Electronic Supplementary Material (ESI) for Green Chemistry.

The Synthesis and Analysis of Advanced Lignin Model Polymers

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Supporting Information

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General Information

Commercially available compounds were purchased and used as received unless otherwise stated. Diisopropylamine was distilled from KOH and stored over KOH prior to use. *n*-BuLi was titrated using menthol/2,2'-bipyridyl prior to use. Dry solvents were obtained from a MBRAUN solvent purification machine (MB-SPS-800). ^{1}H and ^{13}C spectra were obtained with a Bruker Avance II 400 MHz, Bruker Avance 500 MHz or a Bruker Avance III 500 MHz spectrometer with the solvent peak used as the internal standard. Multiplicities are described using the following abbreviations: s = singlet, d = doublet, t = triplet, q = quartet and m = multiplet and the J couplings are reported in Hz. NMR spectra were processed using TopSpin 3.1 (PC version) or MestReNova. Column chromatography was performed using Davisil® silica (40-63 μm, 230-400 mesh). Thin layer chromatography was performed on pre-coated glass plates (Silica Gel 60A, Fluorochem) and visualised under UV light (254 nm) or by staining with $KMnO_4$. IR spectra were obtained on a Shimadzu IRAffinity-1 Fourier-Transform IR spectrophotometer as thin films. Analysis was carried out using Shimadzu IRsolution v1.50 and only characteristic peaks are reported. Melting points were recorded on an Electrothermal 9100 melting point apparatus. Mass spectrometry data were acquired through the University of St Andrews School of Chemistry mass spectrometry service or through the EPSRC national mass spectrometry service centre (Swansea, UK).

Cooling baths: - 78 °C was achieved using dry ice/acetone and 0 °C with ice/water.

Reactions requiring anhydrous conditions were run using oven dried (140 °C) or flame dried glassware under a N_2 atmosphere.

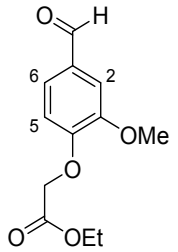
HSQC analysis of polymeric models was performed using the Bruker hsqcedetgpsp.3 pulse sequence on a Bruker Avance III 500 MHz spectrometer equipped with a BBFO+ probe using 20-25 mg of polymer in 0.6 mL of acetone/D_2O (9:1).

Lignin NMR were acquired using our previously reported protocols[1] as follows:

NMR spectra were acquired on a Bruker Avance III 500 MHz spectrometer equipped with a BBFO+ probe. The central solvent peak was used as internal reference. The 1 H, 13C-HSQC experiment was acquired using standard Bruker pulse sequence 'hsqcetgpsp.3' (phase-sensitive gradient-edited-2D HSQC using adiabatic pulses for inversion and refocusing). Composite pulse sequence 'garp4' was used for broadband decoupling during acquisition. 2048 data points was acquired over 12 ppm spectral width (acquisition time 170 ms) in F2 dimension using 24 scans with 1 s interscan delay and the d4 delay was set to 1.8 ms (1/4J, J = 140 Hz). The spectrum was processed using squared cosinebell in both dimensions and LPfc linear prediction (32 coefficients) in F1. Volume integration of cross peaks in the HSQC spectra and export of spectral images was carried out using MestReNova (9.0) software.

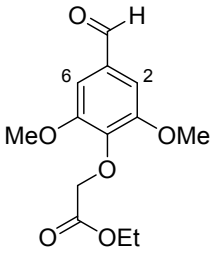
Synthesis of Polymer Monomers

Ethyl 2-(4-formyl-2-methoxyphenoxy)acetate (7)



Vanillin (105.0 g, 690 mmol, 1.00 eq.), ethyl bromoacetate (117.5 g, 704 mmol, 1.02 eq.) and K_2CO_3 (143.0 g, 1035 mmol, 1.50 eq.) in acetone (1100 mL) was heated at reflux for 14 hours. The mixture was then allowed to cool to room temperature and filtered through a pad of celite. The filtrate was concentrated *in vacuo*, to give an oil which rapidly crystallised on standing. The obtained solid was washed with petroleum ether (1000 mL) and the title compound was obtained as a white crystalline solid by filtration (164.4 g, 100%). **M.p.** 63-64 °C (lit.[2] 65-66.5 °C); **^{1}H NMR** (500 MHz, $CDCl_3$) δ = 9.86 (s, 1H, C<u>H</u>O), 7.44 (d, *J* = 1.9, 1H, H2), 7.42 (dd, *J* = 8.1, 1.9, 1H, H6), 6.87 (d, *J* = 8.1, 1H, H5), 4.78 (s, 2H, OC<u>H$_2$</u>CO$_2$Et), 4.27 (q, *J* = 7.1, 2H, OC<u>H$_2$</u>CH$_3$), 3.95 (s, 3H, OMe), 1.29 (t, *J* = 7.1, 3H, OCH$_2$C<u>H$_3$</u>). Analytic data are in accordance with those previously reported.[3]

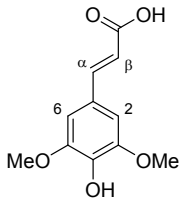
Ethyl 2-(4-formyl-2,6-dimethoxyphenoxy)acetate (8)



Syringaldehyde (30.0 g, 164.7 mmol, 1.00 eq.), ethyl bromoacetate (30.25 g, 181.2 mmol, 1.10 eq.), tetrabutylammonium iodide (1.00 g, 2.71 mmol, 0.016 eq.) and K_2CO_3 (34.1 g, 247 mmol, 1.50 eq.) in acetone (300 mL) were refluxed until TLC analysis indicated complete consumption of syringaldehyde (around 7 hours). The mixture was then allowed to cool to room temperature and filtered through a pad of celite. The filtrate was concentrated *in vacuo* and the resulting oil was dissolved in Et_2O (500 mL) and washed with water (300 mL) and brine (300 mL). The organic layer was then dried ($MgSO_4$) and concentrated *in vacuo* to give an oil which was redissolved in Et_2O (*ca.* 150 mL). The solution was then cooled (ice or freezer) and the product spontaneous crystallised as a white crystalline solid which was collected by filtration (40.9 g, 93%). **M.p.** 46-47 °C; **HRMS** (ESI) calculated for $C_{13}H_{16}O_6H$ 269.1020 $[M + H]^+$, found 269.1016; **IR** (thin film) 2941, 1757, 1732, 1689,

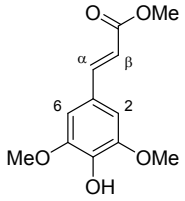
1587, 1327, 1120; **^{1}H NMR** (500 MHz, $CDCl_3$) δ = 9.83 (s, 1H, C<u>H</u>O), 7.10 (s, 2H, H2, H6), 4.73 (s, 2H, OC<u>H$_2$</u>CO_2Et), 4.23 (q, *J* = 7.1, 2H, OC<u>H$_2$</u>CH_3), 3.89 (s, 6H, 2 x OMe), 1.26 (t, *J* = 7.1, 3H, OCH_2C<u>H$_3$</u>); **^{13}C NMR** (126 MHz, $CDCl_3$) δ = 191.0 (<u>C</u>HO), 169.1 (<u>C</u>O_2Et), 152.9 (C3, C5), 141.6 (C4), 131.8 (C1), 106.8 (C2, C6), 69.4 (O<u>C</u>H_2CO_2Et), 61.2 (O<u>C</u>H_2CH_3), 56.4 (2 x OMe), 14.3 (OCH_2<u>C</u>H_3).

Sinapic Acid (3)



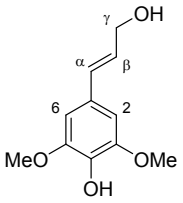
To a solution of syringaldehyde (**2**) (10.0 g, 54.9 mmol,1.00 eq.) in pyridine (27 mL) was added malonic acid (12.6 g, 12.1 mmol, 2.20 eq.) and aniline (658 μL, 7.21 mmol, 0.13 eq.). The mixture was then heated at 60 °C for 14 hours and then cooled and poured onto a mixture of ice (55 g) and conc. HCl (37%, 33 mL). The mixture was stirred once and then left to crystallised for 30 minutes. The product was then collected by filtration, washed with a small volume of cold water and then dried at reduced pressure over $CaCl_2$ for 16 hours to give sinapic acid (**3**) as a white crystalline solid (10.6 g, 86%). **M.p.** 200-202 °C (lit.[4] 198-200 °C); **^{1}H NMR** (500 MHz, DMSO) δ 12.16 (s, 1H, COOH), 8.93 (s, 1H, ArOH), 7.50 (d, *J* = 15.8 Hz, 1H, Hα), 6.99 (s, 2H, H2, H6), 6.43 (d, *J* = 15.8 Hz, 1H, Hβ), 3.80 (s, 6H, 2 x OMe). Analytic data are in accordance with those previously reported.[5]

Methyl Sinapate (4)



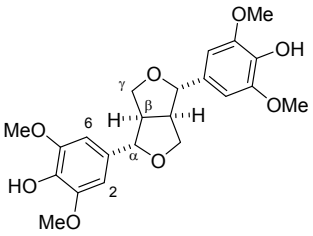
To methanol (100 mL) at 0 °C was added AcCl (3.50 g, 44.6 mmol, 1.0 eq.) dropwise and the mixture was allowed to stir for 15 minutes. Sinapic acid (**3**) (10.0g, 44.6 mmol, 1.0 eq.)was then added and the mixture heated at reflux for 1 hour. The mixture was then cooled and the product started to crystallise. The mixture was then carefully concentrated to remove most of the methanol and the product collected by filtration and washed with a small amount of cold methanol to give methyl sinapate (**4**) as a crystalline white solid (10.1 g, 95%).**M.p.** 90-92 °C (lit.[6] 90 °C); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.57 (d, *J* = 15.9 Hz, 1H, Hα), 6.73 (s, 2H, H2/6), 6.28 (d, *J* = 15.9 Hz, 1H, Hβ), 5.89 (s, 1H, ArOH), 3.88 (s, 6H, 2 x OMe), 3.77 (s, 3H, COOMe). Analytic data are in accordance with those previously reported.[6]

Sinapyl Alcohol (5)



To a solution of $LiAlH_4$ (3.11 g, 81.9 mmol, 1.5 eq.) in THF (250 mL) at 0 °C was added n-BuBr (11.2 g, 81.9 mmol, 1.5 eq.) dropwise and then the mixture was stirred at room temperature for 3 hours. The mixture was then cooled to -78 °C and methyl sinapate (**4**) (13.0 g, 54.6 mmol) in THF (250 mL) was added *via* cannula. The mixture was then allowed to warm to room temperature and stirred for 2 hours until TLC analysis indicated that the reaction was complete. EtOAc (20 mL) was then added slowly and stirred for 30 minutes, followed by the slow addition of water until gas evolution ceases. A saturated solution of NH_4Cl was then added until a semi-solid paste forms. The clear colourless organic layer was decanted and the remaining paste was re-extracted with EtOAc (3 x 250 mL). The organic extracts were combined, washed with brine (1000 mL), dried ($MgSO_4$) and concentrated *in vacuo* to give a light yellow oil which was used immediately in the next reaction (yield taken to be 100%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.63 (s, 2H, H2/6), 6.52 (d, *J* = 15.8 Hz, 1H, Hα), 6.24 (dt, *J* = 15.8, 6.0 Hz, 1H, Hβ), 5.54 (s, 1H, ArOH), 4.36 – 4.26 (m, 2H, 2 x Hγ), 3.90 (s, 6H, 2 x OMe). Analytic data are in accordance with those previously reported. [7]

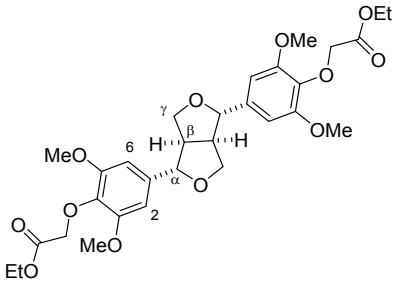
Syringaresinol (6)



To a solution of sinapyl alcohol (**5**) (54.6 mmol, 1.00 eq.) in water (2500 mL) was added $CuSO_4.5H_2O$ (13.6 g, 54.6 mmol, 1.00 eq.) and then the reaction mixture was stirred vigorously in the presence of light and air for 48 hours. A gummy solid was deposited in the flask during the course of the reaction. The reaction mixture was then extracted with EtOAc (4 x 700 mL) and the combined organic extracts were washed with brine (1000 mL), dried (Na_2SO_4) and concentrated *in vacuo* to give an orange gum. This was dissolved in ethanol (*ca.* 50 mL) and left to crystallised in the fridge overnight. The obtained white precipitate was collected by filtration and washed with cold ethanol to give syringaresinol (**6**) as colourless solid (4.34 g, 38% over 2 steps). **M.p.** 172-173 °C (lit.[8] 174 °C). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.57 (s, 4H, 2 x H2, 2 x H6), 5.58 (s, 2H, 2 x ArOH), 4.72 (d, *J* = 4.1 Hz, 2H,

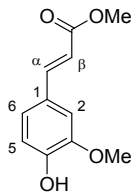
2 x Hα), 4.33 – 4.22 (m, 2H, 2 x Hγ), 3.90 (dd, *J* = 9.4, 3.6 Hz, 2H, 2 x Hγ), 3.88 (s, 12H, 4 x OMe), 3.16 – 3.01 (m, 2H, 2 x Hβ). Analytic data are in accordance with those previously reported.[8]

***rel*-Diethyl 2,2'-((((1*S*,3a*R*,4*S*,6a*R*)-tetrahydro-1*H*,3*H*-furo[3,4-c]furan-1,4-diyl)bis(2,6-dimethoxy-4,1-phenylene))bis(oxy))diacetate (1)**



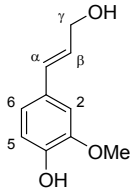
To a solution of syringaresinol (**6**) (2.00 g, 4.78 mmol, 1.0 eq.) in acetone (40 mL) was added ethyl bromoacetate (2.00 g, 11.9 mmol, 2.5 eq.) and K_2CO_3 (1.98 g, 14.3 mmol, 3.0eq.). The mixture was then heated to reflux for 14 hours. The mixture was then allowed to cool, filtered through calcite and concentrated *in vacuo* to give a colourless oil. The oil was triturated with Et_2O to give a white crystalline solid (2.43 g, 86%). **M.p.** 103.5-104.5 °C; **HRMS** (ESI) calculated for $C_{30}H_{38}O_{12}H$ $[M + H]^+$ 591.2436 found 591.2438; **IR** (thin film) 2940, 1757, 1732, 1591, 1198, 1125, 1061; **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.54 (s, 4H, 2 x H2, 2 x H6), 4.72 (d, *J* = 3.9 Hz, 2H, 2 x Hα), 4.59 (s, 4H, 2 x O$\underline{C}H_2CO_2Et$), 4.31 – 4.26 (m, 2H, 2 x Hγ), 4.24 (q, *J* = 7.2 Hz, 4H, 2 x O$\underline{C}H_2CH_3$), 3.91 (dd, *J* = 9.3, 3.3 Hz, 2H, 2 x Hγ), 3.84 (s, 12H, 4 x OMe), 3.20 – 2.97 (m, 2H, 2 x Hβ), 1.28 (t, *J* = 7.2 Hz, 6H, $OCH_2C\underline{H}_3$); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 169.5 (2 x $\underline{C}O_2Et$), 152.9 (2 x C3, 2 x C5), 137.1 (2 x C4), 135.7 (2 x C1), 102.9 (2 x C2, 2 x C6), 85.9 (2 x Cα), 72.1 (2 x Cγ), 69.7 (2 x O$\underline{C}H_2CO_2Et$), 61.0 (2 x O$\underline{C}H_2CH_3$), 56.3 (4 x OMe), 54.4 (2 x Cβ), 14.3 (2 x $OCH_2\underline{C}H_3$).

Methyl ferulate (13)



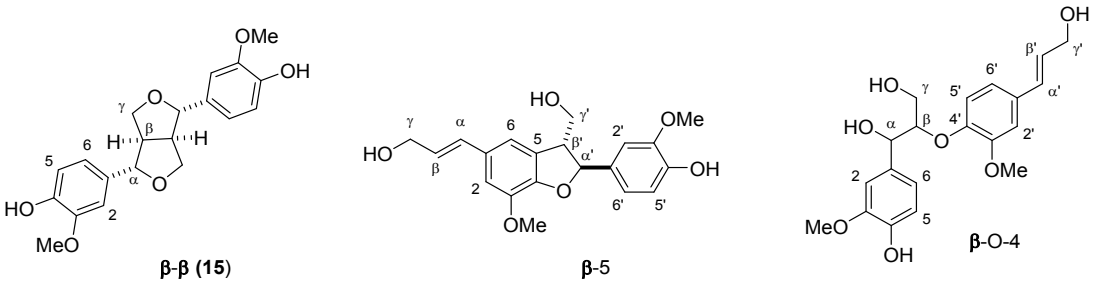
Prepared from ferulic acid (**12**) (40.0 g, 206 mmol, 1.00 eq.) using the same procedure as for the preparation of methyl sinapate (**4**). Methyl ferulate (**13**) was obtained as a light tan coloured oil which crystallised on standing to give a white solid (43.0 g, 100%). **M.p.** 62-65 °C (lit.[9] 65 °C); **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.62 (d, *J* = 15.9 Hz, 1H, Hα), 7.06 (dd, *J* = 8.0, 1.9 Hz, 1H, H6), 7.02 (d, *J* = 1.9 Hz, 1H, H5), 6.91 (d, *J* = 8.0 Hz, 1H, H2), 6.28 (d, *J* = 15.9 Hz, 1H, Hβ), 5.95 (s, 1H, Ar-OH), 3.91 (s, 3H, COOMe), 3.79 (s, 3H, OMe). Analytic data are in accordance with those previously reported.[5]

Coniferyl alcohol (14)



Prepared from methyl ferulate (**13**) (34.4 g, 165 mmol, 1.0 eq.) using the same procedure as for the preparation of sinapyl alcohol (**5**). Crude coniferyl alcohol (**14**) was obtained as a yellow oil which was recrystallised from CH_2Cl_2/pet. ether to give coniferyl alcohol as a light yellow powdery solid (18.0 g, 61%). **M.p** 73-75 °C (lit.[10] 75 °C); **^{1}H NMR** (300 MHz, $CDCl_3$) δ 6.93 – 6.85 (m, 3H, 3 x ArH), 6.52 (d, *J* = 15.8, 1H, Hα), 6.21 (dt, *J* = 15.8, 6.0 Hz, 1H, Hβ), 5.76 (s, 1H, Ar-OH), 4.34 – 4.24 (m, 2H, 2 x Hγ), 3.89 (s, 3H, OMe), 1.71 – 1.63 (m, 1H, γ-OH). Analytic data are in accordance with those previously reported.[11]

Pinoresinol (15), dehydrodiconiferyl alcohol (β-5) and guaiacylglycerol-8-*O*-4′-coniferyl alcohol (β-O-4)



β-β (15) **β-5** **β-O-4**

Coniferyl alcohol (12.0 g, 66.6 mmol, 1.00 eq.) was dissolved in acetone (336 mL) and then diluted with water (3.35 L). A solution of $FeCl_3.6H_2O$ (19.8 g, 73.3 mmol, 1.10 eq.) in water (75 mL) was then added and the mixture stirred for 1 hour before being extracted with EtOAc (6 x 500 mL). The organic extracts were combined, washed with an aqueous solution of sodium ascorbate (0.1 M, 500 mL), brine (1000 mL), dried ($MgSO_4$) and concentrated *in vacuo* to give an organge gum which was purified by column chromatography (20-40% acetone/pet. ether) to give, in order of elution, **15** (2.35 g, 20%), **β-5** (2.58 g, 22%) and **β-O-4** (3.70 g, 30%).

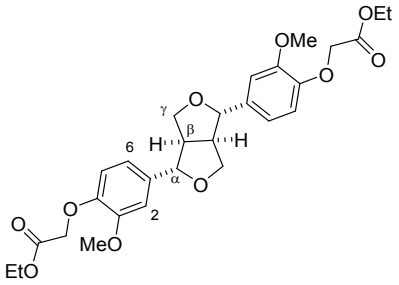
15 – M.p. 117-118 °C (lit.[12] 118-120 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.91 – 6.87 (m, 4H, 4 x ArH), 6.82 (dd, *J* = 8.2, 1.8 Hz, 2H, 2 x H6), 5.60 (s, 2H, ArOH), 4.74 (d, *J* = 4.3 Hz, 2H, Hα), 4.28 – 4.21 (m, 2H, Hγ), 3.91 (s, 6H, OMe), 3.89 – 3.85 (m, 2H, Hγ), 3.15 – 3.05 (m, 2H, Hβ).

β-5 – ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.95 – 6.83 (m, 5H, 5 x ArH), 6.55 (d, *J* = 15.8 Hz, 1H, Hα), 6.23 (dt, *J* = 15.8, 5.9 Hz, 1H, Hβ), 5.68 (s, 1H, ArOH), 5.57 (d, *J* = 7.2 Hz, 1H, Hα'), 4.30 (d, *J* = 5.9 Hz, 2H, 2 x Hγ), 3.96 (dd, *J* = 11.0, 6.0 Hz, 1H, Hγ'), 3.94 – 3.86 (m, 4H, OMe + Hγ'), 3.85 (s, 3H, OMe), 3.64 – 3.57 (m, 1H, Hβ').

β-O-4 - ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.07 – 6.79 (m, 6H, 6 x ArH), 6.59 – 6.50 (m, 1H, Hα'), 6.27 (ap. dtd, *J* = 15.8, 5.7, 2.1 Hz, 1H, Hβ'), 5.70 (s, 0.5H, ArOH), 5.68 (s, 0.5H, ArOH), 5.01 – 4.90 (m, 1H, Hα), 4.31 (s, 2H, Hγ'), 4.15 (ddd, *J* = 5.9, 4.7, 3.4 Hz, 0.5H, -OHγ), 4.02 (dt, *J* = 7.7, 3.7 Hz, 0.5H, -OHγ), 3.95 – 3.79 (m, 7H, 2 x OMe, 1 x Hγ), 3.72 – 3.58 (m, 1H, 0.5 x Hγ, 0.5 x -OHα), 3.55 – 3.44 (m, 1H, 0.5 x Hγ, 0.5 x -OHα), 2.81 (dd, *J* = 7.6, 5.5 Hz, 0.5H, -OHγ'), 2.74 (dd, *J* = 8.2, 5.2 Hz, 0.5H, -OHγ').

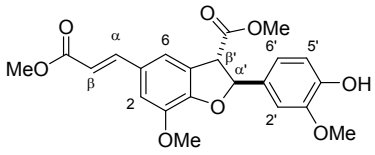
Analytic data are in accordance with those previously reported for **15,**[12] **β-5**[13] and **β-O-4**.[14]

***rel*-Diethyl 2,2'-((((1*S*,3a*R*,4*S*,6a*R*)-tetrahydro-1*H*,3*H*-furo[3,4-c]furan-1,4-diyl)bis(2-methoxy-4,1-phenylene))bis(oxy))diacetate (11)**



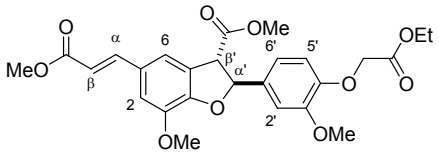
Compound **11** was prepared from pinoresinol (**15**) (1.60 g, 4.46 mmol) using the same procedure as for the preparation of (**1**).Compound **11** was obtained as a white solid after trituration with Et_2O (2.25 g, 95%). **M.p.** 91-93 °C; **HRMS** (ESI) calculated for $C_{28}H_{34}O_{10}NH_4$ $[M + NH_4]^+$ 548.2490 found 548.2484; **IR** (thin film) 2938, 1755, 1732, 1512, 1260, 1194, 1142, 1032; **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.93 (d, *J* = 1.9 Hz, 2H, 2 x H2), 6.83 (dd, *J* = 8.4, 1.6 Hz, 2H, 2 x H6), 6.79 (d, *J* = 8.4 Hz, 2H, 2 x H5), 4.75 (d, *J* = 4.0 Hz, 2H, 2 x Hα), 4.67 (s, 4H, 2 x O$\underline{C}H_2CO_2Et$), 4.30 – 4.21 (m, 6H, 2 x Hγ, 2 x O$\underline{C}H_2CH_3$), 3.90 (s, 6H,) 3.89 – 3.86 (m, 2H, 2 x Hγ), 3.14 – 3.04 (m, 2H, 2 x Hβ), 1.28 (t, *J* = 7.1 Hz, 6H, 2 x $OCH_2C\underline{H}_3$); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 169.0 ($\underline{C}O_2Et$), 149.9 (2 x C3), 146.9 (2 x C4)), 135.4 (2 x C1), 118.2 (2 x C6), 114.3 (2 x C5), 110.0 (2 x C2), 85.7 (2 x Cα), 71.9 (2 x Cγ), 66.7 (2 x O$\underline{C}H_2CO_2Et$), 61.4 (2 x O$\underline{C}H_2CH_3$), 56.1 (2 x OMe), 54.3 (2 x Cβ), 14.3 (2 x $OCH_2\underline{C}H_3$).

β-5 Diferulate 17



Citric acid (6.46 g), Na_2HPO_4 (2.34 g) and methyl ferulate (**13**) (16.1 g, 77.2 mmol, 1.00 eq.) were dissolved in water (3860 mL) and MeOH (526 mL) at 37 °C to give a slightly cloudy solution. Horseradish peroxidase (Sigma, Type I, 30 mg) was then added with vigorous stirring. H_2O_2 (2.21 mL of 50% H_2O_2 in 50 mL of water, 0.5 eq.) was then added over the course of a few minutes during which time product starts to precipitate. The mixture was then stirred for 10 minutes after which time TLC analysis indicated the reaction was complete. The crude product was then collected by filtration and allowed to air dry to give a beige solid. The crude product was then dissolved in methanol (*ca*. 50 mL) and allowed to crystallise in the fridge overnight. The precipitated product was collected by filtration to give diferulate **17** as a white solid (6.95 g, 43%) **M.p.** 152-154 °C (lit.[15] 155 °C); **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.65 (d, *J* = 15.9 Hz, 1H, Hα), 7.22 – 7.16 (m, 1H, H2), 7.05 – 7.00 (m, 1H, H6), 6.98 – 6.84 (m, 3H, 3 x ArH), 6.32 (d, *J* = 15.9 Hz, 1H, Hβ), 6.11 (d, *J* = 8.2 Hz, 1H, Hα'), 5.64 (s, 1H, ArOH), 4.35 (d, *J* = 8.2 Hz, 1H, Hβ'), 3.92 (s, 3H, OMe), 3.88 (s, 3H, OMe), 3.84 (s, 3H, OMe), 3.81 (s, 3H. OMe). Analytic data are in accordance with those previously reported.[15]

***rel-M*ethyl (2S,3S)-2-(4-(2-ethoxy-2-oxoethoxy)-3-methoxyphenyl)-7-methoxy-5-((E)-3-methoxy-3-oxoprop-1-en-1-yl)-2,3-dihydrobenzofuran-3-carboxylate (18)**

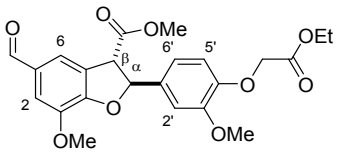


Preparation of ethyl iodoacetate: To a solution of ethyl bromoacetate (1.51 g, 9.05 mmol, 1.50 eq.) in acetone (20 mL) was added NaI (1.36 g, 9.05 mmol, 1.50 eq.). After 30 minutes the mixture was filtered and the solution of ethyl iodoacetate in acetone was used in the following reaction.

To a solution of **17** (2.50 g, 6.03 mmol, 1.00 eq.) in acetone (30 mL) was added the freshly prepared solution of ethyl iodoacetate in acetone (1.5 eq.) followed by K_2CO_3 (1.25 mg, 9.05 mmol, 1.50 eq.) and then the mixture was heated at reflux for 20 hours. The mixture was then allowed to cool, filtered through Celite and concentrated *in vacuo* to give a yellow oil. The crude oil was dissolved in MeOH (30 mL) with gentle heating and then allowed to crystallise in the freezer. The product was collected by filtration and washed with a small amount of cold methanol to give **18** as a very light yellow solid (2.18 g, 72%). **M.p.** 109-110 °C; **HRMS** (ESI) calculated for $C_{26}H_{28}O_{10}H$ $[M + H]^+$ 501.1755 found 501.1751; **IR** (thin film) 2951, 1734, 1713, 1497, 1269, 1194, 1169, 1144; **^{1}H NMR** (500 MHz,

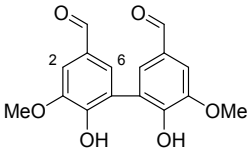
$CDCl_3$) δ 7.64 (d, *J* = 15.9 Hz, 1H, Hα), 7.21 – 7.15 (m, 1H, H6), 7.04 – 7.00 (m, 1H, H2), 6.96 – 6.88 (m, 2H, H2', H6'), 6.78 (d, *J* = 8.2 Hz, 1H, H5'), 6.31 (d, *J* = 15.9 Hz, 1H, Hβ), 6.12 (d, *J* = 8.1 Hz, 1H, Hα'), 4.67 (s, 2H, $OC\underline{H_2}CO_2Et$), 4.33 (d, *J* = 8.0, 1H, Hβ'), 4.24 (q, *J* = 7.1 Hz, 2H, $OC\underline{H_2}CH_3$), 3.91 (s, 3H, OMe), 3.86 (s, 3H, OMe), 3.83 (s, 3H, OMe), 3.80 (s, 3H, OMe), 1.27 (t, *J* = 7.1 Hz, 3H, $OCH_2C\underline{H_3}$); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 170.8 (γ'-CO_2Me), 168.9 ($\underline{C}O_2Et$), 167.7 (γ-CO_2Me), 150.00 (C4/C3'), 149.95 (C4/C3'), 147.7 (C4'), 144.8 (C3, Cα), 133.8 (C1'), 128.8 (C1), 125.7 (C5), 118.6 (C2'), 118.0 (C6), 115.8 (Cβ), 114.2 (C5'), 112.2 (C2), 110.1 (C6'), 87.3 (Cα'), 66.5 ($O\underline{C}H_2CO_2Et$), 61.5 ($O\underline{C}H_2CH_3$), 56.3 (OMe), 56.2 (OMe), 55.6 (Cβ'), 53.1 (OMe), 51.8 (OMe), 14.3 ($OCH_2\underline{C}H_3$).

***rel*-Methyl (2S,3S)-2-(4-(2-ethoxy-2-oxoethoxy)-3-methoxyphenyl)-5-formyl-7-methoxy-2,3-dihydrobenzofuran-3-carboxylate (16)**



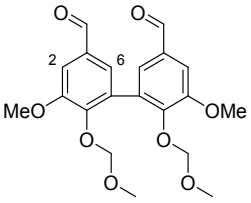
To a solution of $RuCl_3.xH_2O$ (4 mg, 0.016 mmol, 0.002 eq.) to MeCN (57 mL), EtOAc (57 mL) and water (19 mL) at 0 °C was added 1.5 M H_2SO_4 (0.77 mL) followed by $NaIO_4$ (4.28 g, 20.0 mmol, 2.5 eq.). Compound **18** (4.0g, 7.99 mmol, 1.0 eq.) was then added and the mixture was allowed to warm to room temperature and then stirred for 3 hours. The mixture was then diluted with a sat. solution of $NaHCO_3$ (25 mL) and a sat. solution of $Na_2S_2O_3$ (25 mL) and then extracted with EtOAc (3 x 100 mL). The combined organic extracts were washed with brine (200 mL), dried ($MgSO_4$) and concentrated *in vacuo*. Et_2O (50 mL) was then added to the crude product and enough methanol was added to allow the crude product to dissolve. This solution was then left to crystallise in the freezer overnight. The precipitate was collected by filtration to give **16** as an off-white solid (2.49 g, 70%). **M.p.** 121.5-123 °C; **HRMS** (ESI) calculated for $C_{23}H_{24}O_9H$ $[M + H]^+$ 445.1493 found 445.1484; **IR** (thin film) 2595, 1736, 1684, 1317, 1273, 1200, 1134; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 9.84 (s, 1H, C$\underline{H}$O), 7.55 – 7.49 (m, 1H, H6), 7.41 (d, *J* = 1.5 Hz, 1H, H2), 6.95 – 6.88 (m, 2H, H2', H6'), 6.79 (d, *J* = 8.1 Hz, 1H, H5'), 6.19 (d, *J* = 8.0 Hz, 1H, Hα), 4.66 (s, 2H, $OC\underline{H_2}CO_2Et$), 4.38 (d, *J* = 7.9, 1H, Hβ), 4.23 (q, *J* = 7.1 Hz, 2H, $OC\underline{H_2}CH_3$), 3.94 (s, 3H, OMe), 3.86 (s, 3H, OMe), 3.84 (s, 3H, OMe), 1.26 (t, *J* = 7.2 Hz, 3H, $OCH_2C\underline{H_3}$); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 190.5 ($\underline{C}$HO), 170.5 ($\underline{C}O_2Me$), 168.8 ($\underline{C}O_2Et$), 153.4 (C4), 150.0 (C3'), 147.8 (C4'), 145.3 (C3), 133.3 (C1'), 131.7 (C1), 125.5 (C5), 121.8 (C6), 118.6 (C2'), 114.2 (C5'), 112.2 (C2), 110.1 (C6'), 87.9 (Cα), 66.5 ($O\underline{C}H_2CO_2Et$), 61.5 ($O\underline{C}H_2CH_3$), 56.3 (OMe), 56.2 (OMe), 55.1 (Cβ), 53.1 (OMe), 14.3 ($OCH_2\underline{C}H_3$).

Divanillin (22)



To a solution of vanillin (**21**) (11.5 g, 75.6 mmol, 1.00 eq.) in water (500 mL) at *ca*. 90 °C was added $(NH_4)_2Fe(SO_4)_2$ (537 g, 1.89 mmol, 0.025 eq.) followed by the portionwise addition of $K_2S_2O_8$ (10.25 g, 37.8 mmol, 0.50 eq.). The product began to precipitate immediately and once the addition was complete, the solution was allowed to cool slightly and then the product was collected by filtration. The product was washed with water and then dried *in vacuo* over $CaCl_2$ for 16 hours to give divanillin (**22**) as a beige amorphous solid (9.37 g, 82%). **M.p.** 300+ dec. °C (lit.[16] >295 °C dec.); **^{1}H NMR** (500 MHz, DMSO) δ 9.95 (s, 2H, 2 x ArOH), 9.81 (s, 2H, 2 x CHO), 7.43 (s, 4H, 4 x ArH), 3.93 (s, 6H, 2 x OMe). Analytic data are in accordance with those previously reported.[16]

Divanillin Di-methoxy methyl ether (20)



To a solution of dimethoxymethane (6.04 g, 79.4 mmol, 4.00 eq.) in toluene (14 mL) was added $ZnBr_2$ (1.1 mg) followed by the slow addition of acetyl chloride (6.20 g, 79.4 mmol, 4.00 eq.). The mixture was allowed to stir for 3 hours at room temperature. Divanillin (6.00 g, 19.85 mmol, 1.00 eq.) was then added followed by dry DMF (14 mL). Dry hunigs base (12.8, 99.25 mmol, 5.00 eq.) was then added slowly and the solution was allowed to stir at room temperature for 24 hours. A saturated solution of ammonium chloride (30 mL) was then added and the mixture vigorously stirred for 15 minutes (slightly exothermic quench). The mixture was then diluted with water (30 mL) and extracted with toluene (2 x 50 mL). The combined organic extracts were washed with water (100 mL), brine (100 mL), dried ($MgSO_4$) and then concentrated *in vacuo* to give a brown oil. The crude product was purified by column chromatography (15 to 35% EtOAc/Pet ether) and crystallised from ethanol to give the title compound **20** as a colourless crystalline solid (4.93 g, 64%). **M.p.** 107 – 108 °C; **HRMS** (ESI) calculated for $C_{20}H_{22}O_8NH_4$ $[M + NH_4]^+$ 408.1653 found 408.1643; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 9.92 (s, 2H), 7.53 (d, *J* = 1.9 Hz, 2H), 7.49 (d, *J* = 1.9 Hz, 2H), 5.01 (s, 4H), 3.96 (s, 6H), 2.99 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 191.1, 153.4, 149.6, 132.7, 132.5, 128.5, 109.8, 98.7, 57.0, 56.2.

Polymer Synthesis

General procedure for the preparation of LDA: To a solution of diisoproplyamine (1 vol, 1 eq.) in THF (10 vol) at -78 °C was added *n*-BuLi* in hexanes (nominal 2.5M, 1 eq.). The mixture was then aged at -78 °C for 1 hour before use. ***Note**: Commercial *n*-BuLi solution in hexanes (nominal 2.5 M) was titrated with diphenylacetic acid (*ca.* 300 mg) in dry THF (10 mL) before use. Typical titres were 2.20 – 2.36 M for fresh bottles.

General procedure for polymer reductions: The polymer was dissolved in ethanol (10 mL/g) at 50 °C and then $NaBH_4$ (5 eq. per ester group) was added portion-wise (caution! Gas evolution) followed by the addition of methanol (15 eq.) over a few minutes. The mixture was then stirred at 50 °C for 1 hour. Water (10 mL/g) is then added slowly and the mixture allowed to cool to room temperature and then the ethanol is removed *in vacuo*. The crude product is then diluted with a further portion of water (10 mL/g) and then the mixture is acidified slowly with 1M HCl to pH <1. Significant gas evolution can take place as the excess $NaBH_4$ is decomposed. The crude polymer precipitates as the solution is acidified. After stirring for a further 15-30 minutes the crude polymer is collected by filtration or decantation and allowed to air dry (or dried *in vacuo*).

Purification: The crude dry polymer is dissolve in 15% MeOH in acetone (10 mL/g) and filtered into rapidly stirring diethyl ether (100 mL/g). The precipitated polymer is collected by filtration, allowed to air dry and then finally dried *in vacuo* to give the purified polymer.

Preparation of S-G hardwood polymer (9)

Monomers **1** (1.00 g, 1.69 mmol, 0.10 eq.), **7** (1.82 g, 7.63 mmol, 0.45 eq) and **8** (2.04 g, 7.60 mmol, 0.45 eq.) were dissolved in THF (100 mL) and cooled to 0 °C. LDA in THF (1.05 eq.) was then added dropwise *via* a cannula with vigorous stirring during which time the reaction mixture becomes a paste. The mixture was then stirred for 30 minutes and then quenched with a saturated solution of NH_4Cl (50 mL). The reaction mixture was then diluted with water (50 mL) and EtOAc (100 mL) and the organic layer was separated, washed with brine (100 mL), dried $MgSO_4$ and concentrated *in vacuo* to give a yellow foam. Reduction and purification according to the general procedures gave a very light yellow/white powder (1.95 g, *ca.* 48%)

Preparation of S hardwood polymer (10)

Monomers **1** (100 mg, 0.169 mmol, 0.10 eq.) and **8** (409 mg, 1.523 mmol, 0.90 eq.) were dissolved in THF (10 mL) and cooled to 0 °C. LDA (1.05 eq.) was then added dropwise *via* a cannula with vigorous stirring during which time the reaction mixture becomes a paste. The mixture was then stirred for 30 minutes and then quenched with a saturated solution of NH_4Cl (5 mL). The reaction mixture was then diluted with water (5 mL) and EtOAc (10 mL) and the organic layer was separated, washed with brine (10 mL), dried $MgSO_4$ and concentrated *in vacuo* to give a yellow foam. Reduction and purification according to the general procedures gave a light yellow powder (119 mg, *ca.* 28%)

Preparation of non-phenolic softwood polymer (19)

Monomers **7** (250 mg, 1.049 mmol, 0.71 eq.), **11** (55 mg, 0.1049 mmol, 0.071 eq.) and **16** (140 mg, 0.315 mmol, 0.21 eq.) were dissolved in THF (10 mL) and cooled to -78 °C. LDA (1.00 eq.) was then added dropwise *via* a cannula with vigorous stirring during which time the reaction mixture slowly becomes a paste. The mixture was then warmed to 0 °C, stirred for 30 minutes and then quenched with a saturated solution of NH_4Cl (5 mL). The reaction mixture was then diluted with water (5 mL) and EtOAc (10 mL) and the organic layer was separated, washed with brine (10 mL), dried $MgSO_4$ and concentrated *in vacuo* to give a yellow foam. Reduction and purification according to the general procedures gave a light yellow powder (140 mg, *ca.* 40%)

Preparation of phenolic polymer (23)

Monomers **7** (500 mg, 2.10 mmol, 0.65 eq.), **11** (55 mg, 0.1049 mmol, 0.05 eq.), **16** (187 mg, 0.420 mmol, 0.30 eq.) and **20** (82 mg, 0.210, 0.10 eq.) were dissolved in THF (16 mL) and cooled to -78 °C. LDA (1.00 eq.) was then added dropwise *via* a cannula with vigorous stirring during which time the reaction mixture slowly becomes a paste. The mixture was then warmed to 0 °C, stirred for 30 minutes and then quenched with a saturated solution of NH_4Cl (10 mL). The reaction mixture was then diluted with water (10 mL) and EtOAc (20 mL) and the organic layer was separated, washed with brine (20 mL), dried $MgSO_4$ and concentrated *in vacuo* to give a light yellow foam. Reduction and purification according to the general procedures gave a white powder (240 mg, *ca.* 32%)

Lignin Isolation Procedures

Birch and douglas fir lignins were isolated using previously reported procedures.[17,18] Briefly wood sawdusts were suspended in dioxane/water (9:1, 8 mL/g) containing 0.2M HCl and heated at a gentle reflux for 1 hour under N_2. The mixture was then cooled, filtered and the filtrate concentrated *in vacuo*. The crude material was then dissolved in acetone/water (9:1) and precipitated in water and the crude lignin collected by filtration and dried. The dried lignin was then dissolved in acetone/methanol (9:1) and precipitated in diethyl ether. The lignins were then collected by filtration and dried *in vacuo*.

^{31}P NMR

The ^{31}P NMR were obtained on a 500 MHz spectrometer following derivatisation of the polymer sample (20 mg) with 2-chloro-4,4,5,5-tetramethyl-1,3,2-dioxaphospholane (70 μL, Sigma) in pyridine/$CDCl_3$ (1.6:1, 550 μL).[19] A sweep width of 403 ppm was used with a D1 of 20 seconds. Cyclohexanol (144.7 – 145.5 ppm) was used as an internal standard.

GPC Analysis

Samples for GPC analysis were acetylated in acetic anhydride/pyridine (1:1) overnight. Samples were then dried by azeotropic distillation (3 x toluene, 3 x ethanol, 3 x $CHCl_3$), dissolved in THF (1 mL) and filtered (0.45 μm, PTFE) before analysis.

GPC analysis was carried out on a Shimadzu HPLC/GPC system equipped with a CBM-20A communications bus, DGU-20A degassing unit, LC-20AD pump, SIL-20A auto sampler, CTO-20A column oven and SPD-20A UV-Vis dectector. Samples were analysed using a Phenogel 5μm 50A (300 x 7.8 mm) and Phenogel 5μm 500A (300 x 7.8 mm) columns connected in series and eluted with inhibitor free THF (1 mL/min) with a column oven temperature of 30 °C. Absorbance was measured at 280 nm and injection volumes were 10-20 μL.

DFRC Protocol

DFRC analysis was carried out according to literature procedures.[20]

The samples for analysis (*ca.* 8-12 mg) were dissolved in a mixture of acetic acid and acetyl bromide (92:8,v/v, 2.5 mL), stirred at room temperature for 16 hours and then concentrated *in vacuo* at 50 °C. The samples were then dissolved in a mixture of dioxane, acetic acid and water (5:4:1, v/v/v, 2.5 mL) and zinc dust (50 mg) was added and the mixture vigorously stirred for 30 minutes. The mixture was added to saturated NH_4Cl (10 mL), the pH adjusted to <3 with 2M HCl and the extracted with CH_2Cl_2 (1 x 10 mL, 2 x 5 mL). The combined organic extracts were dried over $MgSO_4$ and concentrated *in vacuo*. The residues were the acetylated for 40 min in 1.5 mL of CH_2Cl_2 containing 0.2 mL of acetic anhydride and 0.2 mL of pyridine. All volatile components were removed completely by coevaporation with toluene and then ethanol *in vacuo*.

GC-Analysis of DFRC Monomers

Samples for GC analysis were dissolved in toluene (*ca*. 0.5 mL of lignins and 1.0 mL for polymers) and filtered (0.45 μm, PTFE). Measurements were recorded on a Trace 1300 GC (Thermo Scientific) equipped with a Restek Rtx-1ms column (30 m x 0.25 mm (ID) x 0.25 μm), crossbond 100% dimethyl polysiloxane. He carrier gas: 2 mL/min, inlet injector 300 °C. A temperature gradient of 50 – 300 °C 15 °C/min with a hold time of 2 minutes.

The G:S ratio for polymer **9** was calculated using the peak areas for Gc, Gt, Sc and St and response factors of 1.85 for Gc and Gt and 2.06 for Sc and St, as previously determined by Ralph *et al*.[20]

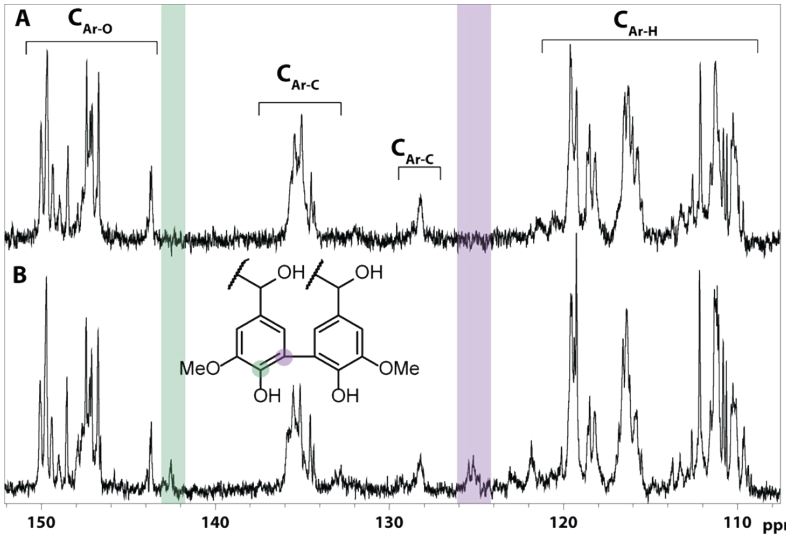


Figure S1 1D C13 NMR analysis of A) **19** and B) **23**. Keys resonances of the phenolic 5-5 unit are highlighted. Assignment based on model compound data available from the USDA NMR Database of Lignin and Cell Wall Model Compounds.[21]

An Example of the Determination of DP_n using 2D HSQC NMR Analysis

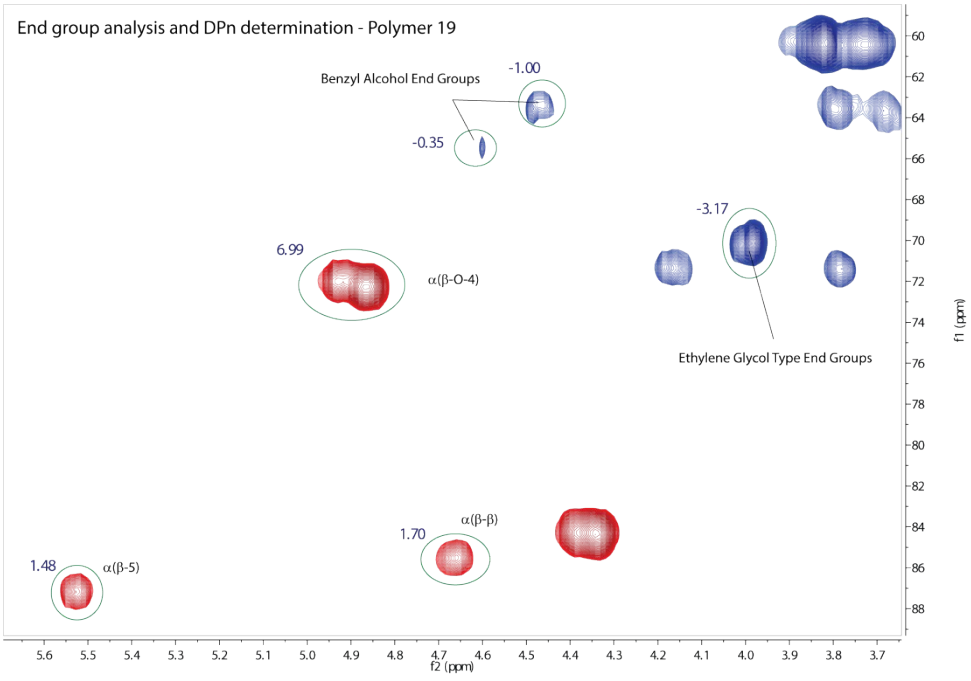


Figure S2 2D HSQC spectra of **19** showing the integrals used to calculated DP_n

Calculation is as follows:

DP_n = (6.99+1.70+1.48)/((3.17+0.35+1.00)/4) = 9.0

There are 2 end groups per polymer chain and each one is a CH_2 group therefore the sum of the end group integrals I divided by 4.

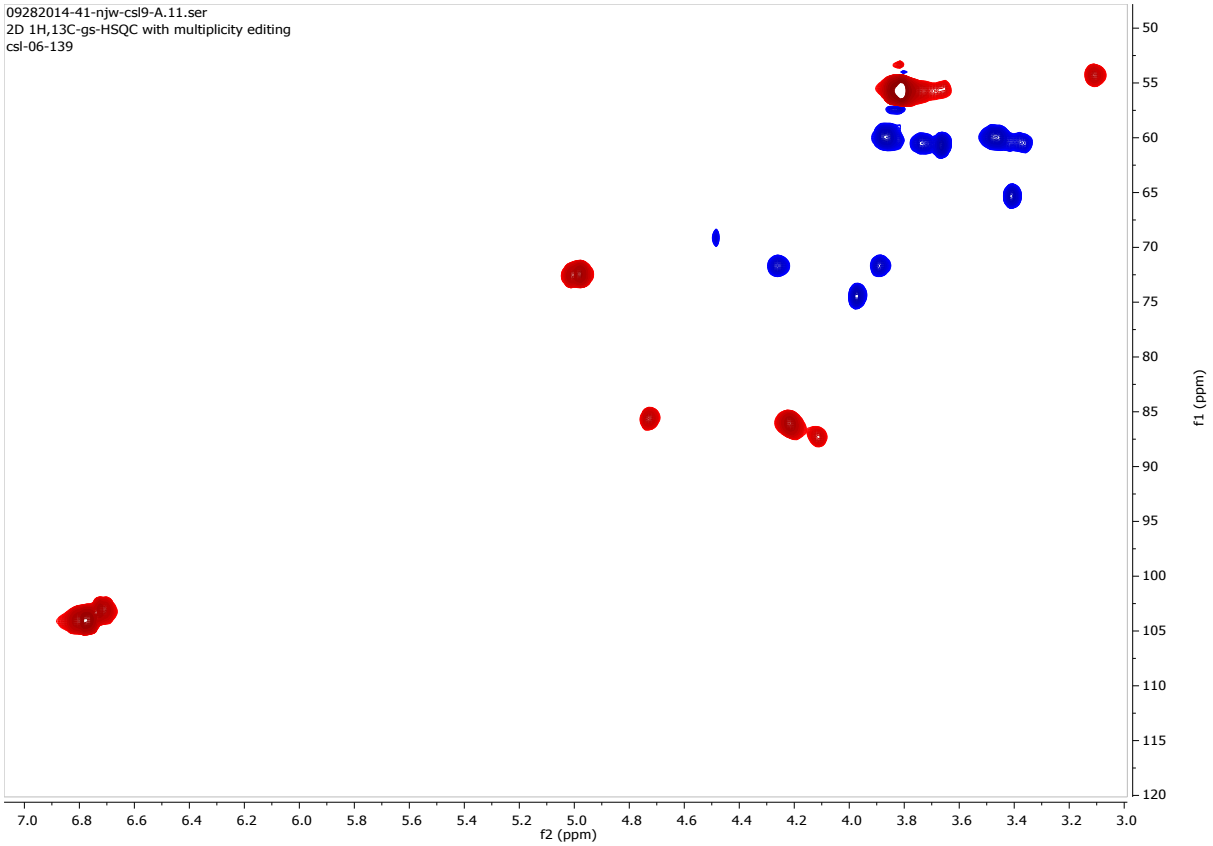


Figure S3 2D HSQC NMR of Polymer **10**. Assignments as for polymer **9**.

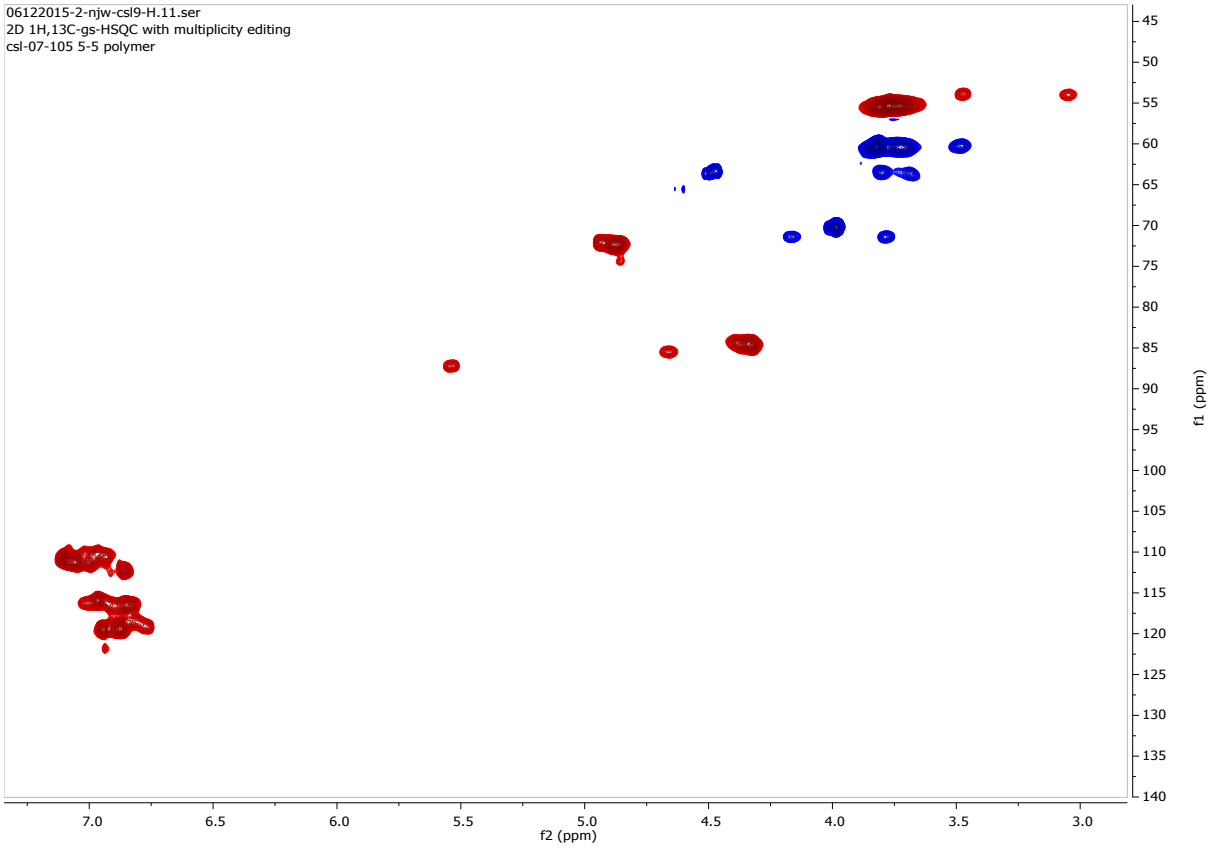
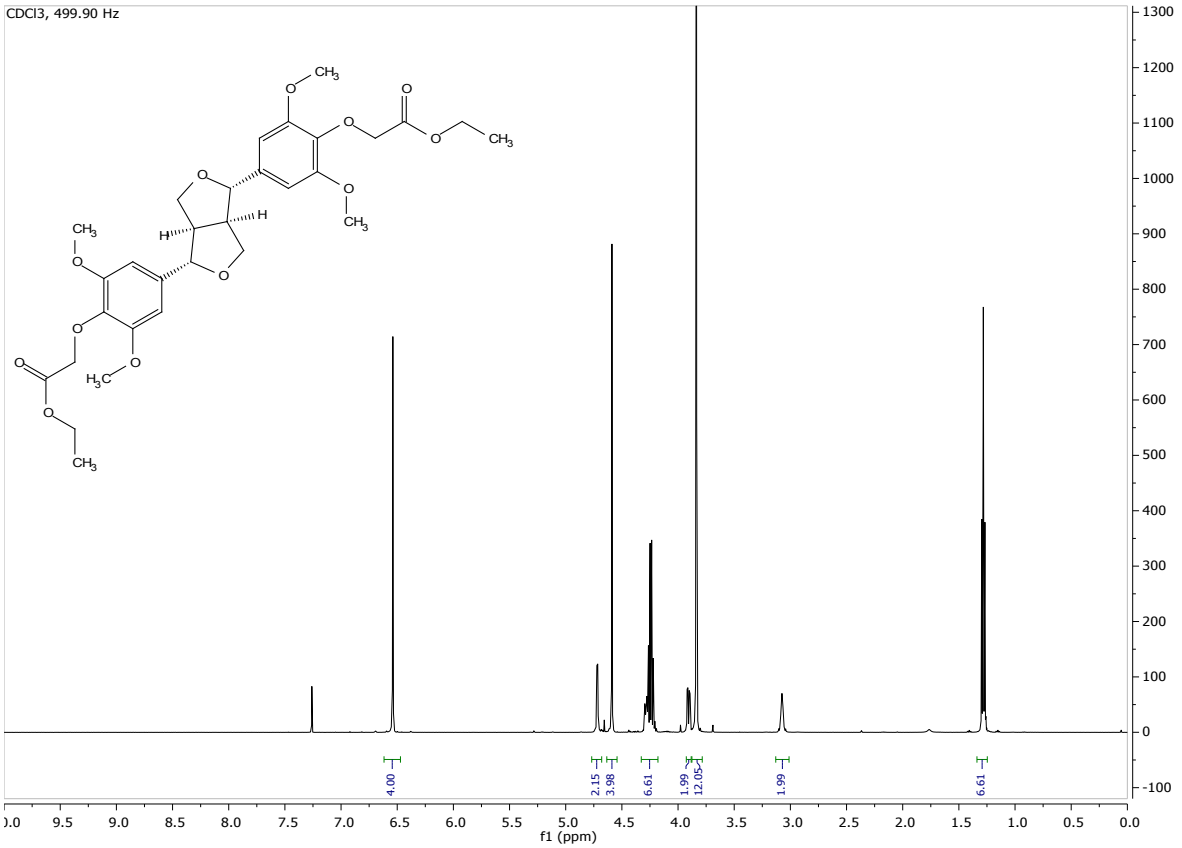
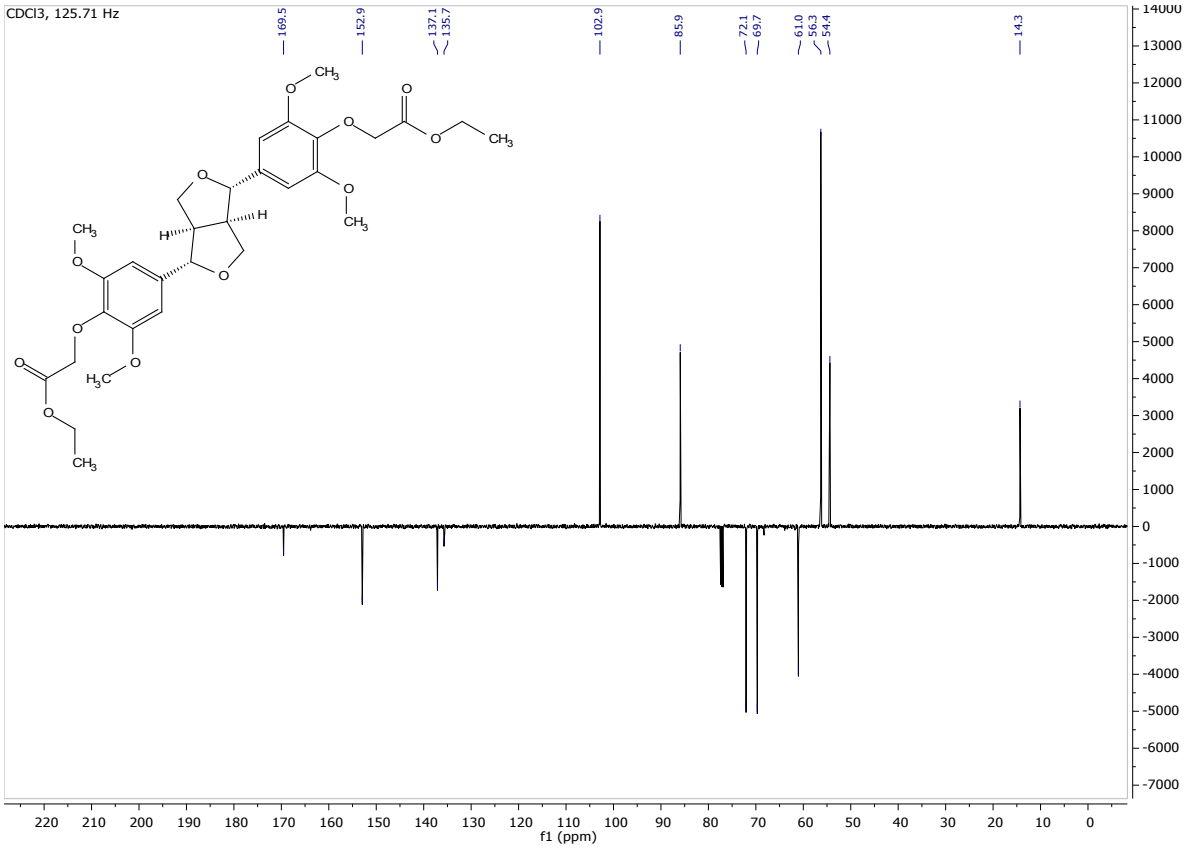
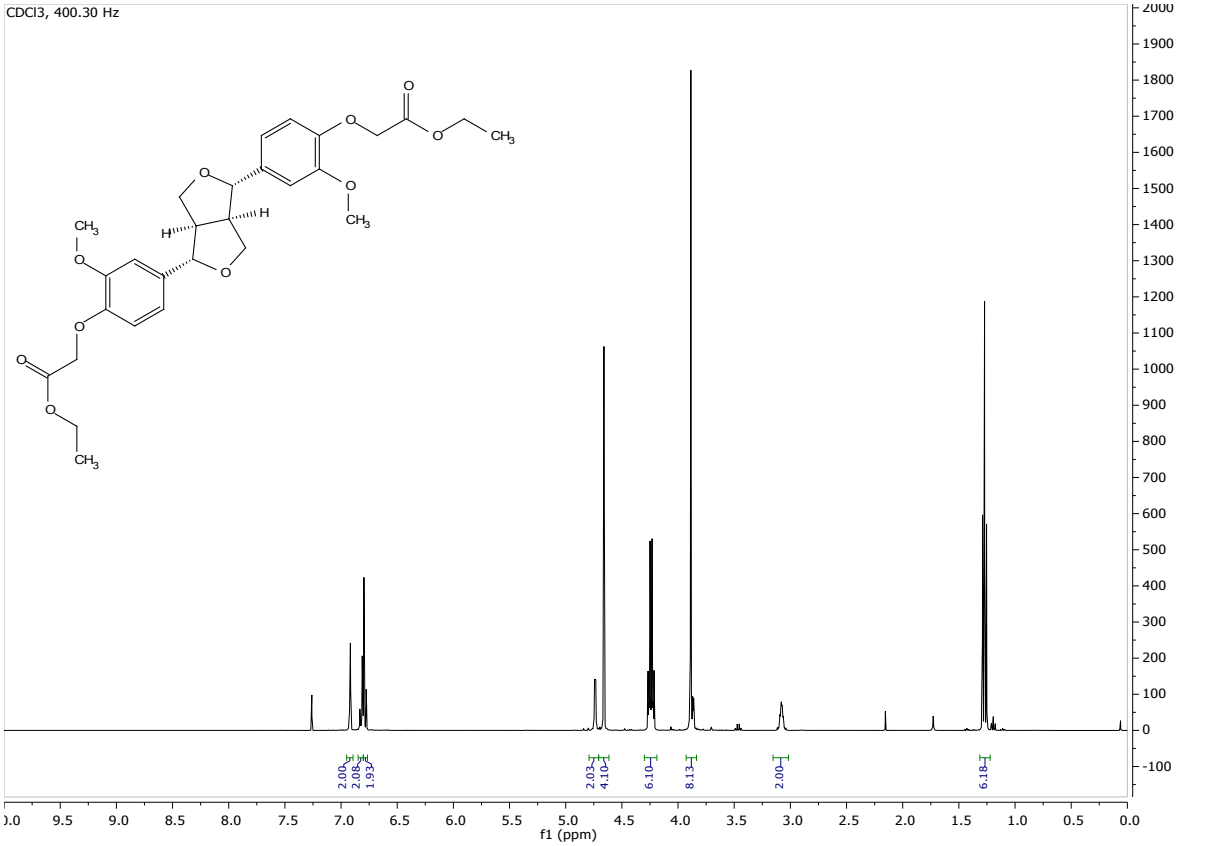


Figure S4 2D HSQC NMR of Polymer **23**. Assignments as for polymer **19**.

NMR Spectra of Novel Compounds



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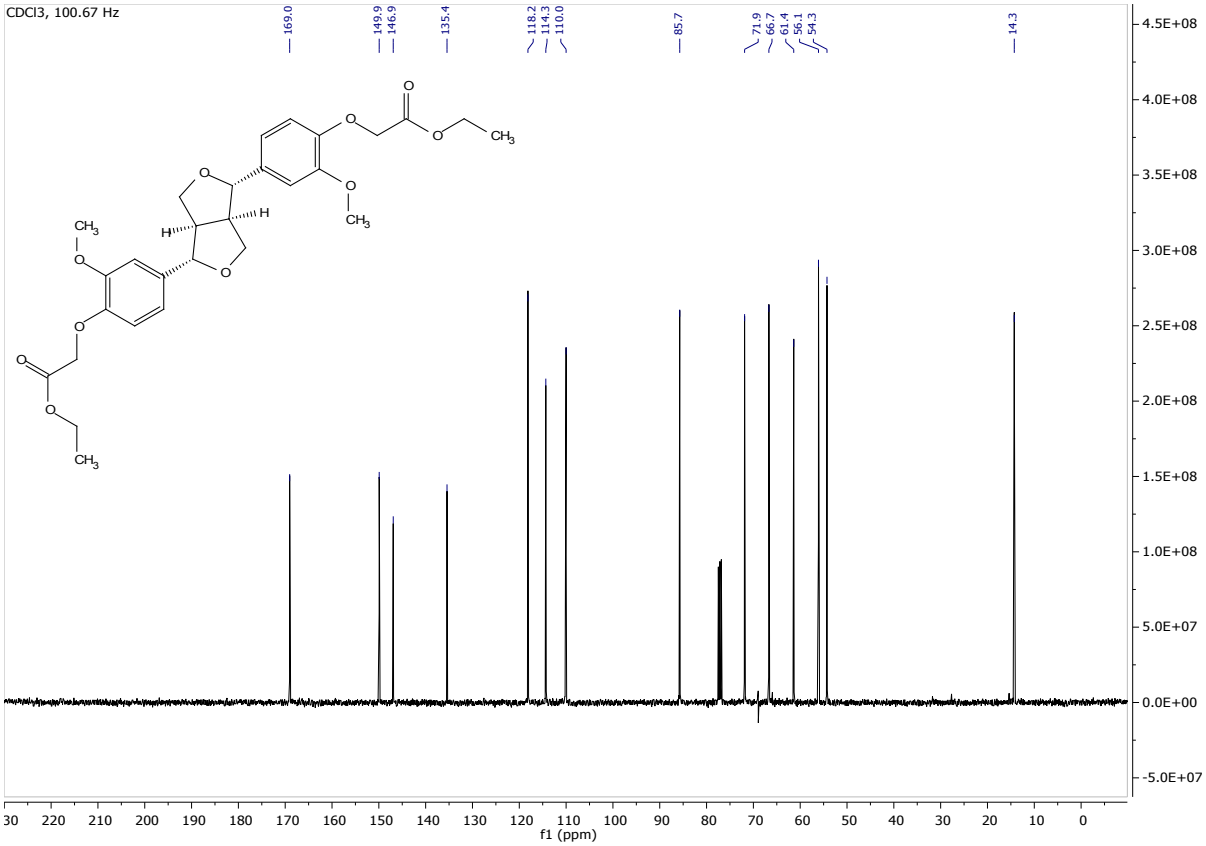
CDCl3, 100.67 Hz
169.0
149.9
146.9
135.4
118.2
114.3
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85.7
71.9
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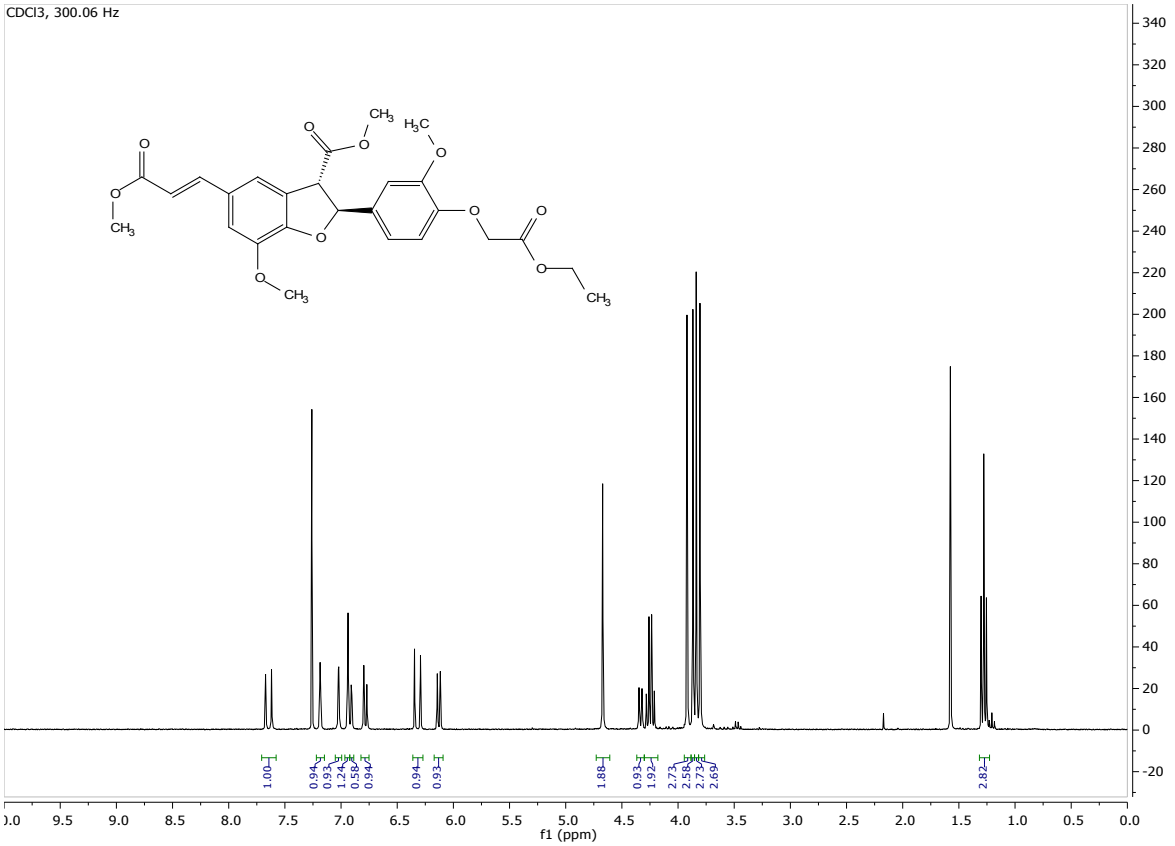
61.4
56.1
54.3
14.3
f1 (ppm)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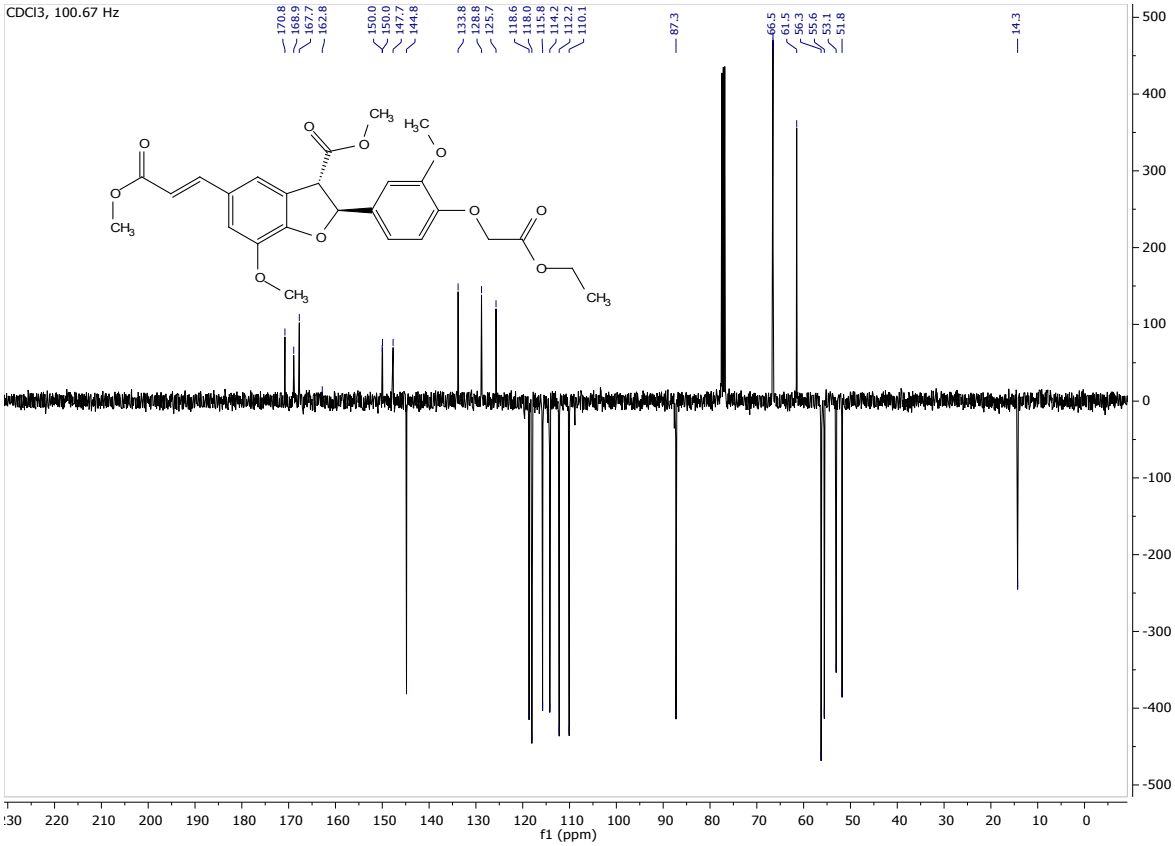
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167.7
162.8
150.0
150.0
147.7
144.8
133.8
128.8
125.7
118.6
118.0
115.8
114.2
112.2
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87.3
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61.5
56.3
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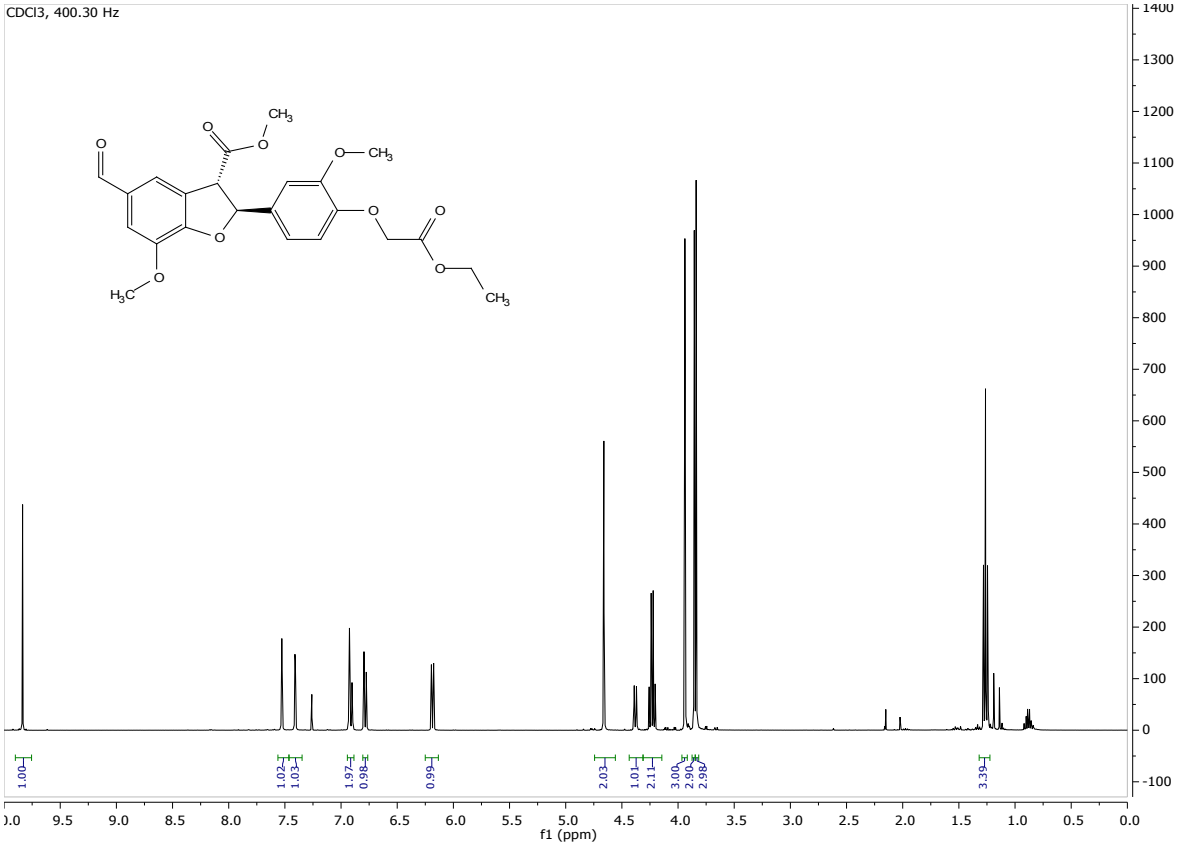
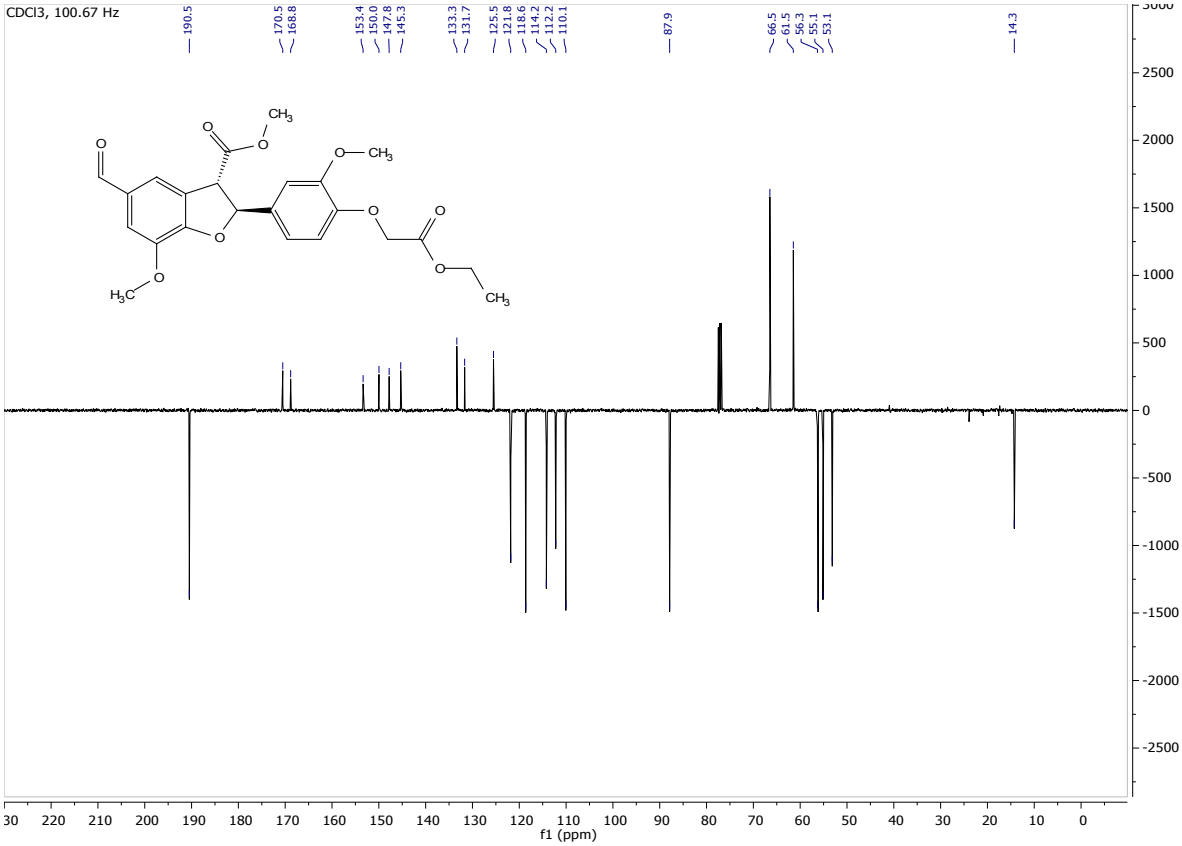
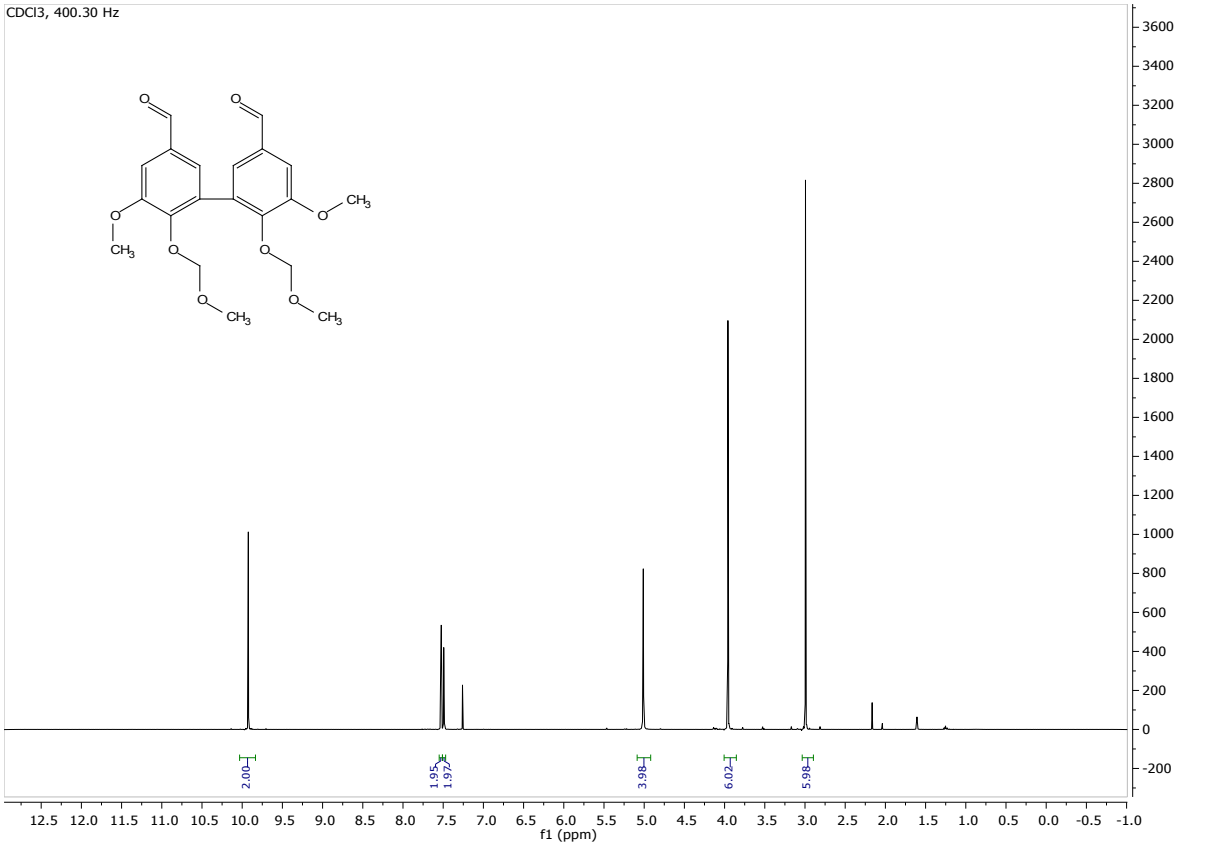
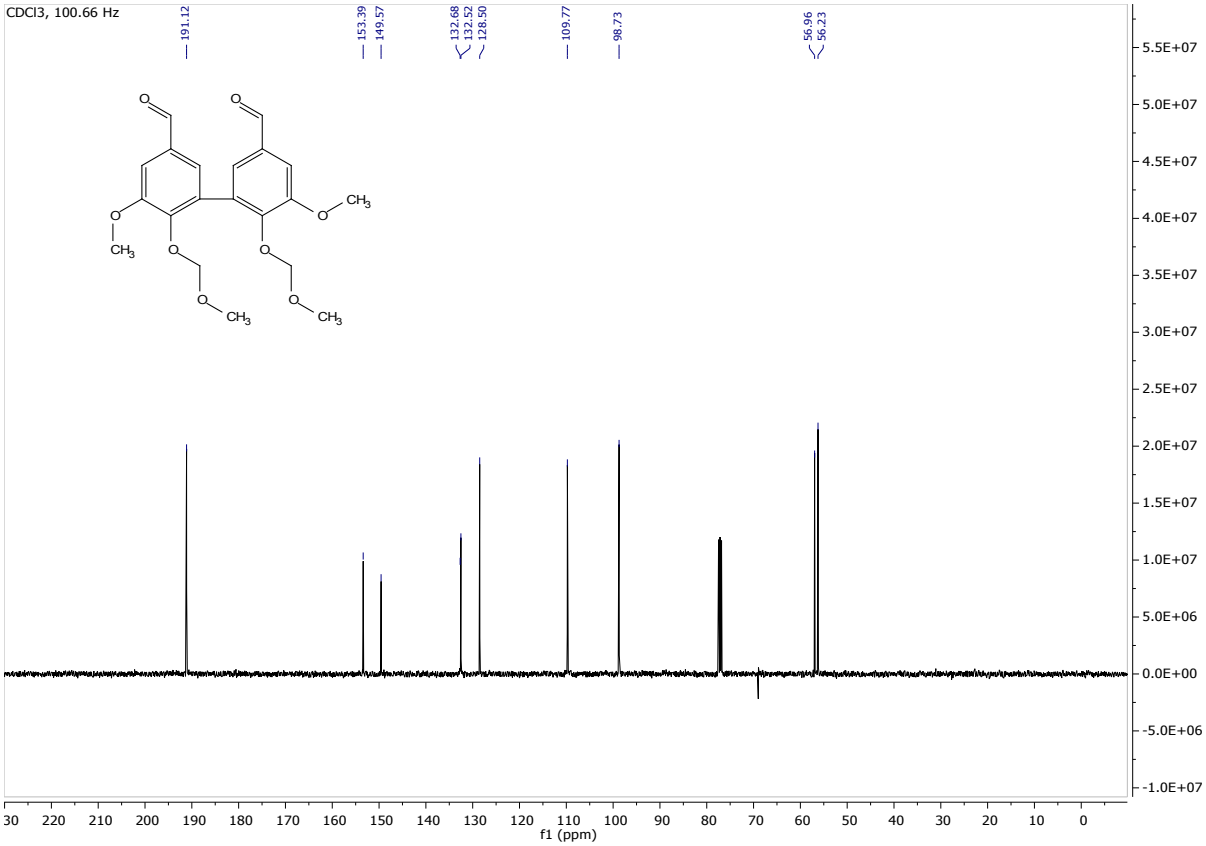
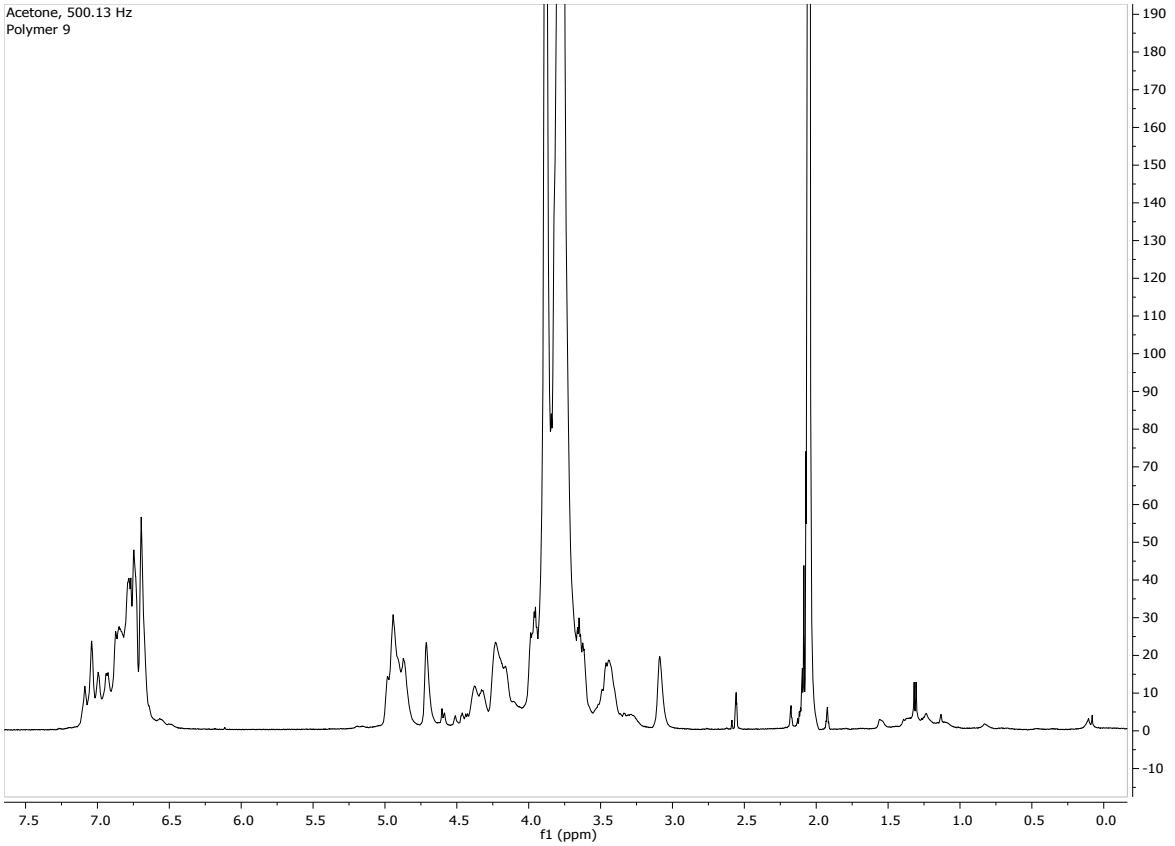
53.1
51.8
14.3
f1 (ppm)

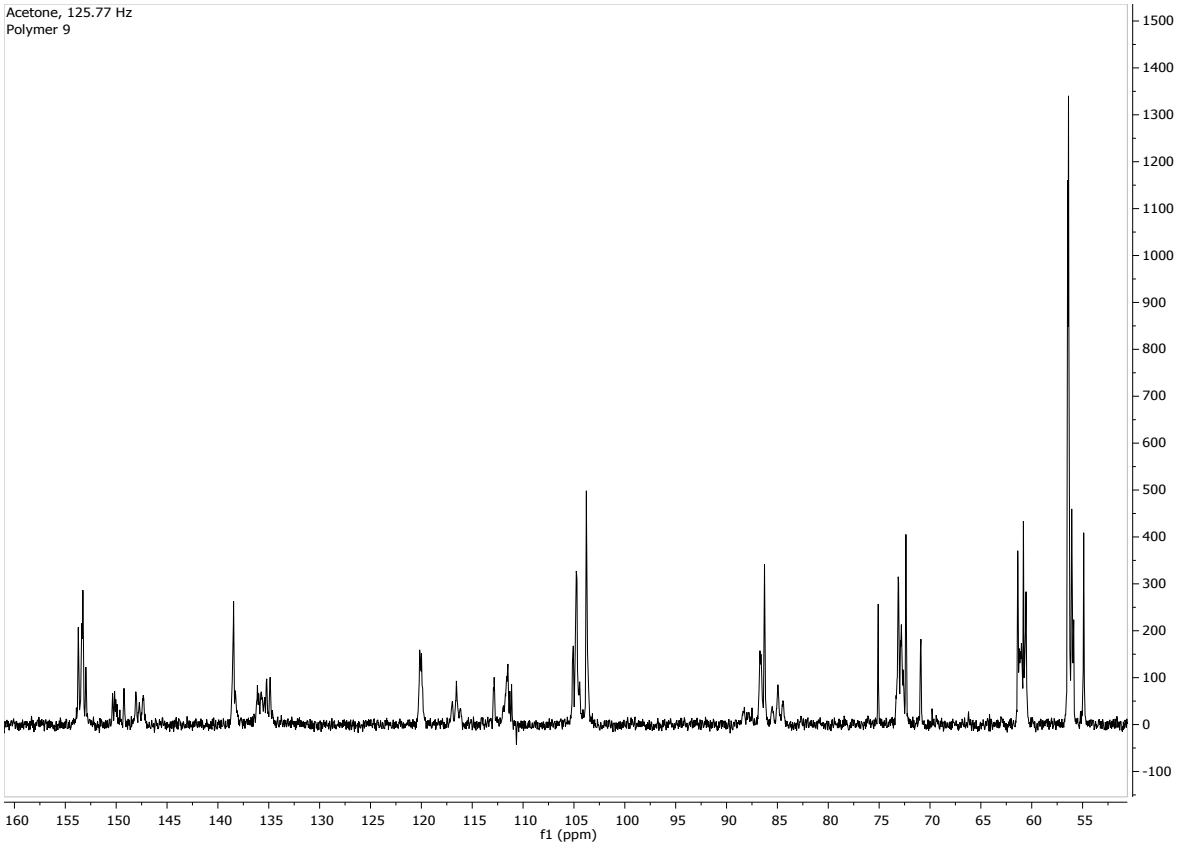

CDCl3, 400.30 Hz
f1 (ppm)

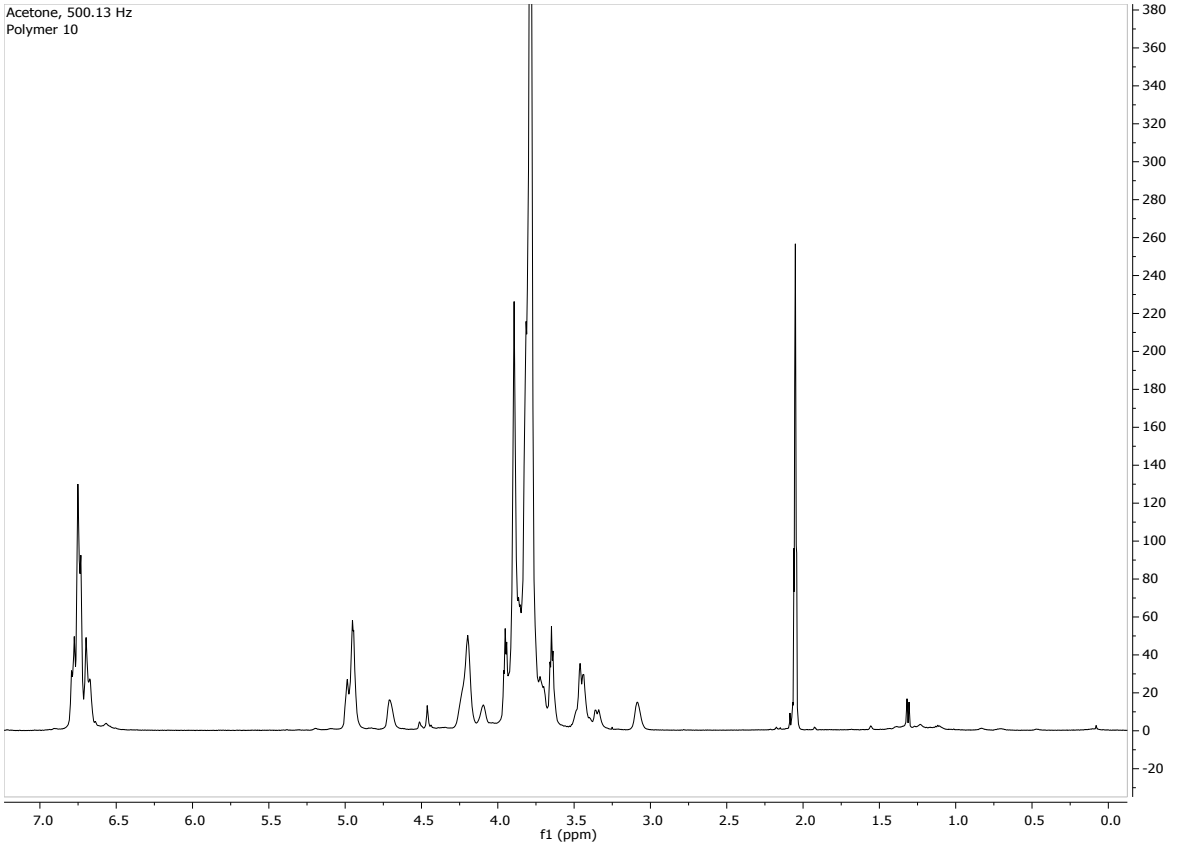

CDCl3, 100.67 Hz
190.5
170.5
168.8
153.4
150.0
147.8
145.3
133.3
131.7
125.5
121.8
118.6
114.2
112.2
110.1
87.9
66.5
61.5
56.3
55.1
53.1
14.3
f1 (ppm)

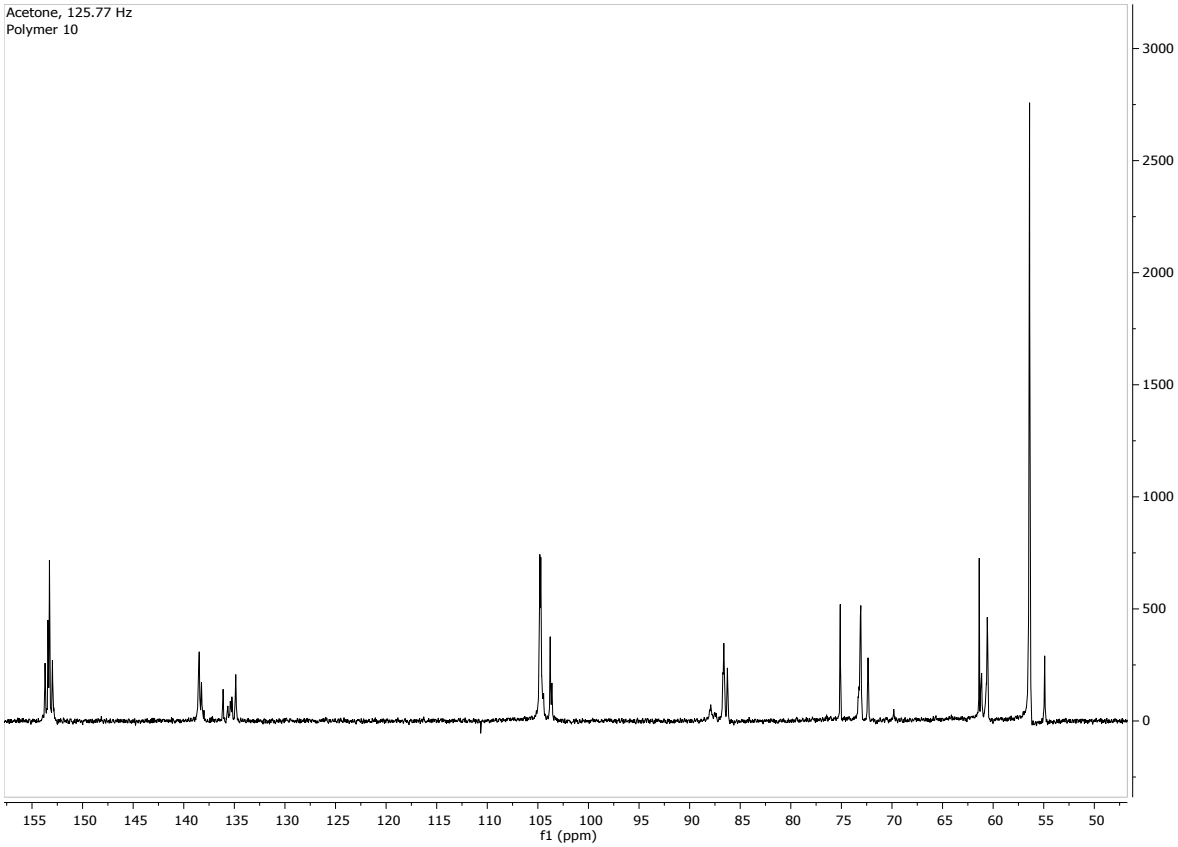

CDCl3, 400.30 Hz
2.00
1.95
1.97
3.98
6.02
5.98
f1 (ppm)

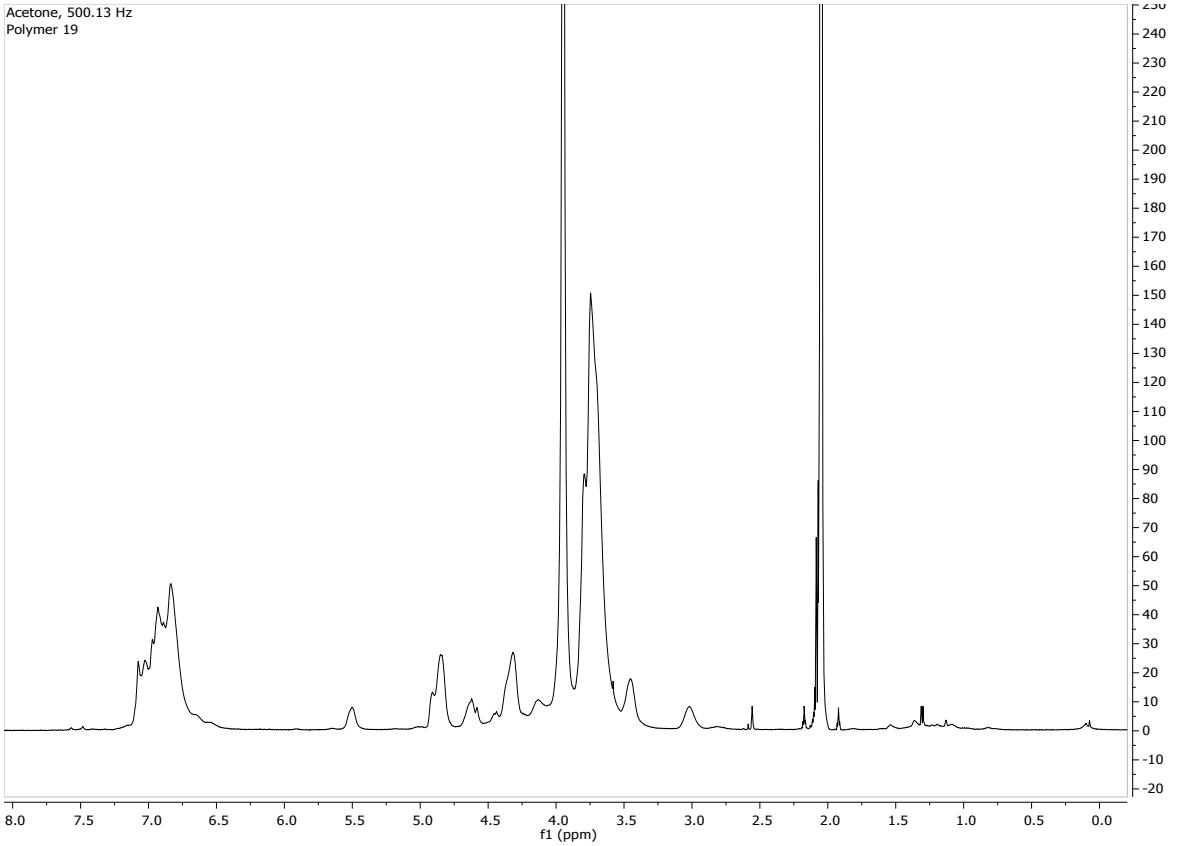

CDCl3, 100.66 Hz
191.12
153.39
149.57
132.68
132.52
128.50
109.77
98.73
56.96
56.23
f1 (ppm)

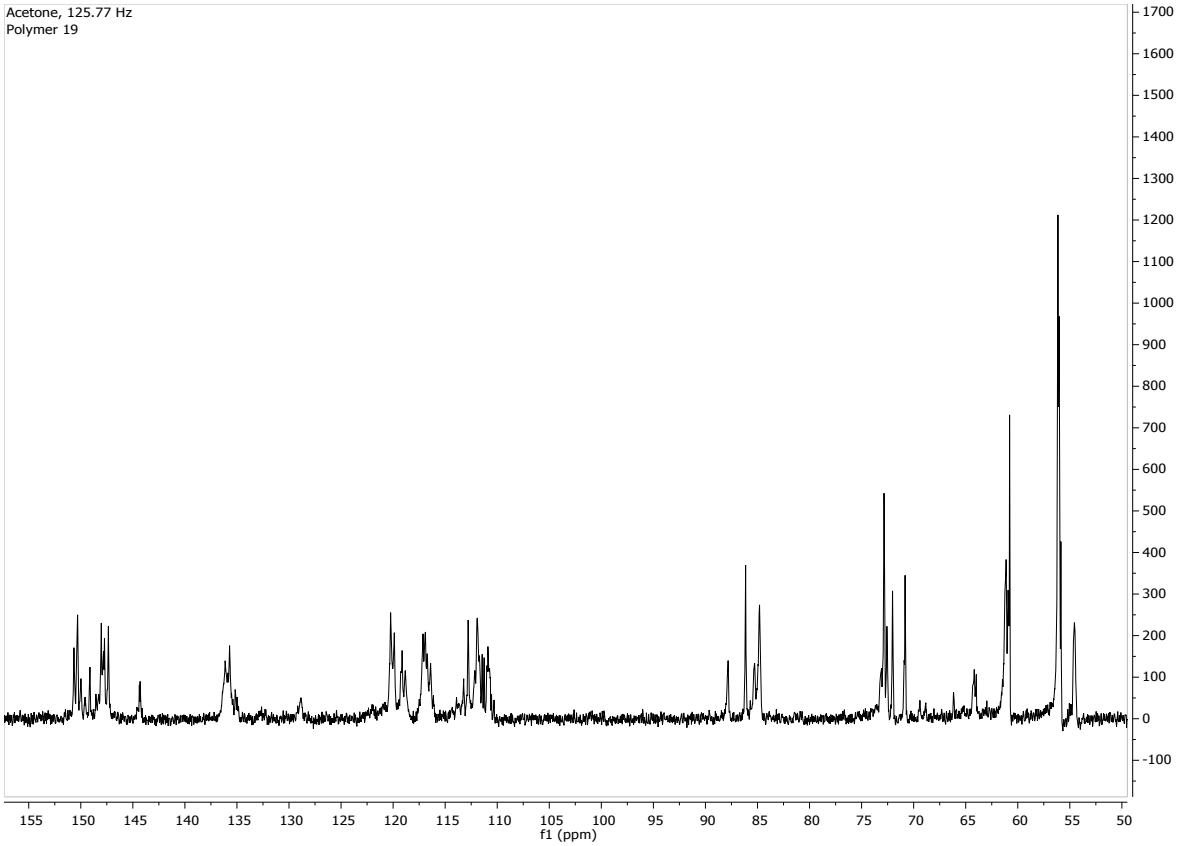

Acetone, 500.13 Hz
Polymer 9
f1 (ppm)

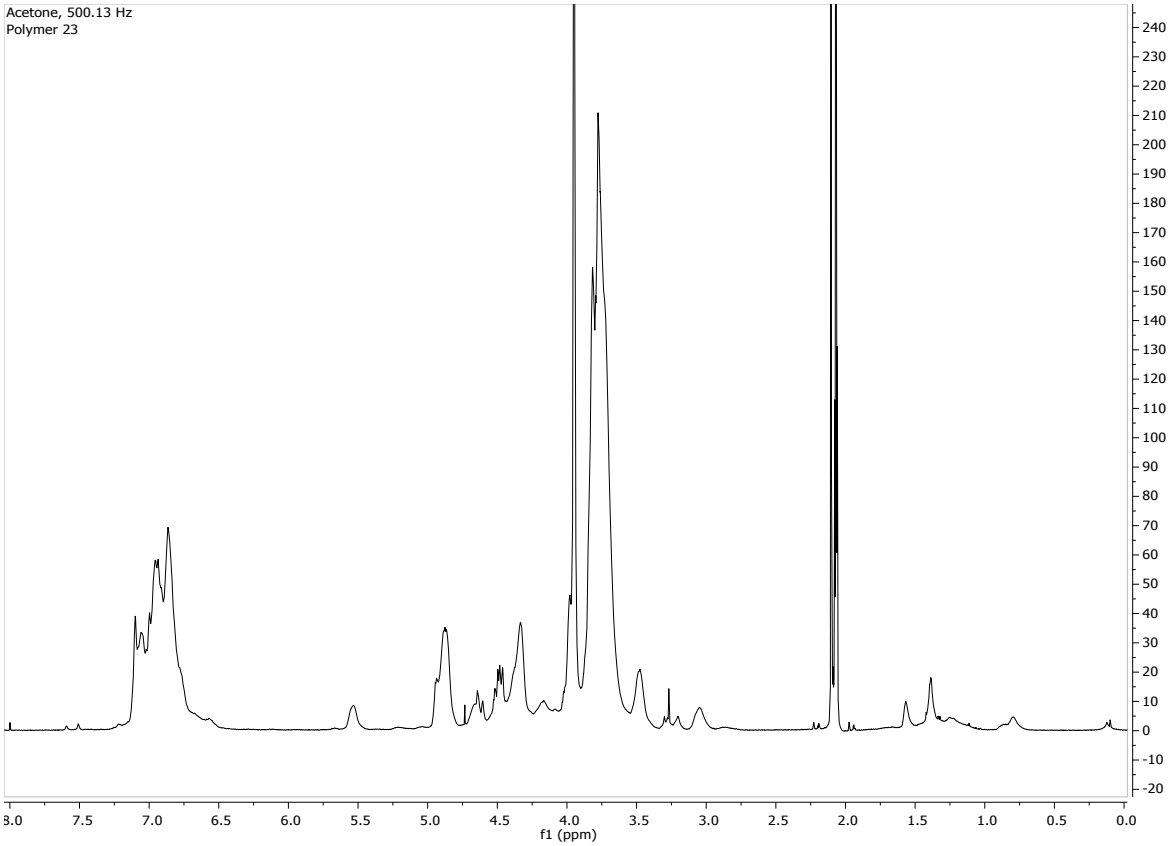

Acetone, 125.77 Hz
Polymer 9
f1 (ppm)

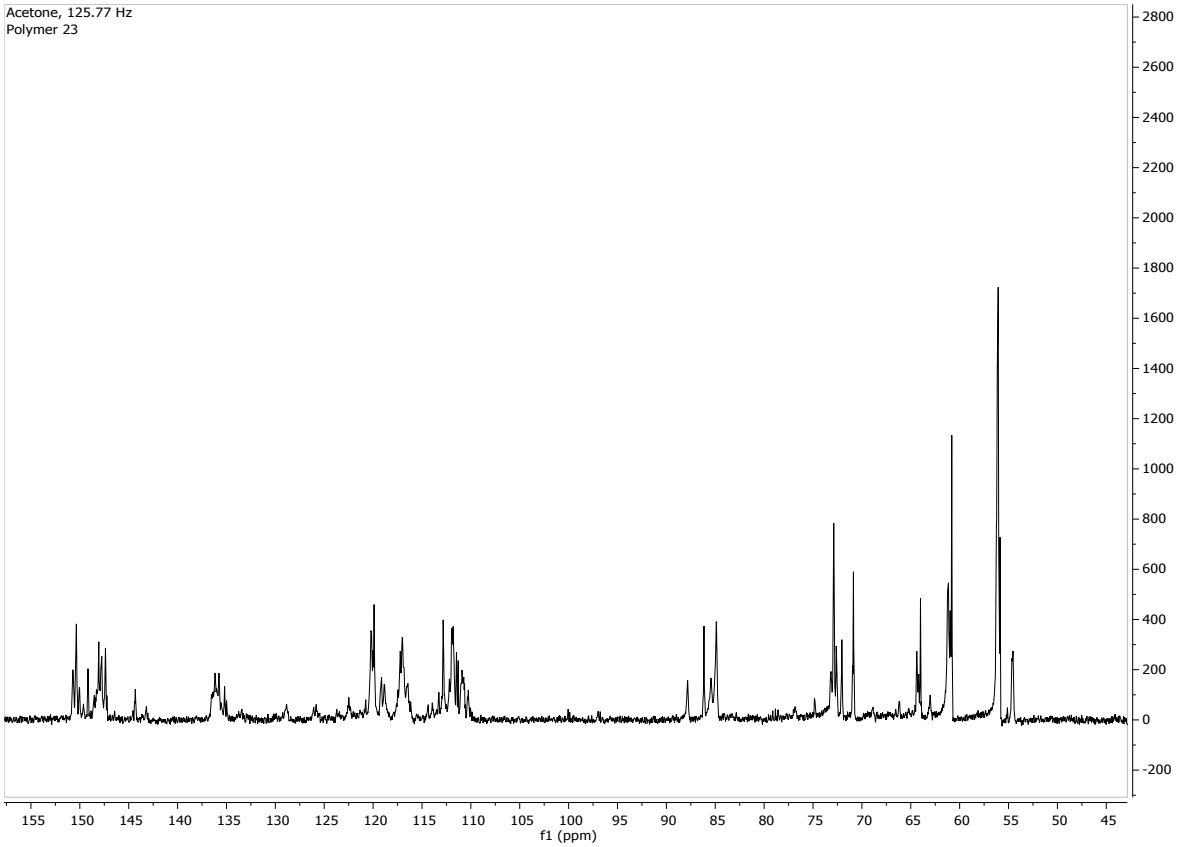

Acetone, 500.13 Hz
Polymer 10
f1 (ppm)


Acetone, 125.77 Hz
Polymer 10
f1 (ppm)


Acetone, 500.13 Hz
Polymer 19
f1 (ppm)


Acetone, 125.77 Hz
Polymer 19
f1 (ppm)


Acetone, 500.13 Hz
Polymer 23
f1 (ppm)


Acetone, 125.77 Hz
Polymer 23
f1 (ppm)

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