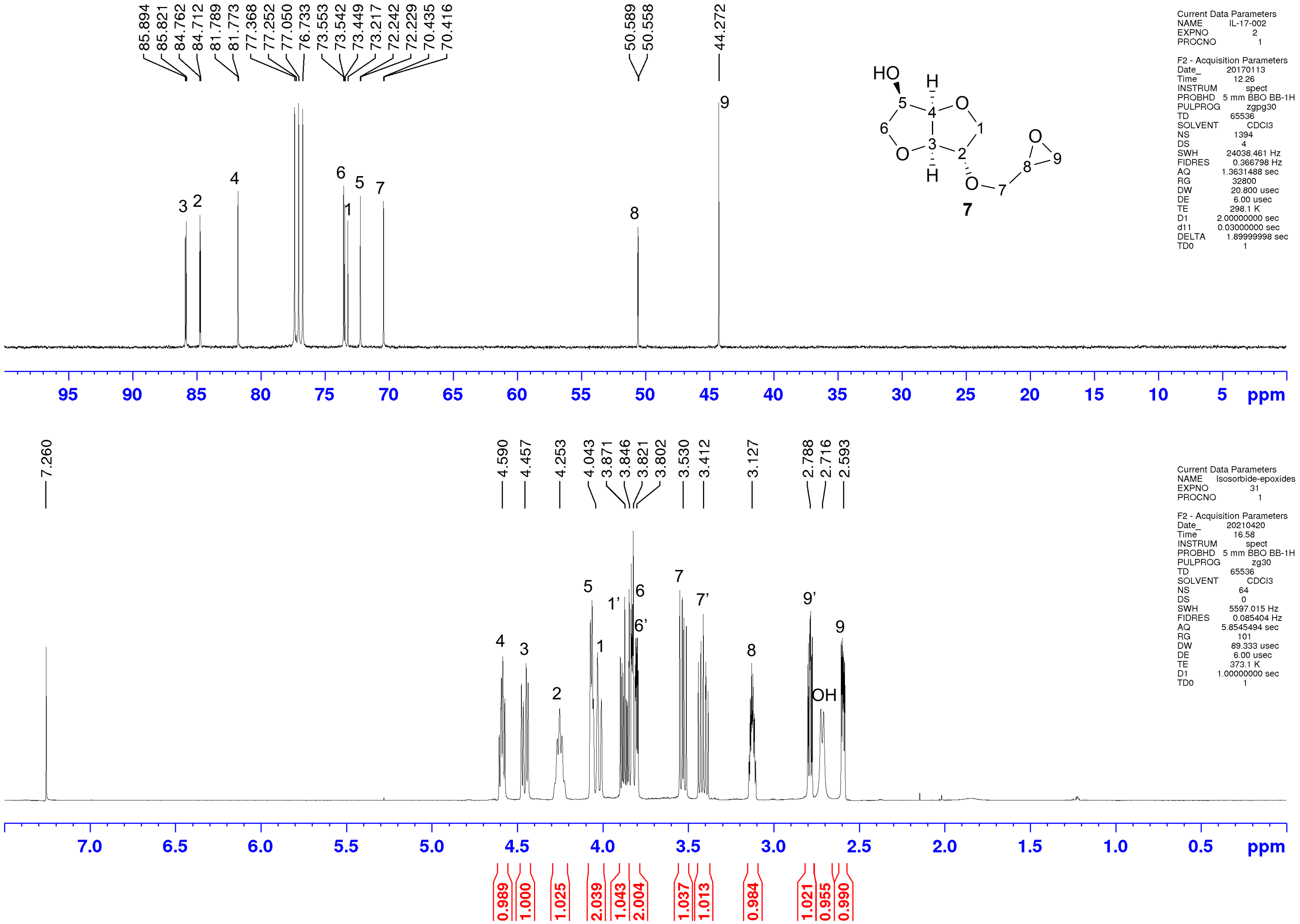


Fig. S5 ^{1}H and ^{13}C NMR spectra of 2-epoxy-isosorbide (**7**).

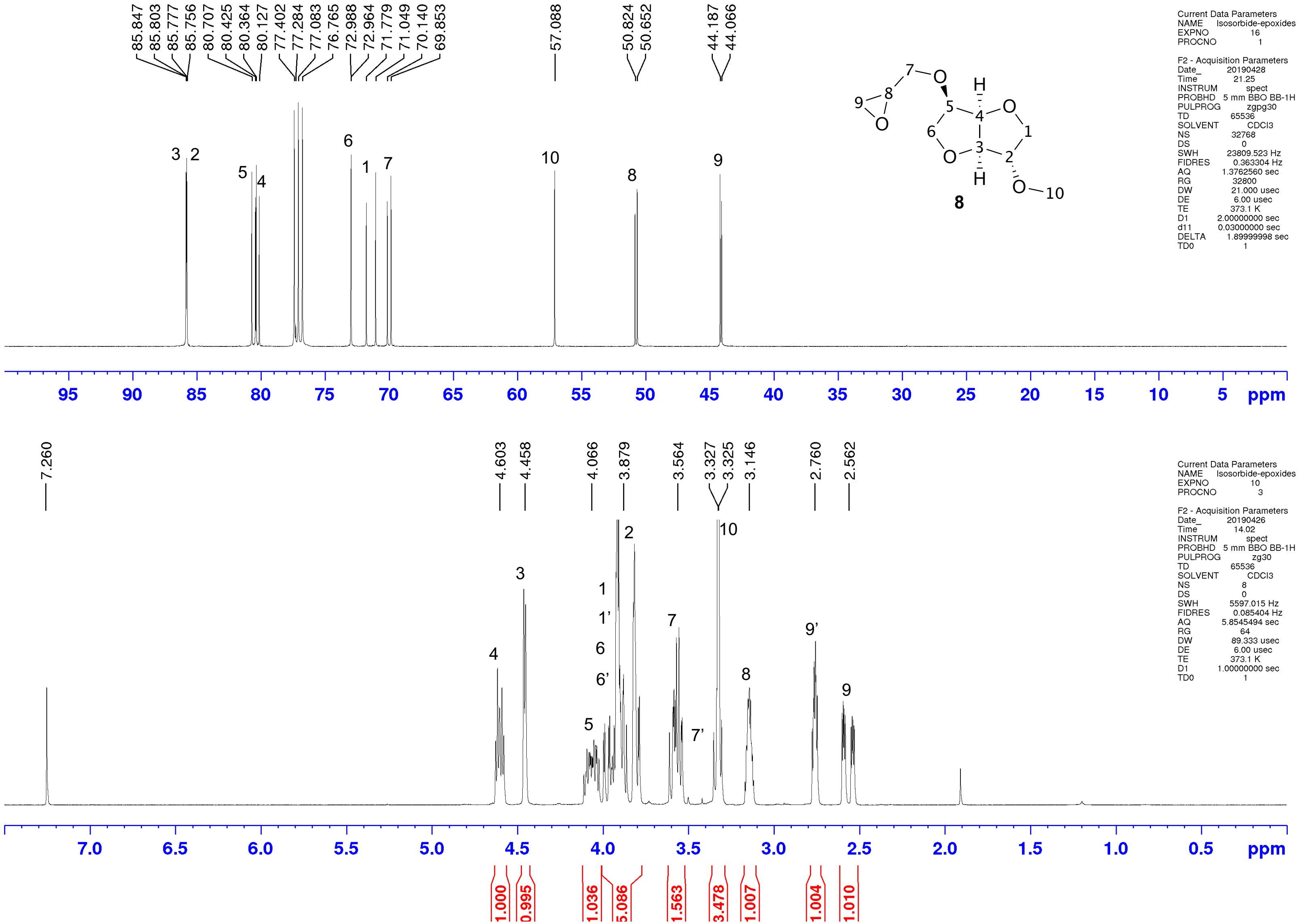


Fig. S6 ^{1}H and ^{13}C NMR spectra of 2-methoxy-5-epoxy-isosorbide (**8**).

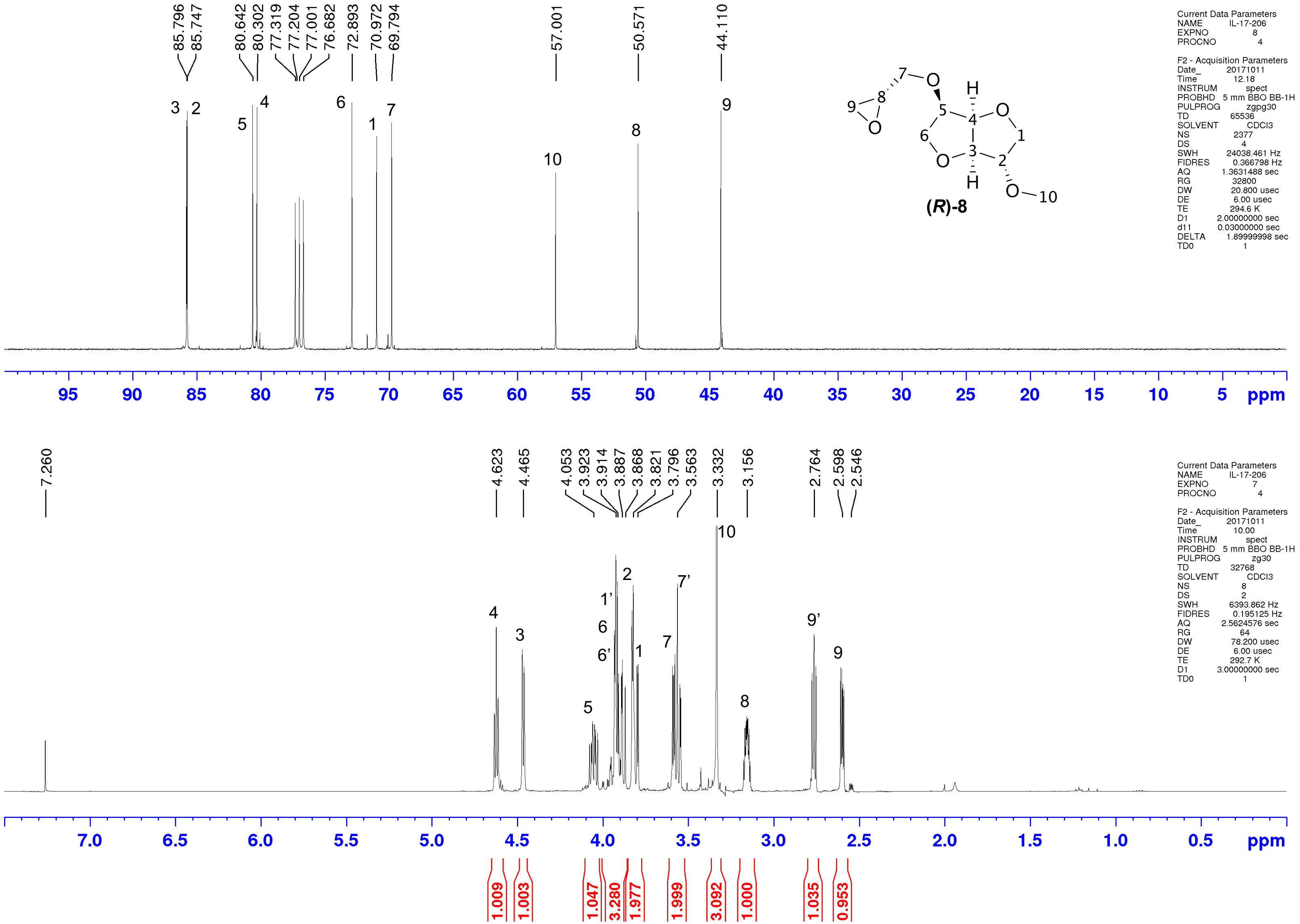


Fig. S7 ^{1}H and ^{13}C NMR spectra of 2-methoxy-(*R*)-(-)-5-epoxy-isosorbide ((***R*)-8**).

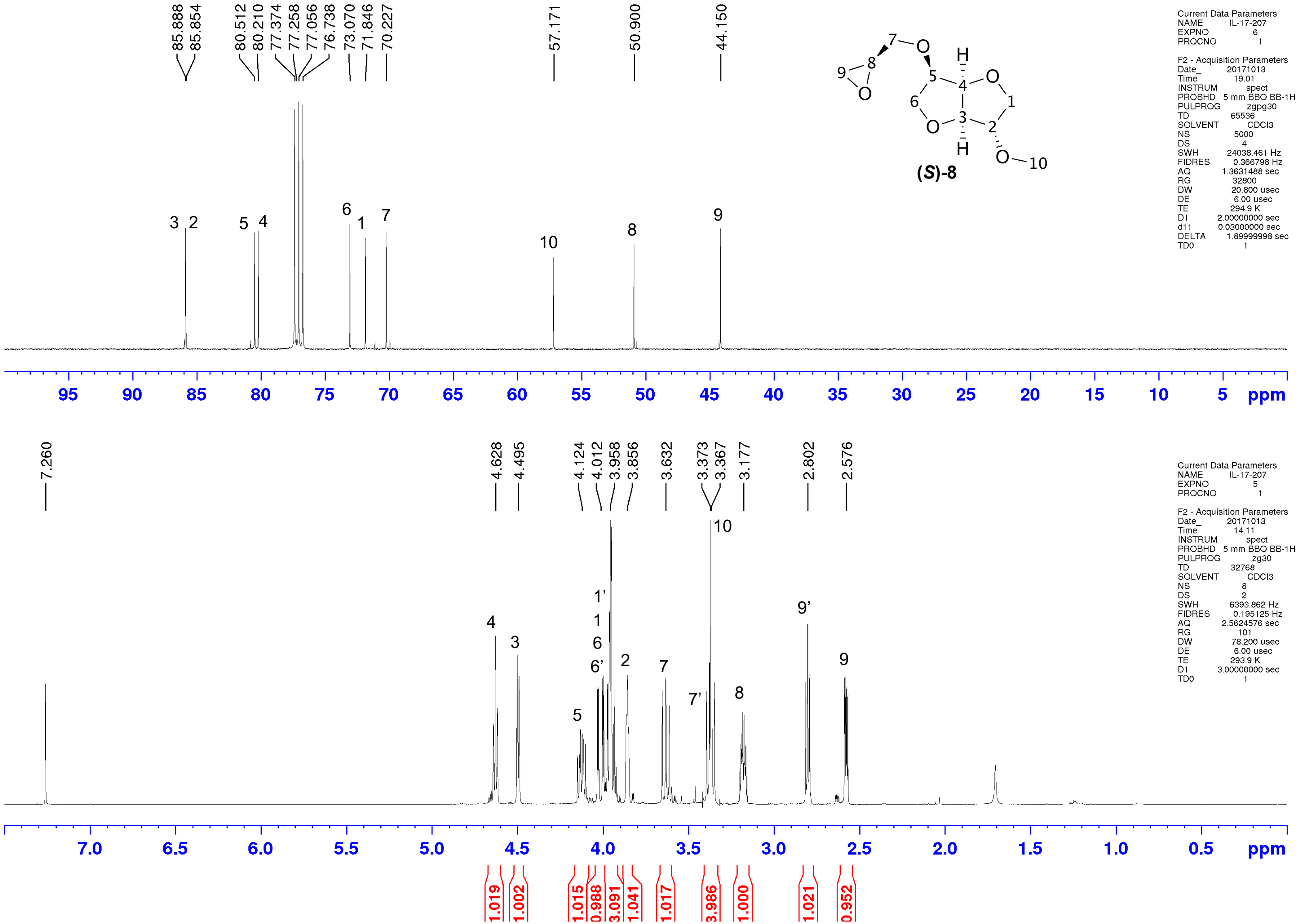


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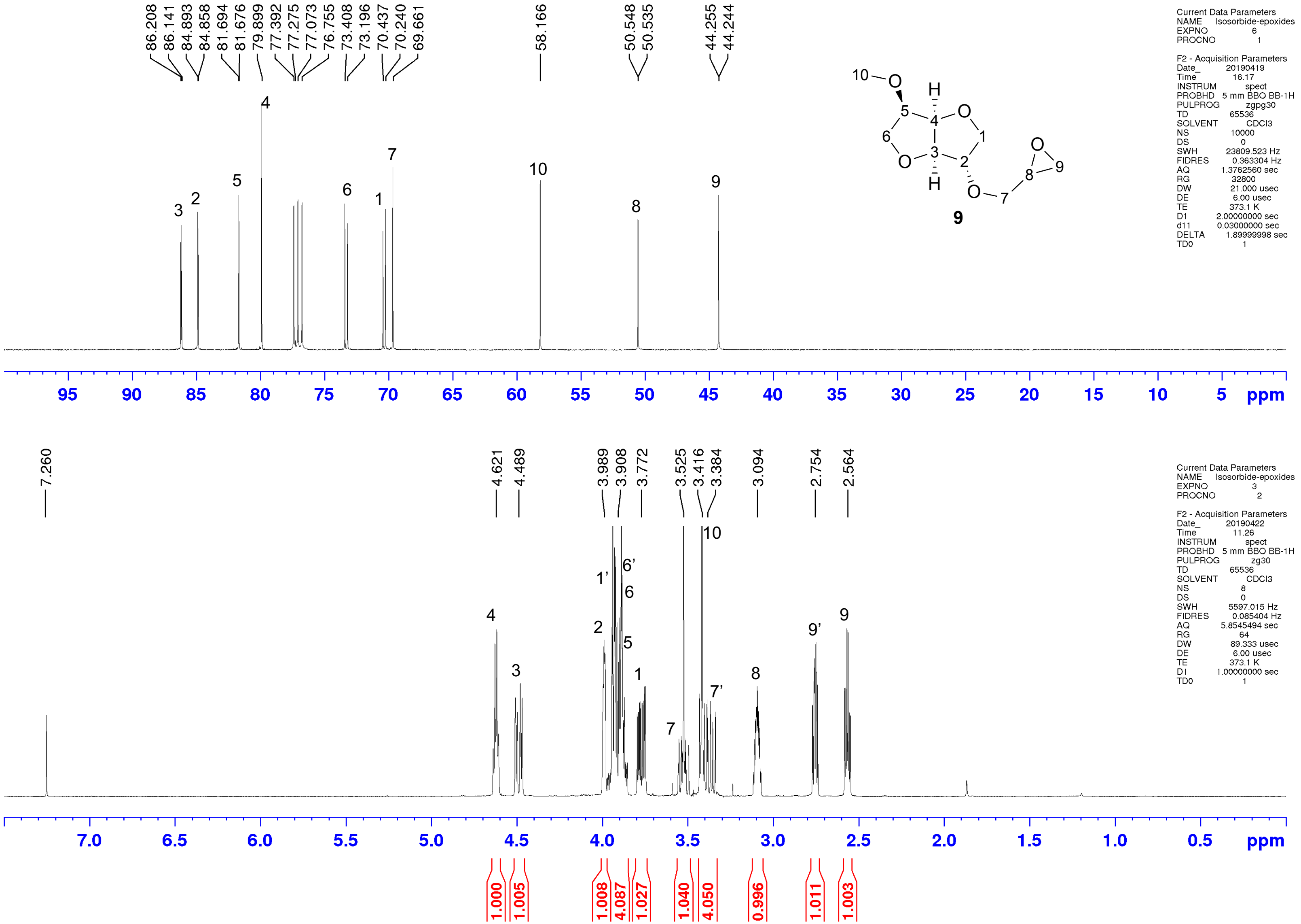
Fig. S8 ^{1}H and ^{13}C NMR spectra of 2-methoxy-(*S*)-(-)-5-epoxy-isosorbide (**(*S*)-8**).



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FIDRES       0.085404 Hz
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RG                   64
DW           89.333 usec
DE             6.00 usec
TE              373.1 K
D1         1.00000000 sec
TD0                   1
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Fig. S9 ^{1}H and ^{13}C NMR spectra of 2-epoxy-5-methoxy-isosorbide (**9**).

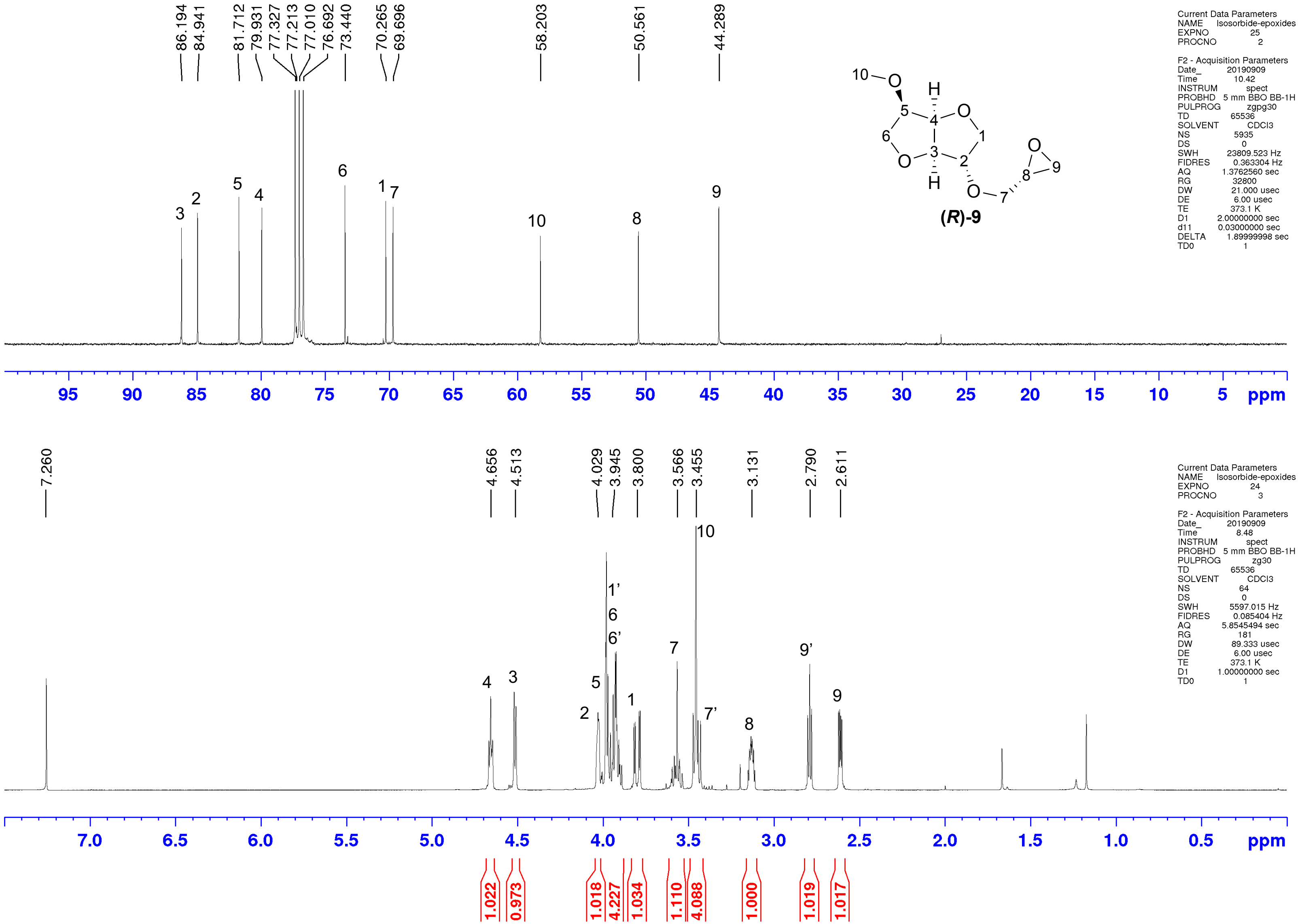

Fig. S10 ^{1}H and ^{13}C NMR spectra of (*R*)-(-)-2-epoxy-5-methoxy-isosorbide ((***R***)-**9**).

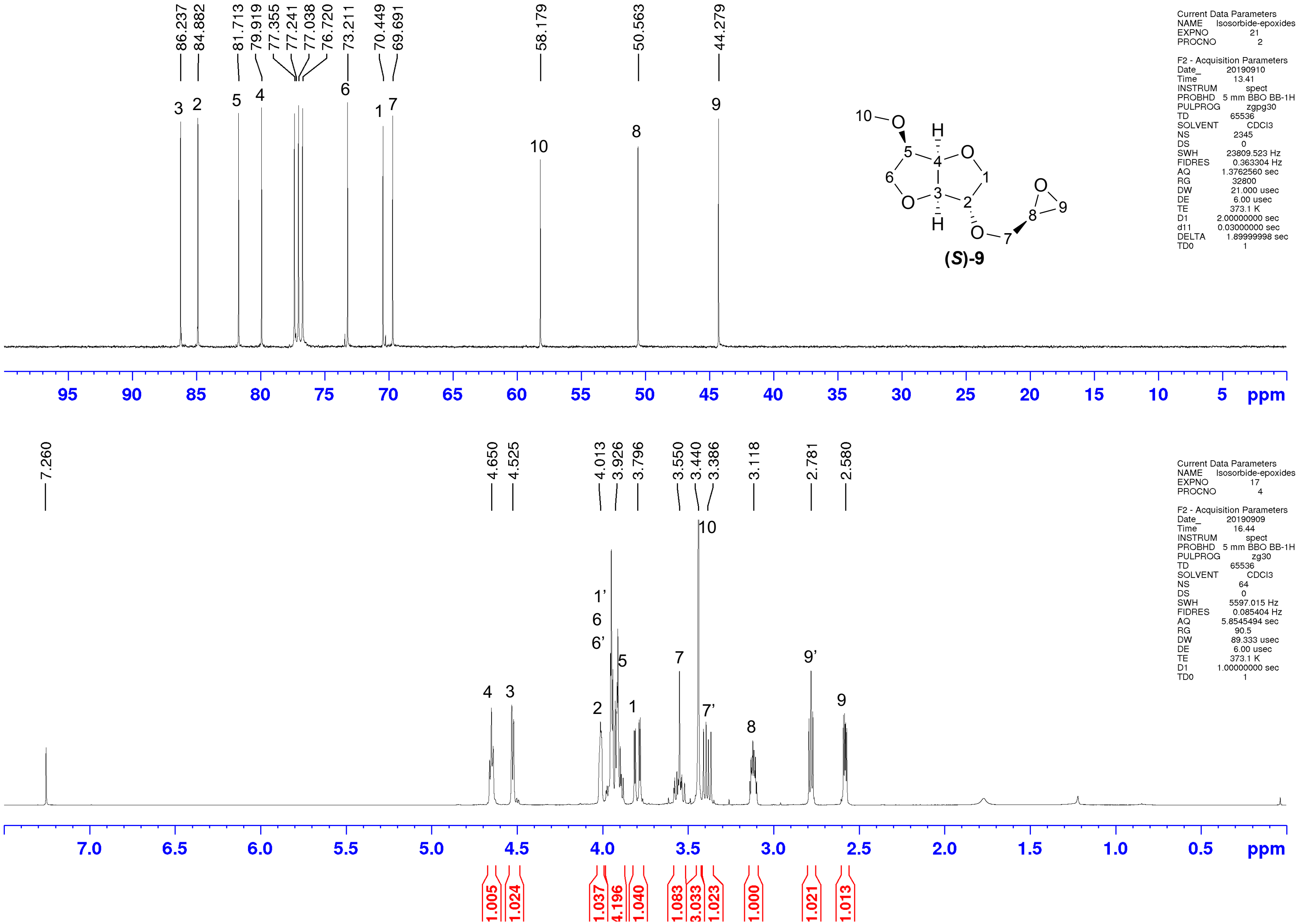

Fig. S11 ^{1}H and ^{13}C NMR spectra of (*S*)-(-)-2-epoxy-5-methoxy-isosorbide ((***S***)**-9**).

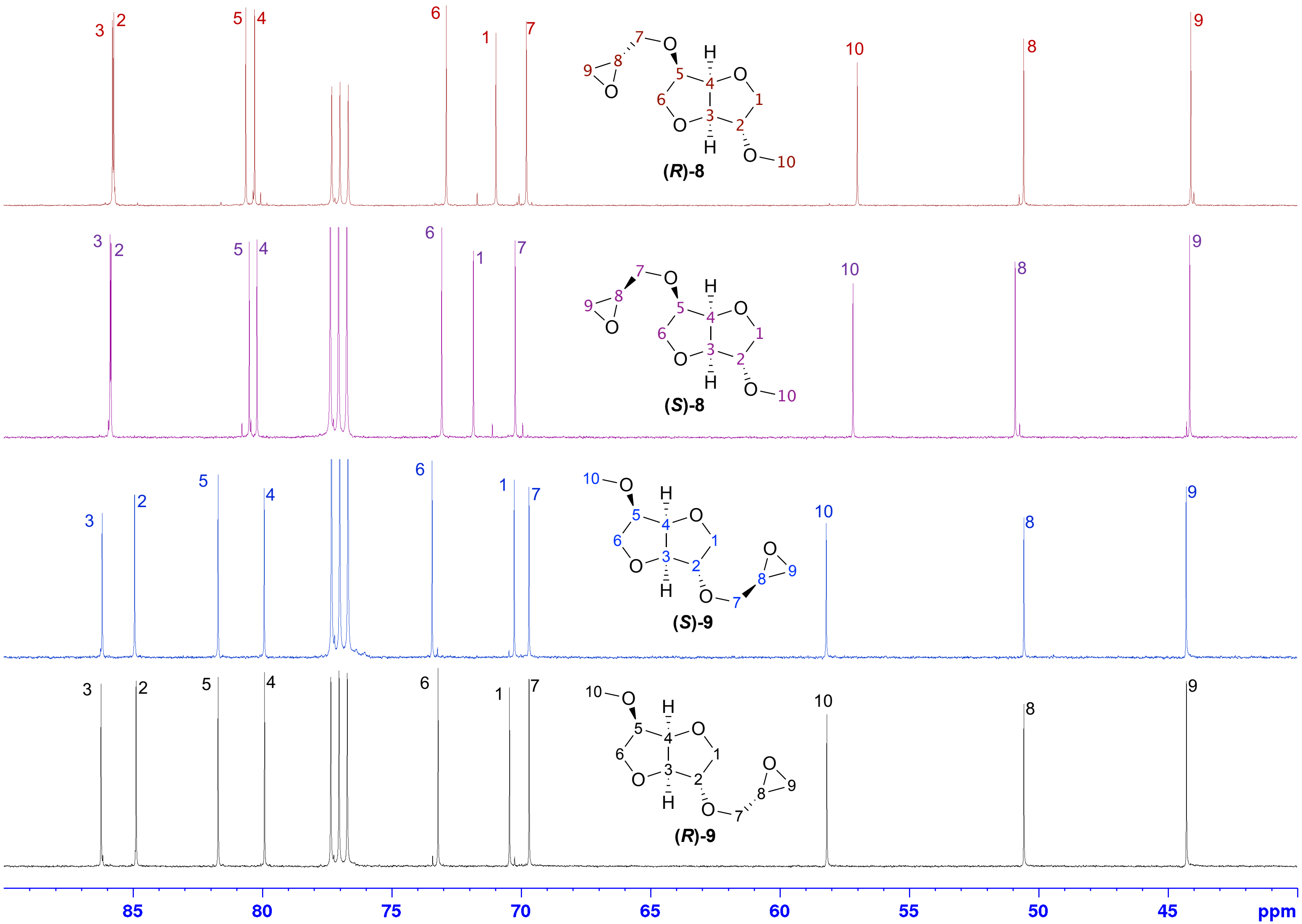

Fig. S12 Comparison of ^{13}C NMR spectra of **(*R*)-8**, **(*S*)-8**, **(*R*)-9**, and **(*S*)-9**.

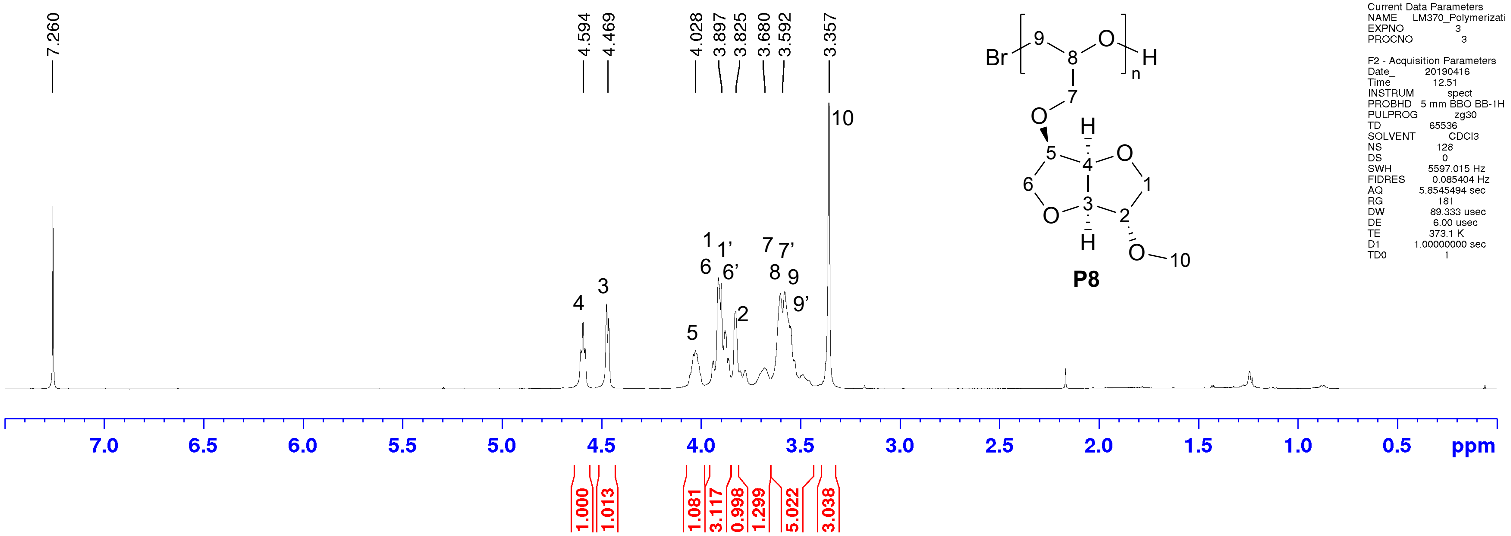

Fig. S13 ^{1}H NMR spectrum of polyether **P8**.

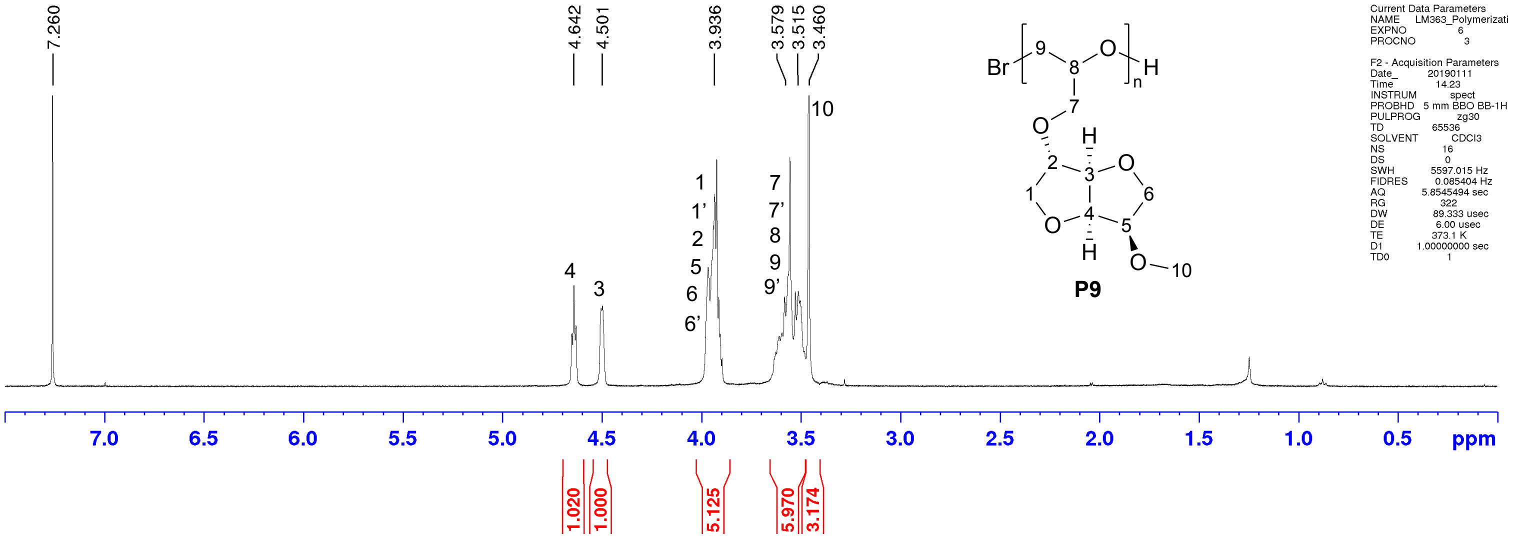

Fig. S14 ^{1}H NMR spectrum of polyether **P9**.

References

1 A. L. Shaikh, A. S. Kale, M. A. Shaikh, V. G. Puranik and A. R. A. S. Deshmukh, *Tetrahedron*, 2007, **63**, 3380-3388.

2 D. Abenhaïm, A. Loupy, L. Munnier, R. Tamion, F. Marsais and G. Quéguiner, *Carbohydr. Res.*, 1994, **261**, 255-266.

3 A. Loupy and D. A. Monteux, *Tetrahedron*, 2002, **58**, 1541-1549.

4 P. Che, F. Lu, X. Si and J. Xu, *RSC Adv.*, 2015, **5**, 24139-24143.

5 R. Tamion, F. Marsais, P. Ribereau, G. Queguiner, D. Abenhaim, A. Loupy and L. Munnier, *Tetrahedron: Asymmetry*, 1993, **4**, 1879-1890.

6 P. Tundo, F. Aricò, G. Gauthier, L. Rossi, A. E. Rosamilia, H. S. Bevinakatti, R. L. Sievert and C. P. Newman, *ChemSusChem*, 2010, **3**, 566-570.