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Asymmetric synthesis of new γ-butenolides via organocatalyzed epoxidation of chalcones

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Supplementary information

Unless otherwise noted, all commercially available reagents were purchased from Aldrich Chemical Co. and used without purification. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker ARX-400 (400 and 100 MHz respectively). HPLC chromatograms were obtained on a Shimadzu apparatus, LC-10AT Pump, SPD-10A UV-Vis Detector, SCL-10A System Controller, using a Chiralpak AD-H (4,6 mmØ x 250 mmL, particle size 5 µm) or a Chiralcel OD-H or OD (4,6 mmØ x 250 mmL, particle size 5 µm). Ultrafast chromatography was performed on a Waters ACQUITY UPC^2 system using a Trefoil CEL1 OD column (2.5 µm, 3 mm x 150 mm). Optical rotations were measured with a Perkin-Elmer Polarimeter, Mod. 241, at 589 nm, 30 °C. High-resolution mass spectra were recorded on a Bruker - AutoFlex Speed, MALDI-TOF/TOF MS (λ = 355 nm, f = 500 Hz, matrix HCCA, calibration standard TPP, PEG 600) or on a Shimadzu Nexera X2 UHPLC system coupled to a Bruker Impact HD QqTOF mass spectrometer (FAPESP PROEM 2014/50244-6). The microwave-assisted reactions were carried out in a CEM Discovery focused oven. Column chromatography was performed using Merck Silica Gel (230-400 mesh). Thin layer chromatography (TLC) was performed using Merck Silica Gel GF254, 0.25 mm thickness. For visualization, TLC plates were either placed under ultraviolet light, stained with iodine vapor or acidic vanillin. The following solvents were dried and purified by distillation from the reagents indicated: tetrahydrofuran from sodium with a benzophenone ketyl indicator; dichloromethane from calcium hydride.

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General procedure for chalcone synthesis[1]

The appropriate benzaldehyde (9.9 mmol) was added dropwise to a solution of desired acetophenone (10 mmol) in ethanol (3 mL) and an aqueous solution of NaOH (12.7 mmol; 0.507 g) in H_2O (4.5 mL). The reaction mixture was stirred for 4 hours at room temperature. Added an aqueous solution of NH_4Cl (10 mL) and extracted with ether (3 x 20 mL). The combined organic layers were dried over anhydrous $MgSO_4$ and solvent removed under reduced pressure. The chalcones **7** were obtained through column chromatography purification using silica gel (100–200 mesh) in hexane/ethyl acetate (95:5).

(*E*)-3-phenyl-1-phenylprop-2-en-1-one (7a)[1]

Yield: 91%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.05-8.03 (m, 1H), 8.02 (d, *J* = 15.7 Hz, 1H), 7.82 (d, *J* = 15.7 Hz, 1H), 7.68-7.63 (m, 2H), 7.62-7.57 (m, 1H), 7.56-7.49 (m, 3H), 7.45-7.40 (m, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 190.7, 145.0, 138.4, 135.0, 132.9, 130.7, 129.1, 128.8, 128.6, 128.6, 122.2.

(*E*)-3-(4-chlorophenyl)-1-phenylprop-2-en-1-one (7b)[2]

Yield: 82%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.01 (d, *J* = 7 Hz, 2H), 7.74 (d, *J* = 16 Hz, 1H), 7.60-7.47 (m, 6H), 7.37 (d, *J* = 8 Hz, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 190.1, 143.2, 138.0, 136.4, 133.3, 132.9, 129.6, 129.2, 128.6, 128.5, 122.4.

(*E*)-1-(benzo[d][1,3]dioxol-5-yl)-3-(4-bromophenyl)prop-2-en-1-one (7c)[3]

Yield: 92%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.71 (d, *J* = 15.7Hz, 1H), 7.63 (dd, *J* = 8.1, 1.7 Hz, 1H), 7.55-7.48 (m, 5H), 7.46 (d, *J* = 15.7Hz, 1H), 6.89 (d, *J* = 8.1Hz, 1H), 6.06 (s, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 187.7, 151.8, 148.3, 142.7, 133.9, 132.8, 132.2, 129.7, 124.7, 124.6, 121.9, 108.3, 107.8, 101.8. MS (relative intensity %) *m/z*: 330 (76); 149 (100); 102 (82); 65 (41).

(*E*)-1-(4-bromophenyl)-3-phenylprop-2-en-1-one (7d)[4]

Yield: 83%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.43-7.41 (m, 3H), 7.47 (d, *J* = 15.8 Hz, 1H), 7.65-7.63 (m, 4H), 7.81 (d, *J* = 15.8 Hz, 1H), 7.88 (d, *J* =

8.5 Hz, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 189.4, 145.4, 137.0, 134.7, 132.0, 130.8, 130.0, 129.0, 128.6, 127.9, 121.5. MS (relative intensity %) *m/z*: 287 (22), 131 (52), 103 (92), 77 (41).

(*E*)-1-(4-methoxyphenyl)-3-phenylprop-2-en-1-one (7e)[1]

Yield: 48%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.05 (d, *J* = 8.9 Hz, 2H), 7.81 (d, *J* = 15.7 Hz, 1H), 7.66-7.63 (m, 2H), 7.55 (d, *J* = 15.7 Hz, 1H), 7.45-7.38 (m, 3H), 6.99 (d, *J* = 8.9 Hz, 2H), 3.89 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 188.9, 163.6, 144.0, 135.2, 131.3, 131.0, 130.5, 129.0, 128.5, 122.0, 114.0, 55.6.

(*E*)-3-(4-nitrophenyl)-1-phenylprop-2-en-1-one (7f)[5]

Yield: 86%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.28 (d, *J* = 8.7 Hz, 2H), 8.05-8.03 (m, 2H), 7.84-7.78 (m, 3H), 7.67-7.61 (m, 2H), 7.55-7.52 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 189.8, 148.7, 141.6, 141.2, 137.7, 133.5, 129.1, 129.0, 128.7, 125.9, 124.4.

(*E*)-1-(2-methoxyphenyl)-3-phenylprop-2-en-1-one (7g)[6]

Yield: 78%. Yellow oil. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.62 (d, *J* = 16.0 Hz, 1H), 7.62 (dd *J* = 7.6, 1.8 Hz, 1H), 7.59 – 7.58 (m, 2H), 7.48 (ddd, *J* = 8.7, 7.4, 1.8 Hz, 1H), 7.40 – 7.35 (m, 4H), 7.04 (td, J = 7.5, 0.95 Hz, 1H), 7.00 (d, J = 8.4 Hz, 1H), 3.90 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 193.2, 158.3, 143.4, 135.3, 133.0, 130.5, 130.4, 129.0, 128.5, 127.2, 120.9, 111.8, 55.9

(*E*)-1-(4-nitrophenyl)-3-phenylprop-2-en-1-one (7h)[7]

Yield: 94%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.35 (d, *J* = 8.9 Hz, 2H), 8.14 (d, *J* = 8.9 Hz, 2H), 7.8 (d, *J* = 15.7 Hz, 1H), 7.67-7.65 (m, 2H), 7.48 (d, *J* = 15.7 Hz, 1H), 7.46-7.43 (m, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 189.2, 150.2, 147.0, 143.2, 134.4, 131.4, 129.5, 129.3, 128.8, 124.0, 121.4.

(*E*)-3-(4-chlorophenyl)-1-(4-iodophenyl)prop-2-en-1-one (7i)

Yield: 71%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.87 (d, *J* = 8.6 Hz, 2H), 7.76 (d, *J* = 15.8 Hz, 1H), 7.72 (d, *J* = 8.6 Hz, 2H), 7.57 (d, *J* = 8.4 Hz, 2H), 7.43

(d, *J* = 15.7 Hz, 1H), 7.40 (d, J = 8.5 Hz, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 189.5, 144.0, 138.1, 137.4, 136.8, 133.3, 130.0, 129.8, 129.5, 121.9, 101.0.

(*E*)-1-(4-bromophenyl)-3-(4-fluorophenyl)prop-2-en-1-one (7j)

Yield: 85%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: δ: 7.90-7.87 (m, 2H), 7.78 (d, *J* = 15.7 Hz, 1H), 7.66-7.61 (m, 4H), 7.40 (d, *J* = 15.7 Hz, 1H), 7.15-7.09 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 189.2, 165.6, 144.3, 136.8, 132.0, 131.0, 130.5, 130.0, 128.0, 121.2, 116.1.

General procedure for synthesis of chalcone 7k – 7m[8]

The aldehyde (3.6 mmol, 1.2 eq.) was added to the solution of 85% KOH (0.24 mL) in MeOH (3 mL) and H_2O (0.60 mL) at 0ºC. Then, the appropriate ketone (3.0 mmol, 1.0 eq) was added dropwise. The mixture was stirred for 18 h at 0ºC. The chalcones **7j** e **7m** were obtained through column chromatography purification using silica gel (100–200 mesh) in hexane/ethyl acetate (95:5).

(*E*)-1-(furan-2-yl)-3-phenylprop-2-en-1-one (7k)

Yield: 80%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.85 (d, *J* = 15.8 Hz, 1H), 7.63-7.60 (m, 3H), 7.43 (d, *J* = 15.8 Hz, 1H), 7.39-7.37 (m, 3H), 7.32 (d, *J* = 3.2 Hz, 1H), 6.56 (dd, J = 3.6, 1.7 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 178.0, 153.7, 146.6, 143.9, 134.7, 130.6, 129.0, 128.5, 121.2, 117.6, 112.6.

(*E*)-3-phenyl-1-(thiophen-2-yl)prop-2-en-1-one (7l)

Yield: 96%. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.87 (dd, *J* = 8.4, 7.4 Hz, 1H), 7.69 (dd, *J* = 4.9, 0.9 Hz, 1H), 7.67 – 7.63 (m, 1H), 7.47 – 7.40 (m, 2H), 7.19 (dd, *J* = 4.9, 3.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 190.05, 182.15, 162.87, 145.67, 144.12, 134.72, 133.94, 131.85, 130.63, 128.99, 128.52

(*E*)-1-phenyl-3-(pyridin-2-yl)prop-2-em-1-one (7m)

Yield: 26%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.69 (d, *J* = 4.6 Hz, 1H), 8.15 – 8.08 (m, 3H), 7.78 (d, *J* = 15.1 Hz, 1H), 7.75 (dt, *J* = 7.7, 1.9 Hz, 1H), 7.62 – 7.57 (m, 1H), 7.54 – 7.46 (m, 3H), 7.30 (ddd, *J* = 7.6, 4.7, 1.1 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 190.41,

153.21, 150.18, 142.38, 137.84, 137.72, 136.93, 133.10, 128.76, 128.67, 125.59, 125.43, 124.16.

General procedure for synthesis of racemic epoxychalcones 8[9]

To a solution of appropriate chalcone **7** (0.3 mmol) in methanol (3.0 mL) was added an aqueous solution of NaOH (5 drops, 4%) at 0ºC. Then, added dropwise a solution of H_2O_2 (0.15 mL, 35%) and NaOH (0.17 mL, 4%). The mixture was stirred for 3 hours at 0ºC. The reaction was quenched in H_2O (5 mL) and extracted with dichloromethane (3 x 10 mL). The organic layer was washed with brine (2 x 15 mL), and dried over Na_2SO_4. The epoxychalcone **8** was obtained through column chromatography purification using silica gel (100–200 mesh) in hexane/ethyl acetate (95:5).

(2-methoxyphenyl)(3-phenyloxiran-2-yl)methanone (8g)[10]

Yield: 94%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.83 (dd, *J* = 7.8, 1.8 Hz, 1H), 7.52 (ddd, J= 8.5, 7.3, 1.8 Hz, 1H), 7.42-7.34 (m, 5H), 7.05 (td, J= 7.5, 0.9 Hz, 1H), 6.93 (d, *J* = 8.07 Hz, 1H), 4.31 (d, *J* = 1.9 Hz, 1H), 4.01 (d, J = 1.9 Hz, 1H), 3.60 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 195.0, 159.7, 136.6, 135.0, 130.9, 128.8, 128.7, 126.1, 125.9, 121.2, 111.7, 64.7, 59.9, 55.7.

(4-nitrophenyl)(3-phenyloxiran-2-yl)methanone (8h)[11]

Yield: 48%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.34 (d, *J* = 8.9 Hz, 2H), 8.19 (d, *J* = 8.9 Hz, 2H), 7.45-7.40 (m, 3H), 7.38-7.35 (m, 2H), 4.26 (d, *J* = 1.8 Hz, 1H), 4.10 (d, J = 1.8 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.4, 150.9, 139.8, 134.9, 129.7, 129.5, 129.1, 125.9, 124.2, 61.6, 59.7.

(3-(4-chlorophenyl)oxiran-2-yl)(4-iodophenyl)methanone (8i)

Yield: 71%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.87 (d, *J* = 8.6 Hz, 2H), 7.71 (d, *J* = 8.5 Hz, 2H), 7.38 (d, *J* = 8.5 Hz, 2H), 7.29 (d, *J* = 8.5 Hz, 2H), 4.17 (d, *J* = 1.8 Hz, 1H), 4.05 (d, *J* = 1.7 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.4, 138.4, 135.2, 134.6, 133.9, 129.8, 129.2, 127.2, 102.6, 61.0, 58.8.

(4-bromophenyl)(3-(4-fluorophenyl)oxiran-2-yl)methanone (8j)

Yield: 67%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.88 (d, *J* = 8.6 Hz, 2H), 7.64 (d, *J* = 8.6 Hz, 2H), 7.36-7.31 (m, 2H), 7.12-7.07 (m, 2H), 4.19 (d, *J* = 1.8 Hz, 1H), 4.06 (d, *J* = 1.7 Hz, 1H).^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.4, 164.3, 134.0, 132.3, 131.0, 130.0, 129.5, 127.5, 116.0, 61.0, 58.8.

Procedure for synthesis of epoxychalcone 8k[10]

To a solution of chalcone **7k** (2.0 mmol) in MeOH (5 mL) was slowly added a mixture of 0.5 mL of 35% H_2O_2 and 0.5 mL NaOH 2 M at 0ºC. The mixture was stirred for 1 h at ambient temperature and filtered to collect colorless solid, which was then washed with water and cold MeOH. This solid was recrystallized from MeOH.

Furan-2-yl(3-phenyloxiran-2-yl)methanone (8k)

Yield: 72%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.66 (dd, *J* = 1.7, 0.6 Hz, 1H), 7.45 (dd, *J* = 3.6, 0.6 Hz, 1H), 7.41-7.32 (m, 5H), 6.59 (dd, *J* = 3.6, 1.7 Hz, 1H), 4.14 (s, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 182.1, 151.3, 147.8, 135.4, 129.1, 128.8, 125.9, 119.7, 112.8, 60.7, 59.7.

Procedure for synthesis of epoxychalcone (8l) [12]

The chalcone **7l** (2 mmol) was suspended in a mixture of ethanol (2.0 mL) and 10% aqueous NaOH (2 mL, 1:1 in v/v) at 0ºC. Then was added dropwise a solution of H_2O_2 (0.17 mL, 35%). The mixture was stirred for 5 hours and the reaction was quenched in ice (10g) and neutralized with acetic acid. The mixture was filtered to collect colorless solid, which was then washed with cold MeOH.

(3-phenyloxiran-2-yl)(thiophen-2-yl)methanone (8l)

Yield: 91%. white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.92 (dd, *J* = 3.9, 1.1 Hz, 1H), 7.66 (dd, *J* = 4.9, 1.1 Hz, 1H), 7.36 – 7.24 (m, 5H), 7.09 (dd, *J* = 4.9, 3.9 Hz, 1H), 4.09 (d, *J* = 1.8 Hz, 1H), 4.00 (t, *J* = 1.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 186.48, 140.97, 135.28, 133.65, 129.10, 128.77, 128.50, 125.80, 61.99, 59.48.

Procedure for synthesis of epoxychalcone (8m) [13]

A solution of chalcone **7m** (0.3 mmol) in MeOH (9 mL) was treated with K_2CO_3 (0.9 mmol) and H_2O_2 35% at 0ºC. The mixture was stirred for 3h at ambient temperature. Then neutralized with NH_4Cl and extracted with ethyl acetate (3 x 30 mL). The epoxychalcone 8l was obtained through column chromatography purification using silica gel (100–200 mesh) in hexane/ethyl acetate (70:30).

Phenyl(3-(pyridin-2-yl)oxiran-2-yl)methanone (8m)

Yield: 96%. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.64 (ddd, *J* = 4.8, 1.7, 0.9 Hz, 2H), 8.06 – 8.01 (m, 4H), 7.75 (td, *J* = 7.7, 1.7 Hz, 2H), 7.65 – 7.59 (m, 2H), 7.52 – 7.45 (m, 4H), 7.40 (dt, *J* = 7.8, 0.9 Hz, 2H), 7.31 (ddd, *J* = 7.6, 4.8, 1.2 Hz, 2H), 4.58 (d, *J* = 1.3 Hz, 1H), 4.21 (d, *J* = 1.9 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 193.05, 154.62, 149.91, 137.01, 135.44, 134.05, 128.88, 128.47, 123.90, 121.20, 59.32.

General procedure to asymmetric epoxidation reaction using catalyst 2c[14]

An aqueous solution of NaOCl 14% (0.300 mL, 0.340 mmol) was added to a solution of chalcone **7** (0.170 mmol) and catalyst **2c** (9.0 mg, 0.0170 mmol) in toluene (1.7 mL) at -20ºC. The reaction mixture was stirred for 48 hours at -20ºC. Added water (5 mL) and extracted with ethyl acetate (2 x 5mL). The solvent was removed under reduced pressure and the products were purified by flash chromatograph using hexane:ethyl acetate (10:1) as eluente.

(+)-Phenyl((2*S*,3*R*)-3-phenyloxiran-2-yl)methanone (8a)[15]

Yield: 64%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.08 (d, *J* = 7.1 Hz, 2H), 7.72-7.68 (m, 1H), 7.58-7.54 (m, 2H), 7.49-7.43 (m, 5H), 4.37 (d, *J* = 1.8 Hz, 1H), 4.15 (d, *J* = 1.7 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 193.2, 135.5, 134.1, 129.1, 129.0, 128.9, 128.4, 125.9, 61.1, 59.5. ee: 85%, measured by HPLC with chiral column Chiralpak OD-H (2% 2-propanol/hexane, 1.0 mL/min) t_{major} = 15.36 min, t_{minor} = 18.23 min. $[\alpha]_D^{20}$= +165.7 (*c* 0.3, $CHCl_3$). Lit.: +207.7 (*c* 0.78, CH_2Cl_2).

(+)-((2*S*,3*R*)-3-(4-chlorophenyl)oxiran-2-yl)(phenyl)methanone (8b)[16]

Yield: 83%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.08 (d, *J* = 7.3 Hz, 2H), 7.71 (t, *J* = 7.5 Hz, 1H), 7.57 (t, *J* = 7.8 Hz, 2H), 7.46 (d, *J* = 8.4 Hz, 2H), 7.39 (d, *J* = 8.5 Hz, 2H), 4.33 (d, *J* = 1.7 Hz, 1H), 4.14 (d, *J* = 1.5 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.7, 135.3, 134.9, 134.1, 129.0, 128.9, 128.9, 127.1, 60.9, 58.6. ee: 87%, measured by HPLC with chiral column Chiralpak OD-H (2% 2-propanol/hexane, 1.0 mL/min) t_{major} = 16.75 min, t_{minor} = 19.96 min. $[\alpha]_D^{20}$= +185.1 (*c* 0.3, $CHCl_3$). Lit.: +201.2 (*c* 0.46, CH_2Cl_2).

(+)-Benzo[*d*][1,3]dioxol-5-yl((2*S*,3*R*)-3-(4-bromophenyl)oxiran-2-yl)methanone (8c)[17]

Yield: 68%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.70 (dd, *J* = 8.1, 1.6 Hz, 1H), 7.61 (d, *J* = 8.5 Hz, 2H), 7.53 (d, *J* = 1.6 Hz, 1H), 7.33 (d, *J* = 8.4 Hz, 2H), 6.95 (d, *J* = 8.2 Hz, 1H), 6.15 (s, 2H), 4.23 (d, *J* = 1.7 Hz, 1H), 4.11 (d, *J* = 1.5 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 190.6, 152.8, 148.6, 134.7, 130.3, 127.5, 125.1, 123.1, 108.3, 108.0, 102.2, 60.8, 58.7. *ee*: 96%, measured by HPLC with chiral column Chiralpak OD-H (2% 2-propanol/hexane, 1.0 mL/min) t_{major} = 46.62 min, t_{minor} = 54.17 min. $[\alpha]_D^{20}$= +135.2 (*c* 0.9, $CHCl_3$), Lit.: +203.0 (*c* 1.14, $CHCl_3$).

(+)-((2*S*,3*R*)-3-(4-bromophenyl)oxiran-2-yl)(phenyl)methanone (8d)[16]

Yield: 68%. Yellow solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.90-7.87 (m, 2H), 7.65-7.62 (m, 2H), 7.44-7.35 (m, 5H), 4.23 (d, *J* = 1.8, 1H), 4.07 (d, *J* = 1.8, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.3, 135.2, 134.1, 132.2, 129.9, 129.4, 129.2, 128.8, 125.8, 61.0, 59.4. *ee*: 81%, measured by ACQUITY UPC^2 system (Waters Corp., Milford, MA, USA). Separation was performed on an ACQUITY UPC^2 Trefoil CEL1 column OD (2.5 µm, 3 mm x 150 mm) using a gradient method with the mobile phase containing $SCCO_2$ (purity ≥ 99.99%) 100% during 1 min, $SCCO_2$ (purity ≥ 99.99%) : ACN (100% to 60:40, v/v, 4 min), $SCCO_2$ (purity ≥ 99.99%) : ACN (60:40, v/v, 1 min), delivered at a flow rate of 1.0 mL/min. t_{major} = 4.53 min, t_{minor} = 4.63 min. $[\alpha]_D^{20}$= +149.6 (*c* 1.0, $CHCl_3$), Lit.: +161.2 (*c* 0.48, CH_2Cl_2).

(+)-(4-methoxyphenyl)((2S,3R)-3-phenyloxiran-2-yl)methanone (8e)[17]

Yield: 91%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.02 (d, *J* = 9.1 Hz, 2H), 7.42-7.37 (m, 5H), 6.96 (d, *J* = 9.1 Hz, 2H), 4.26 (d, *J* = 2.0 Hz, 1H), 4.08 (d, *J* = 1.9 Hz, 1H), 3.89 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 191.3, 164.2, 135.7, 130.8, 128.9, 128.7, 128.6, 125.8, 114.1, 60.9, 59.2, 55.5. *ee*: 91%, measured by HPLC with chiral column Chiralpak AD-H (10% ethanol/hexane, 0.5 mL/min) t_{major} = 92.8 min, t_{minor} = 84.5 min. $[\alpha]_D^{20}$= +215.6 (*c* 1.1, $CHCl_3$), Lit.: +220.6 (*c* 0.80, $CHCl_3$).

(+)-((2S,3R)-3-(4-nitrophenyl)oxiran-2-yl)(phenyl)methanone (8f)[16]

Yield: 90%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 8.28 (d, *J* = 8.9 Hz, 2H), 8.02 (dd, *J* = 8.3, 1.2 Hz, 2H), 7.68-7.64 (m, 1H), 7.58-7.50 (m, 4H), 4.29 (d, *J* = 1.9 Hz, 1H), 4.22 (d, *J* = 1.6 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 192.1, 148.3, 142.7, 135.2, 134.3, 129.0, 128.4, 126.6, 124.1, 60.8, 58.0. *ee*: 92%, measured by HPLC with chiral column Chiralpak OD-H (2% 2-propanol/hexane, 1.0 mL/min) t_{major} = 78.87 min, t_{minor} = 103.37 min. $[\alpha]_D^{20}$= +255.2 (*c* 0.9, $CHCl_3$), Lit.: +179.0 (*c* 0.33, CH_2Cl_2).

Synthesis of (*Z*)-ethyl 3-phenyl-3-(3-phenyloxiran-2-yl)acrylate (9a)[18]

Triethyl phosphonoacetate (1.59 g, 7.1 mmol) was added to a suspension of NaH (0.289 g, 7.1 mmol) in dry THF (10mL) under N_2 atmosphere. The reaction mixture was stirred for 20 minutes and then added a solution of **8a** (1.0 g, 4.4 mmol) in dry THF (10mL). The reaction was refluxed for 3 hours. The solvent was removed under reduced pressure, crude was dissolved in ethyl acetate (15mL) and washed with H_2O (2 x 5 mL) and brine (2 x 5 mL). After purification by column chromatography using hexane/ether (9:1) as eluente, product was obtained as colorless oil (0.924 g, 71%).

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.51-7.48 (m, 2H), 7.41-7.39 (m, 3H), 7.35-7.32 (m, 5H), 6.18 (d, *J* = 1.1 Hz, 1H), 4.77 (dd, *J* = 1.9, 1.1 Hz, 1H), 4.23-4.14 (m, 2H), 3.63 (d, *J* = 2.0 Hz, 1H), 1.22 (t, *J* = 7.2 Hz, 3H).

General procedure for synthesis of γ-butenolides

Triethyl phosphonoacetate (0.318 g, 1.42 mmol) was added to a suspension of NaH (0.059 g, 1.42 mmol) in dry THF (2 mL) under N_2 atmosphere. The reaction mixture was stirred for 20 minutes and then added a solution of desired

epoxychalcone **8** (0.892 mmol) in dry THF (4 mL). The reaction was refluxed for 3 hours. The solvent was removed under reduced pressure, crude was dissolved in ethyl acetate (15mL) and washed with H_2O (2 x 5 mL) and brine (2 x 5 mL). The solvent was removed under reduced pressure and the crude dissolved in ethanol (6 mL). Montmorillonite K10 (40 mg) was added and the resulting mixture was stirred at room temperature for 7 hours. The solvent was removed under reduced pressure and the product purified by column chromatography using hexane/ethyl acetate (9:1) as eluente.

General procedure for synthesis of γ-butenolides under microwave irradiation

Triethyl phosphonoacetate (0.266 µL, 1.34 mmol) was added to a suspension of NaH (54 mg, 1.34 mmol) in dry THF (3.0 mL) under N_2 atmosphere. The reaction mixture was stirred for 20 minutes and then added a solution of desired epoxychalcone **8** (0.47 mmol) in dry THF (1.7 mL). The reaction was performed under microwave irradiation (30 min., 300 W, 90 ºC). The solvent was removed and the crude dissolved in ethanol (3.0 mL). Montmorillonite K10 (111 mg) was added and the resulting mixture was performed under microwave irradiation (30 min., 300 W, 100 ºC). The solvent was removed under reduced pressure and the product purified by column chromatography using hexane/ethyl acetate (9:1) as eluente.

(±)-5-(hydroxy(phenyl)methyl)-4-phenylfuran-2(5*H*)-one (10a)

Yield: 66% (0.081 g). White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.58-7.55 (m, 2H), 7.45-7.43 (m, 3H), 7.39-7.34 (m, 5H), 6.35 (s, 1H), 5.66 (d, *J* = 5.0 Hz, 1H), 4.99 (dd, *J* = 7.3, 5.0 Hz, 1H), 2.66 (d, *J* = 7.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.5, 155.1, 136.2, 134.4, 130.7, 129.0, 128.8, 128.8, 126.9, 126.4, 116.5, 84.0, 67.9. m.p. 115.3-116.7˚C. IR (KBr): 3420, 3080, 3040, 2920, 1680, 1610, 1480, 1260, 1080, 1040, 750, 690 cm^{-1}. HRMS (ESI) for $C_{17}H_{15}O_3$ $[M+H]^+$: calcd 267.10157, found 267.10162.

(±)-5-((4-chlorophenyl)(hydroxy)methyl)-4-phenylfuran-2(5H)-one (10b)

Yield: 64% (0.089 g). White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.55-7.52 (m, 2H), 7.43 (d, *J* = 7.3 Hz, 2H), 7.35-7.28 (m, 4H), 6.30 (s, 1H), 5.60 (d, *J* = 5.0 Hz, 1H), 4.94-4.91 (m, 1H), 2.98 (d, *J* = 7.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.3, 155.3, 134.8, 134.7, 134.2, 130.8, 129.1, 129.0, 127.8, 126.8, 116.3, 83.3, 67.8. m.p. 152.2-155.8˚C. IR (KBr): 3420, 3050, 3040, 1680, 1600, 1480, 1280, 1080, 880, 830, 780, 700 cm^{-1}. HRMS (ESI) for $C_{17}H_{14}O_3Cl$ $[M+H]^+$: calcd 301.06260, found 301.06131.

(±)-4-(benzo[*d*][1,3]dioxol-5-yl)-5-((4-bromophenyl)(hydroxy)methyl)furan-2(5*H*)-one (10c)

Yield: 67% (0.121 g). White solid. ^{1}H NMR (400 MHz, DMSO-*d6*) δ: 7.58 (d, *J* = 8.5 Hz, 2H), 7.31 (d, *J* = 6,8 Hz, 2H), 7.26 (dd, *J* = 8.2, 1.9 Hz, 1H), 6.97 (d, *J* = 8.2 Hz, 1H), 6.38 (s, 1H), 6.20-6.19 (m, 1H), 6.07 (s, 2H), 5.63 (d, *J* = 3.7 Hz, 1H), 4.94-4.93 (m, 1H). ^{13}C NMR (100 MHz, DMSO-*d6*) δ: 163.1, 153.8, 149.2, 147.9, 137.0, 131.4, 128.5, 128.4, 122.0, 121.2, 113.9, 108.4, 106.9, 101.6, 82.7, 65.5. m.p 177.4 to 178.8˚C. IR (KBr): 3440, 3060, 2900, 1700, 1600, 1500, 1220, 1090, 1040, 810, 600 cm^{-1}. HRMS (ESI) for $C_{18}H_{14}O_5Br$ $[M+H]^+$: calcd 389.00191, found 389.00034.

(±)-4-(4-bromophenyl)-5-(hydroxy(phenyl)methyl)furan-2(5*H*)-one (10d)

Yield: 80% (0.128 g). White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.55 (d, *J* = 8.6 Hz, 2H), 7.43 (d, *J* = 8.6 Hz, 2H), 7.39-7.33 (m, 5H), 6.31 (s, 1H), 5.63 (d, *J* = 5.0 Hz, 1H), 4.94-4.92 (m, 1H), 2.91 (d, *J* = 7.3 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.3, 154.2, 135.9, 133.3, 132.2, 128.9, 128.4, 126.4, 125.2, 116.7, 84.0, 67.9. m.p. 122.1-123.3˚C. IR (KBr): 3340, 3060, 3020, 2920, 1680, 1580, 1480, 1260, 1080, 1000, 880, 820, 760, 700 cm^{-1}. HRMS (ESI) for $C_{17}H_{14}O_3Br$ $[M+H]^+$: calcd 345.01208, found 345.01114.

(±)-5-(hydroxy(phenyl)methyl)-4-(4-methoxyphenyl)furan-2(5H)-one (10e)

Yield: 72% (0.190 g). White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.54 (d, *J* = 8.9 Hz, 2H), 7.38 - 7.29 (m, 5H), 6.93 (d, *J* = 8.9 Hz, 2H), 6.27 (s, 1H), 5.67 (d, *J* = 4.3 Hz, 1H), 4.95 (s, 1H), 3.83 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 161.9, 154.3, 136.5, 129.0, 128.8, 128.7, 126.5, 126.5, 114.6, 114.4, 84.0, 67.9, 55.6.

m.p. 114.2 -115.3ºC. IR (KBr): 3531, 3080, 3040, 2920, 1682, 1600, 1570, 1514, 1499, 1457, 1184, 1051, 836, 750, 697 cm^{-1}. HRMS (ESI) for $C_{18}H_{17}O4$ $[M+H]^+$: calcd 297.112135, found 297.112213.

(±)-5-(hydroxy(4-nitrophenyl)methyl)-4-phenylfuran-2(5H)-one (10f)

Yield: 40% (0.112 g). Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.23 (d, *J* = 8.8 Hz, 2H), 7.59 (d, *J* = 8.7 Hz, 2H), 7.53 (dd, *J* = 7.4, 1.5 Hz, 2H), 7.47 - 7.41 (m, 3H), 6.33 (s, 1H), 5.71 (d, *J* = 5.4 Hz, 1H), 4.97 (d, *J* = 5.3 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 162.9, 155.8, 148.2, 143.6, 134.0, 131.2, 129.4, 127.6, 127.0, 124.1, 116.4, 82.8, 67.9. m.p 139.4-140.8˚C. IR (KBr): 3415, 3080, 2926, 1712, 1521, 1350, 1261, 1226, 1099, 1049, 854, 771, 694 cm^{-1}. HRMS (ESI) for $C_{17}H_{13}NNaO_5$ $[M+Na]^+$: calcd 334.068593, found 334.069362 .

(±)-5-(hydroxy(phenyl)methyl)-4-(2-methoxyphenyl)furan-2(5H)-one (10g)

Yield: 64% (0,170 g). White solid. ^{1}H NMR (400 MHz, DMSO-*d6*) δ: 7.41 (d, *J* = 4.4, 4H), 7.40 – 7.38 (m, 1H), 7.37 – 7.35 (m, 1H), 7.33 (dd, *J* = 7.5, 1.6 Hz, 1H), 7.03 – 7.01 (m, 1H), 6.98 (dd, *J* = 7.5, 1.0 Hz, 1H), 6.17 (d, *J* = 0.6 Hz,1H), 5.80 (d, *J* = 7.7 Hz,1H), 5.48 (d, *J* = 6.2 Hz,1H), 4.94 (ddd, *J* = 8.0, 6.3, 0.6, 1H), 3.67 (s, 3H). ^{13}C NMR (100 MHz, DMSO-*d6*) δ: 163.2, 157.7, 157.0, 137.6, 130.9, 129.8, 128.3, 128.1, 126.9, 124.7, 120.5, 117.7, 111.5, 83.6, 67.1, 55.5. m.p 209.7-210.7˚C. IR (KBr): 3516, 3053, 3028, 1711, 1597, 1489, 1460, 1377, 1256, 1095, 1033, 1024, 760, 752, 702 cm^{-1}. HRMS (ESI) for $C_{18}H_{17}O4$ $[M+H]^+$: calcd 297.112135, found 297.112373.

(±)-5-(hydroxy(phenyl)methyl)-4-(4-nitrophenyl)furan-2(5H)-one (10h)

Yield: 55% (0.154 g). Yellow solid. ^{1}H NMR (400 MHz, $CO(CD_3)_2$) δ: 8.28 (d, *J* = 9.1 Hz, 2H), 7.96 (d, *J* = 9.1 Hz, 2H), 7.49 – 7.46 (m, 2H), 7.43 – 7.38 (m, 2H), 7.37 – 7.33 (m, 1H), 6.52 (d, *J* = 0.5 Hz, 1H), 5.67 (d, *J* = 5.5 Hz, 1H), 5.37 (d, J = 7.7 Hz, 1H), 5.23 (ddd, *J* = 7.7, 5.5, 0.4 Hz, 1H). ^{13}C NMR (100 MHz, $CO(CD_3)_2$) δ: 163.1, 154.9, 149.4, 142.8, 138.3, 129.4, 129.3, 129.3, 127.7, 124.4, 120.0, 84.9, 68.1. m.p. 145.1-146.5˚C. IR (KBr): 3359, 3111, 3078, 2933, 2850, 1694, 1511, 1349, 1269, 1080, 1013, 892, 850, 715, 698, cm^{-1}. HRMS (ESI) for $C_{17}H_{13}NNaO_5$ $[M+Na]^+$: calcd 334.068593, found 334.068174 .

(±)-5-((4-chlorophenyl)(hydroxy)methyl)-4-(4-iodophenyl)furan-2(5H)-one (10i)

Yield: 46% (0.174 g). White solid. ^{1}H NMR (400 MHz, DMSO-*d6*) δ: 7.84 (d, *J* = 8.4 Hz, 2H), 7.34 (d, *J* = 8.4 Hz, 2H), 7.23 (d, *J* = 8.4 Hz, 2H), 6.95 (d, *J* = 8.4 Hz, 2H), 6.46-6.45 (m, 1H), 6.09 (d, *J* = 4.7 Hz, 1H), 6.03-6.02 (m, 1H), 4.97 (dd, *J* = 7.8, 4.8 Hz, 1H). ^{13}C NMR (100 MHz, DMSO-*d6*) δ: 172.1, 164.3, 137.8, 137.5, 137.1, 132.1, 129.4, 128.7, 127.4, 116.2, 98.5, 84.7, 72.6. m.p 166.1-199.9˚C. IR (KBr): 3454, 3144, 3096, 2947, 1693, 1622, 1472, 1383, 1219, 1053, 1013, 824, 750, 586 cm^{-1}. HRMS (ESI) for $C_{17}H_{12}ClINaO_3$ $[M+Na]^+$: calcd 448.941191; found 448.940394.

(±)-4-(4-bromophenyl)-5-((R)-(4-fluorophenyl)(hydroxy)methyl)furan-2(5H)-one (10j)

Yield: 18% (0.0133 g). Yellow solid. ^{1}H NMR (400 MHz, $CO(CD_3)_2$) δ: 7.65-7.60 (m, 4H), 7.52-7.48 (m, 2H), 7.16 (dd, *J* = 12.2, 5.4 Hz, 2H), 6.36 (s, 1H), 5.62 (d, *J* = 5.5 Hz, 1H), 5.24 (d, *J* = 7.7 Hz, 1H), 5.12 (dd, *J* = 7.5, 5.5 Hz, 1H). ^{13}C NMR (100 MHz, $CO(CD_3)_2$) δ: 163.4 (d, *J* = 245.1 Hz), 163.3, 155.8, 135.5, 134.7, 132.6, 130.0, 129.8 (d, *J* = 8.3 Hz), 124.8, 117.7, 116.1 (d, *J* = 21.7 Hz), 84.2, 67.9. m.p. 171.1 to 171.8˚C. IR (KBr): 3478, 2914, 2849, 1709, 1605, 1585, 1512, 1487, 1219, 1159, 1082, 1042, 1009, 881, 824, 737, 725, 567, 546 cm^{-1}.

(±)-2'-(hydroxy(phenyl)methyl)-[2,3'-bifuran]-5'(2'H)-one (10k)

Yield: 52% (0.118 g). Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.55 (d, *J* = 1.6 Hz, 1H), 7.40-7.31 (m, 5H), 7.00 (d, *J* = 3.5 Hz, 1H), 6.51 (dd, *J* = 3.5, 1.8 Hz, 1H), 6.38 (s, 1H), 5.56 (d, *J* = 5.2 Hz, 1H), 4.83 (d, *J* = 5.2 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 164.2, 148.9, 146.0, 143.3, 136.2, 129.0, 126.6, 115.7, 112.9, 111.3, 83.9, 67.3. m.p. 121.4-122.5˚C. IR (KBr): 3453, 3099, 2928, 1732, 1618, 1582, 1315, 1177, 1005, 824, 762, 687 cm^{-1}. HRMS (ESI) for $C_{15}H_{12}NaO_4$ $[M+Na]^+$: calcd 279.062780; found 279.063203.

(±)-5-(hydroxy(phenyl)methyl)-4-(thiophen-2-yl)furan-2(5H)-one (10l)

Yield: 53% (0.145g). White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.55 (dd, *J* = 3.8, 1.0 Hz, 1H), 7.49 (dd, *J* = 5.1, 1.0 Hz, 1H), 7.41 – 7.32 (m, 5H), 7.10 (dd, *J* = 5.1, 3.8 Hz, 1H), 6.33 (s, 1H), 5.62 (d, *J* = 4.8 Hz, 1H), 4.92 (d, *J* = 4.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) 163.69, 147.97, 137.85, 136.13, 130.36, 129.52, 128.90, 128.44, 126.46, 113.07, 83.74, 68.53. m.p 126.
6-127.8˚C. IR (KBr): 3385, 3090, 2910, 1693, 1585, 1611, 1356, 1263, 1087, 1022, 850, 758, 704 cm^{-1}. HRMS (ESI) for $C_{15}H_{12}NaO_3S$ $[M+Na]^+$: calcd 295.039936; found 295.039482.

4.7. General procedure for asymmetric synthesis of γ-butenolides

An aqueous solution of NaOCl 14% (2.20 mL, 2.80 mmol) was added to a solution of chalcone (1.40 mmol) and catalyst **2c** (98.0 mg, 0.140 mmol) in toluene (10 mL) at -20ºC. The reaction mixture was stirred for 48 hours at -20ºC. The reaction mixture was filtered through celite with ethyl acetate (10 mL) and the organic layer concentrated. The crude was dissolved in dry THF (10 mL) and added to a solution of triethyl phosphonoacetate (0.516g, 2.30 mmol) and NaH (0.092 g, 2.30 mmol) in dry THF (4 mL). The reaction was refluxed for 3 hours. The solvent was removed under reduced pressure, crude was dissolved in ethyl acetate (25 mL) and washed with H_2O (2 x 10 mL) and brine (2 x 10 mL). The solvent was removed under reduced pressure and the crude dissolved in ethanol (9mL). Montmorillonite K10 (70 mg) was added and the resulting mixture was stirred at room temperature for 7 hours. The solvent was removed under reduced pressure and the product purified by column chromatography using hexane/ethyl acetate (9:1) as eluent.

(-)-(*S*)-5-((*R*)-hydroxy(phenyl)methyl)-4-phenylfuran-2(5*H*)-one (10a)

Overall yield: 44%. White solid. ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 7.57-7.54 (m, 2H), 7.45-7.41 (m, 3H), 7.38-7.32 (m, 5H), 6.34 (s, 1H), 5.65 (d, *J* = 5.0 Hz, 1H), 4.98 (dd, *J* = 7.3; 5.0 Hz, 1H), 2.65 (d, *J* = 7.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.5, 155.2, 136.3, 134.4, 130.8, 129.1, 128.9, 128.8, 126.9, 126.4, 116.6, 84.0, 68.0. *ee*: 97%, measured by HPLC with chiral column Chiralpak IC (2% 2-propanol/hexane, 0.2 mL/min) t_{major} = 71.77 min, t_{minor} = 48.56 min. $[\alpha]_D^{20}$= -106.2 (*c* 5.8, $CHCl_3$). m.p. 115.3-116.7˚C. IR (KBr): 3420, 3080, 3040, 2920,

1680, 1610, 1480, 1260, 1080, 1040, 750, 690 cm^{-1}. HRMS (ESI) for $C_{17}H_{15}O_3$ $[M+H]^+$: calcd 267.10157, found 267, 10162.

(-)-(*S*)-5-((*R*)-(4-chlorophenyl)(hydroxy)methyl)-4-phenylfuran-2(5*H*)-one (10b)

Overall yield: 30%. White solid. ^1H NMR ($CDCl_3$, 400 MHz) δ: 7.56-7.53 (m, 2H), 7.46-7.41 (m, 3H), 7.35 (d, *J* = 8.7 Hz, 2H), 7.30 (d, *J* = 8.6 Hz, 2H), 6.31 (s, 1H), 5.61 (d, *J* = 5.0 Hz, 1H), 4.95-4.92 (m, 1H), 2.99 (d, *J* = 7.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.4, 155.4, 134.9, 134.8, 134.3, 130.9, 129.2, 129.1, 127.9, 126.9, 116.4, 83.4, 67.9. *ee*: 89%, measured by HPLC with chiral column Chiralpak OD-H (10% 2-propanol/hexane, 1.0 mL/min) t_{major} = 30.89 min, t_{minor} = 63.45 min. $[\alpha]_D^{20}$= -54.5 (*c* 7.4, $CHCl_3$). m.p. 152.2-155.8˚C. IR (KBr): 3420, 3050, 3040, 1680, 1600, 1480, 1280, 1080, 880, 830, 780, 700 cm^{-1}. HRMS (ESI) for $C_{17}H_{14}O_3Cl$ $[M+H]^+$: calcd 301.06260, found 301.06131.

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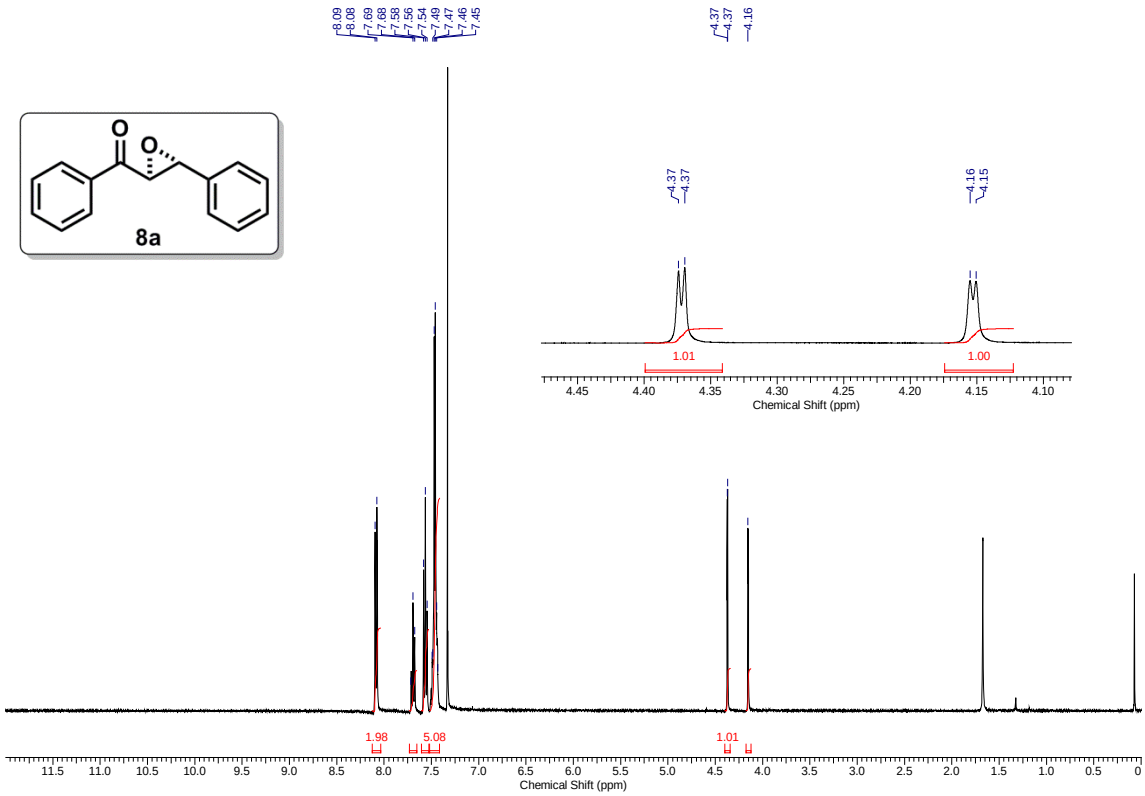
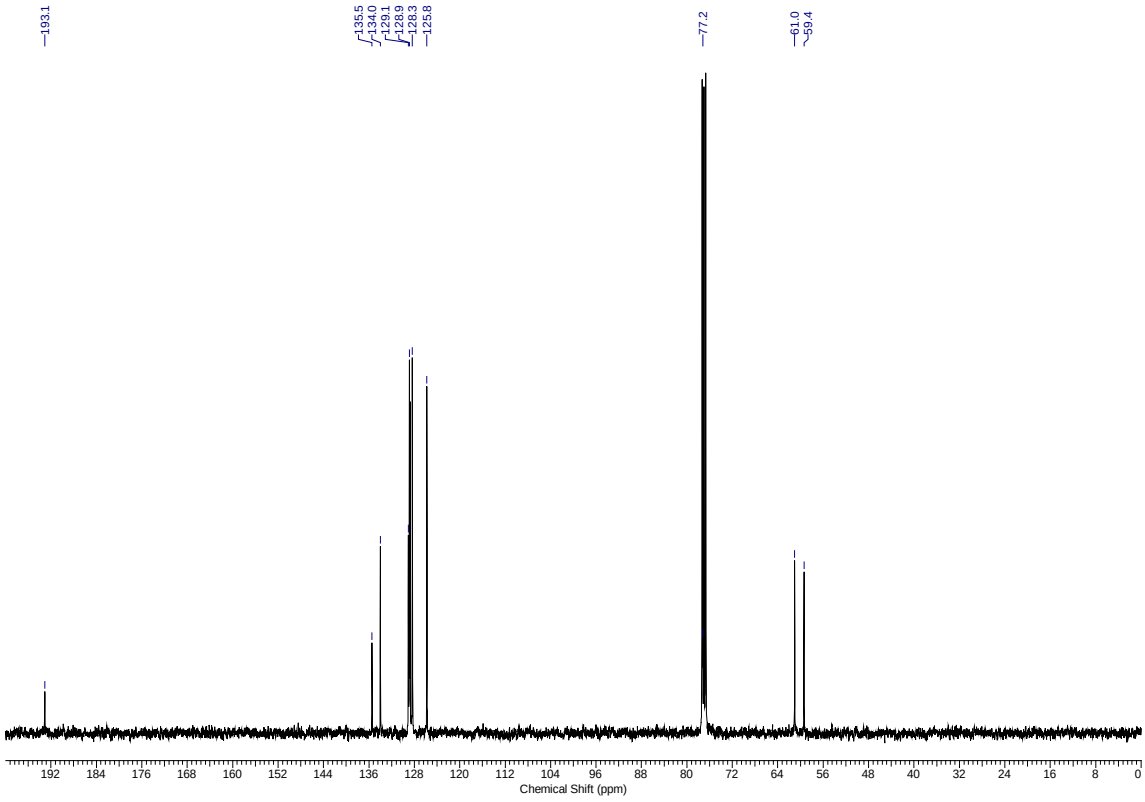
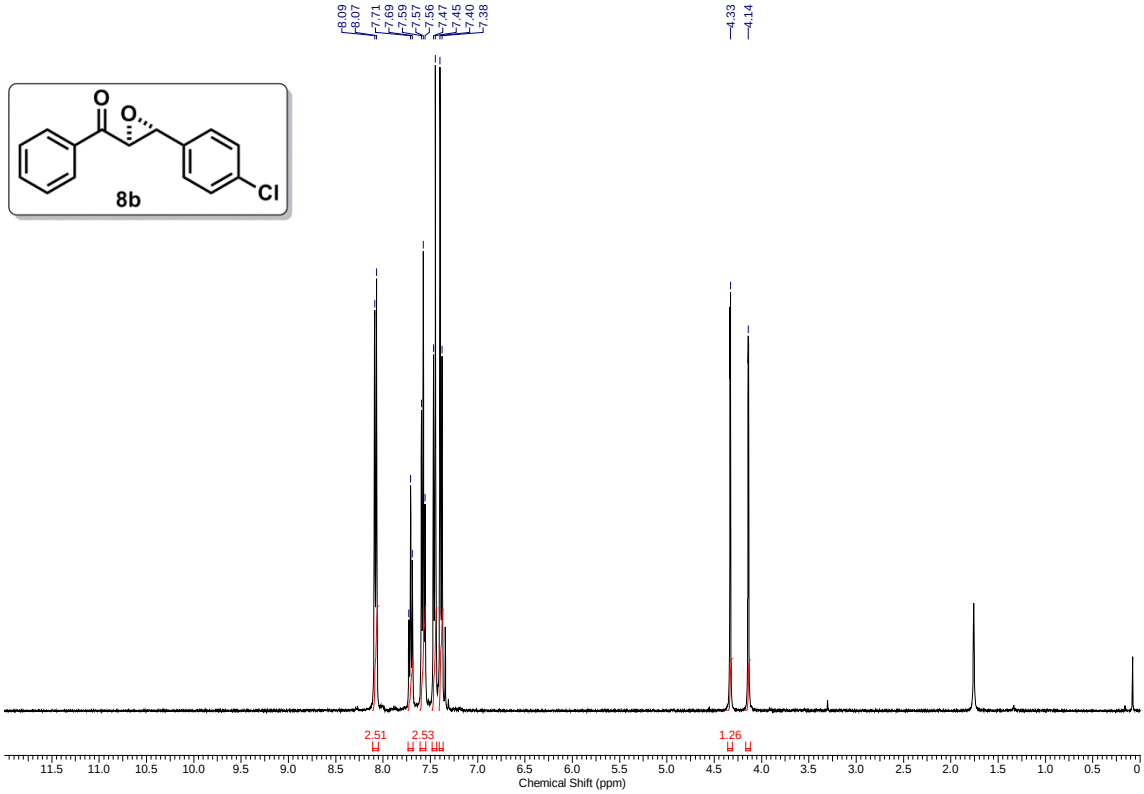


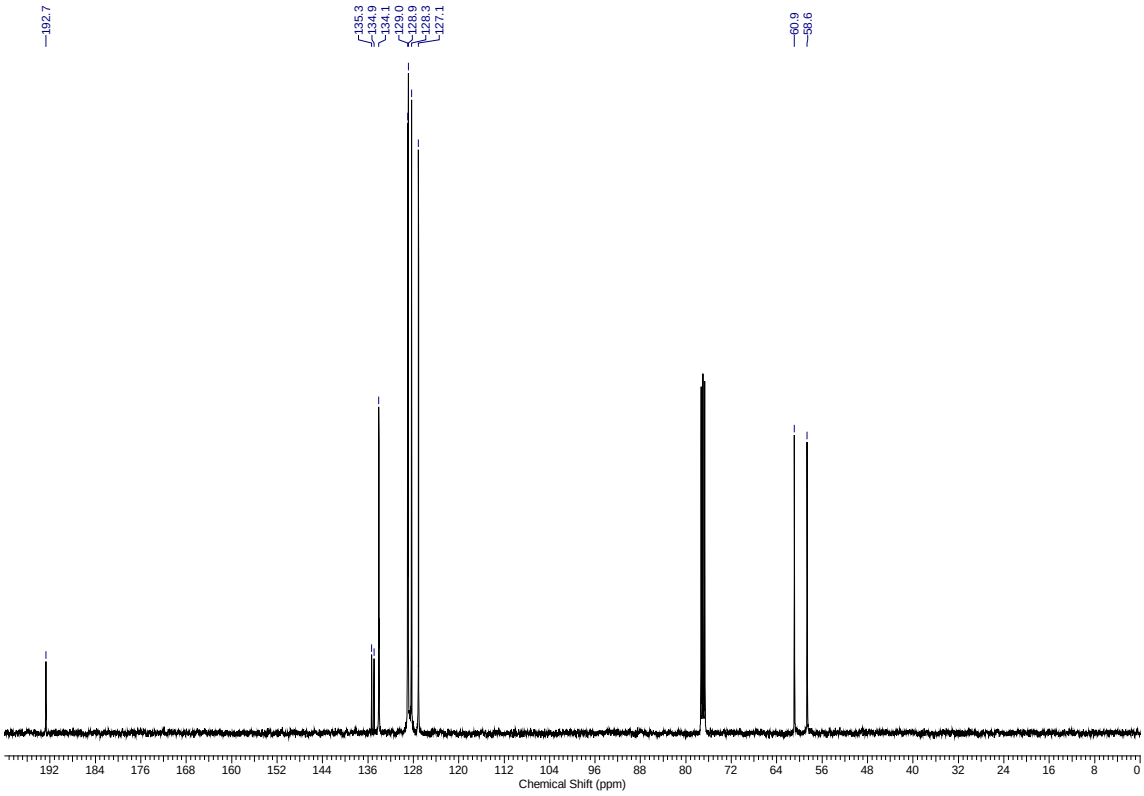
^{1}H NMR of compound **8a**



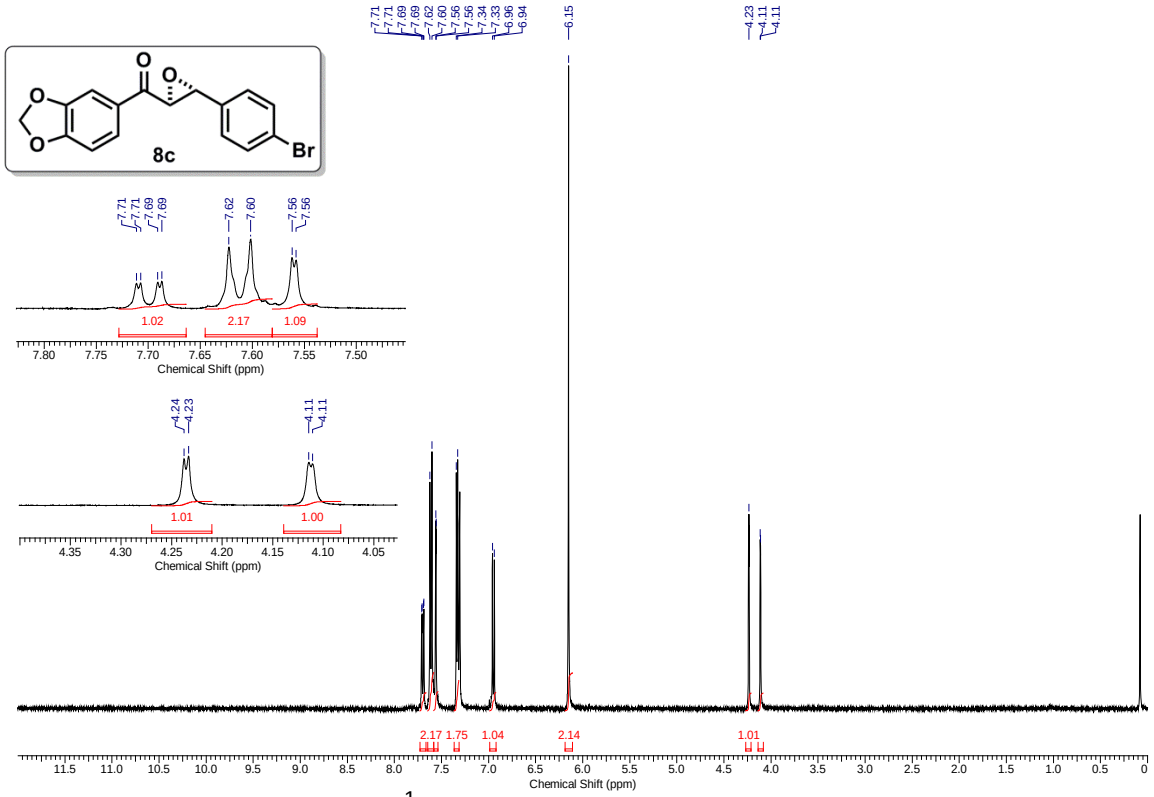
^{13}C NMR of compound **8a**



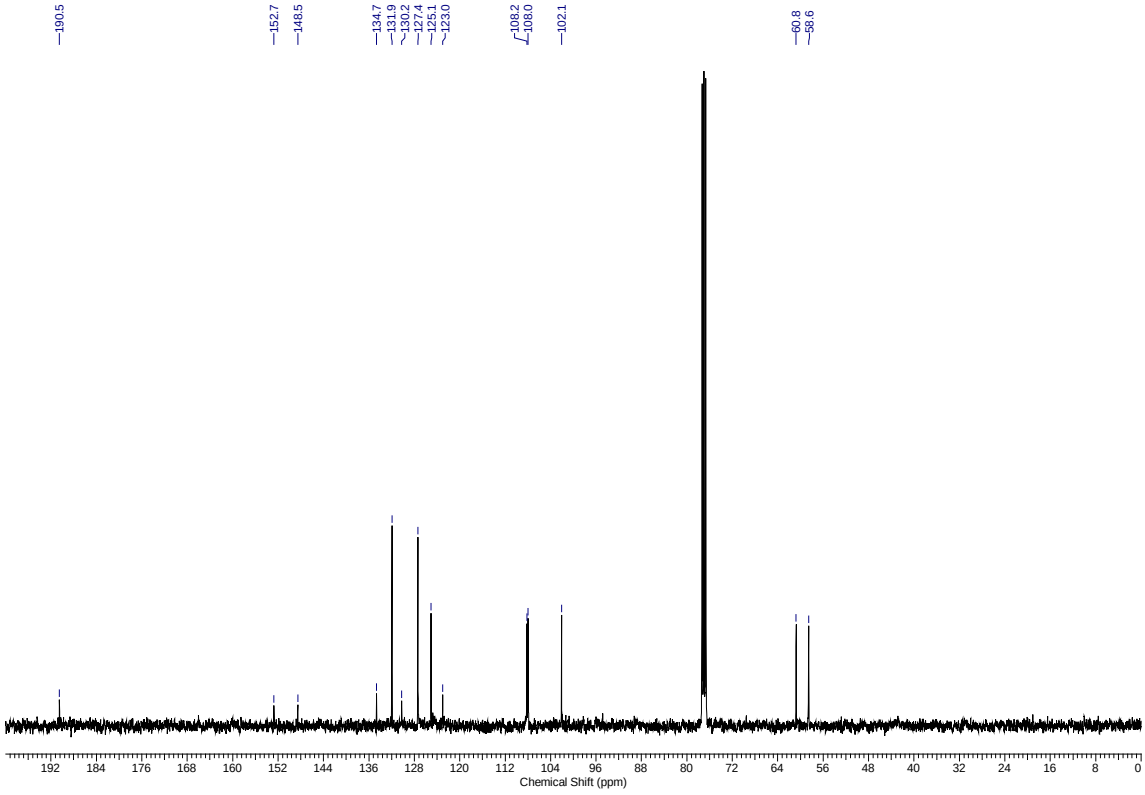
^{1}H NMR of compound **8b**



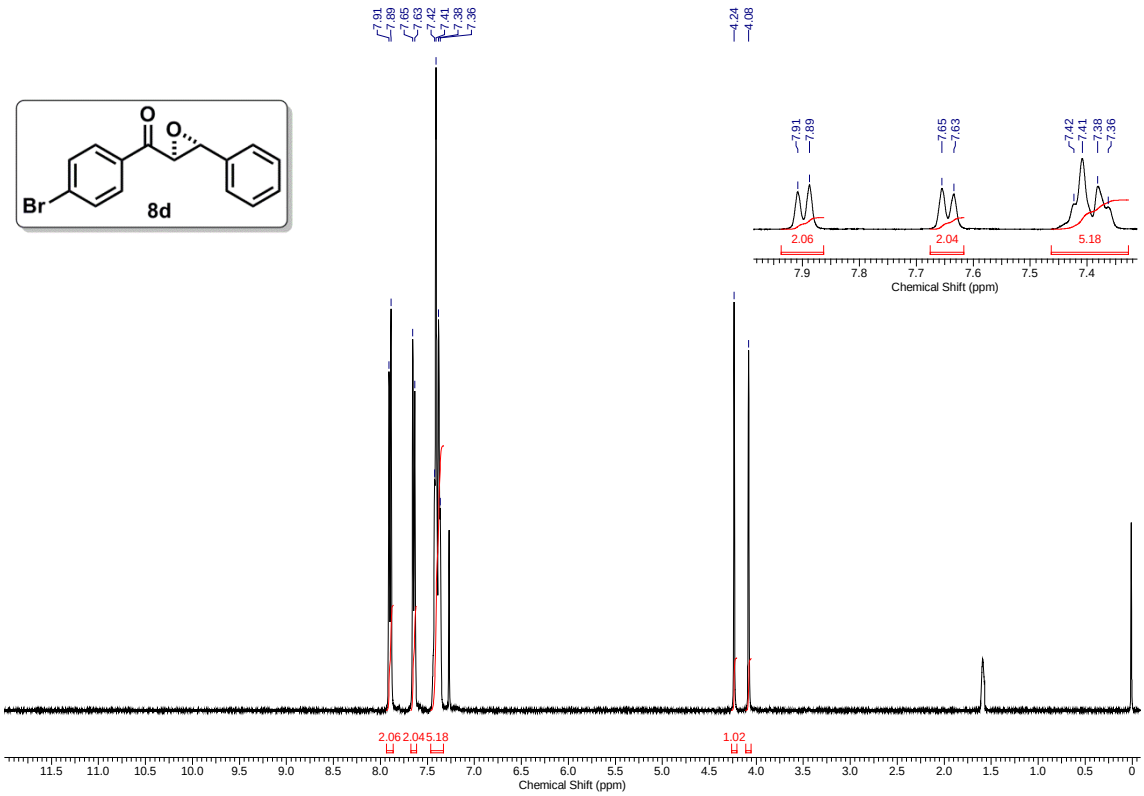
^{13}C NMR of compound **8b**



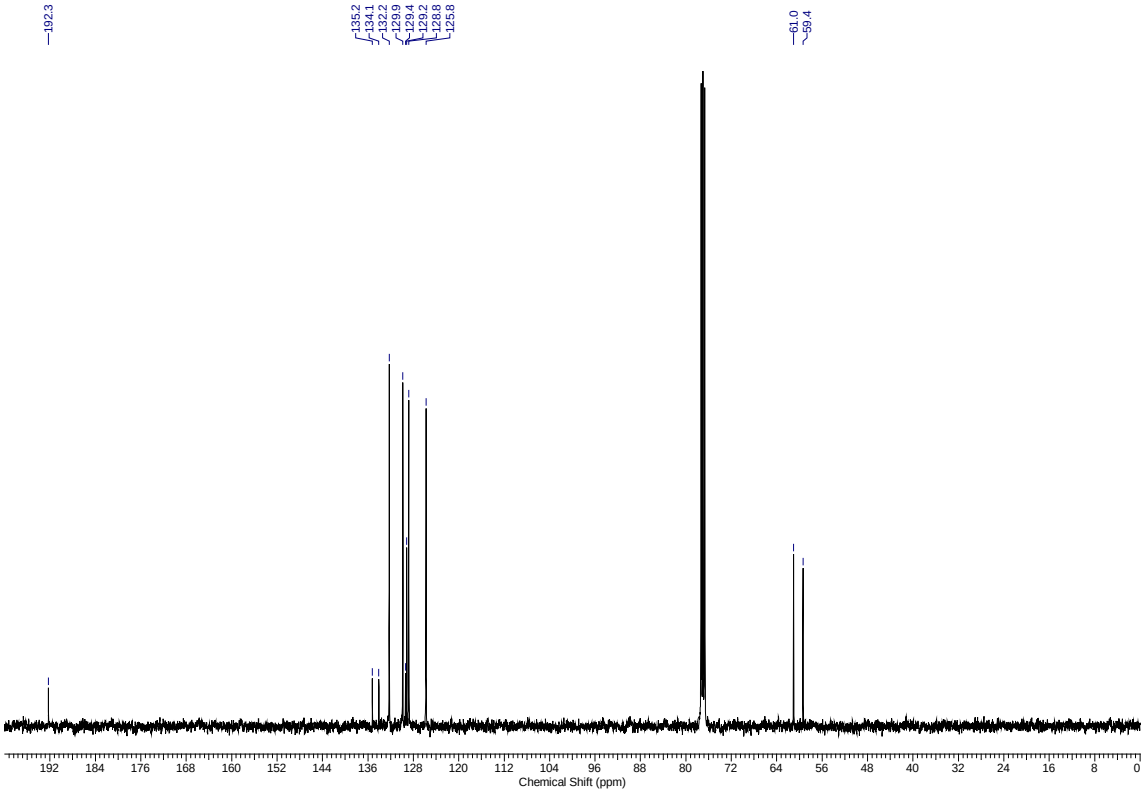
^{1}H NMR of compound **8c**



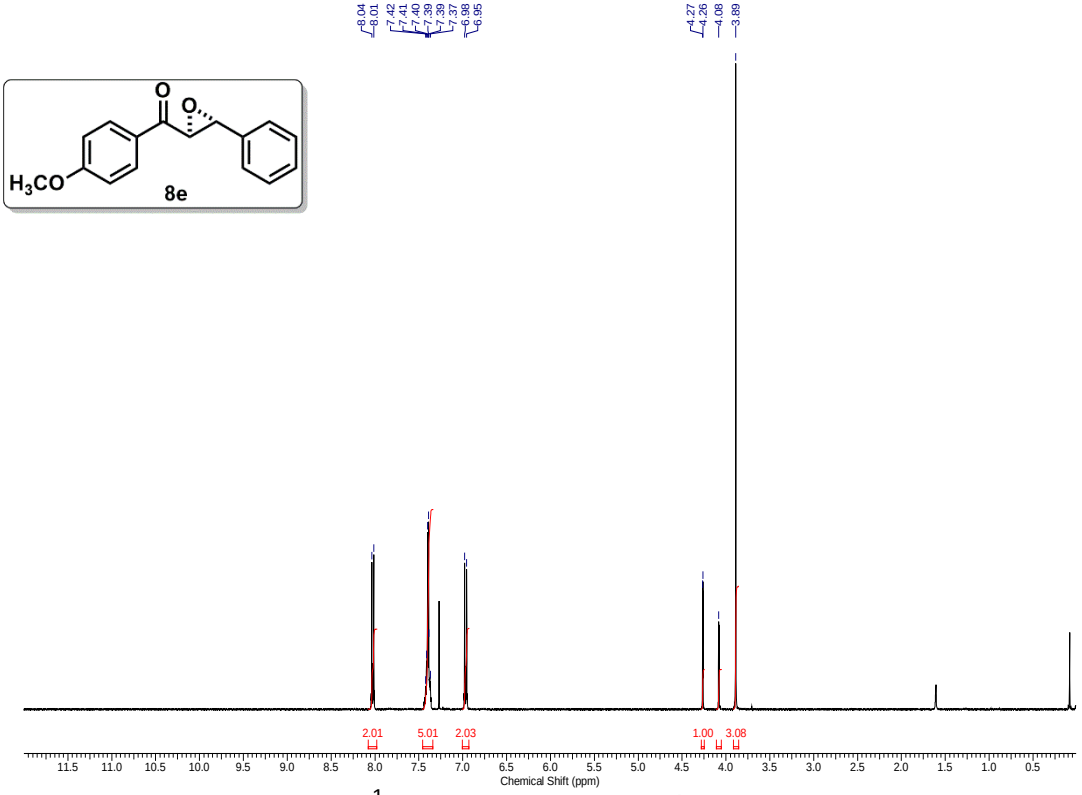
^{13}C NMR of compound **8c**



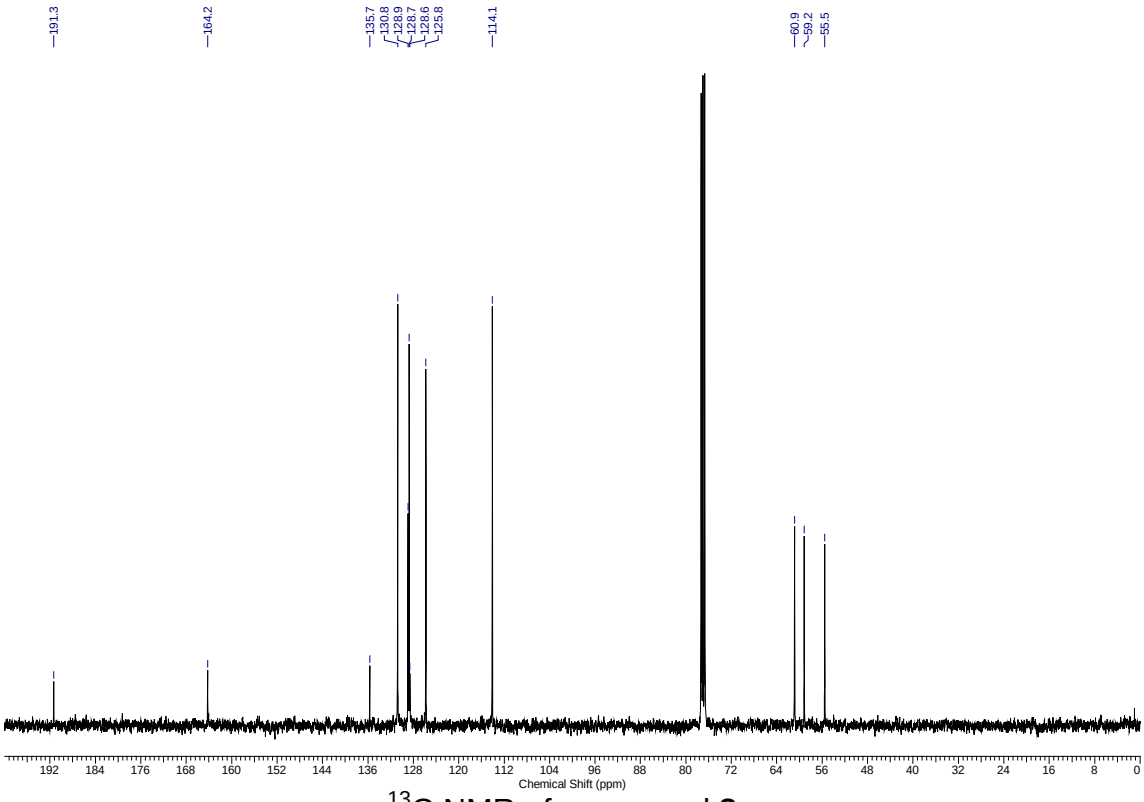
^{1}H NMR of compound **8d**



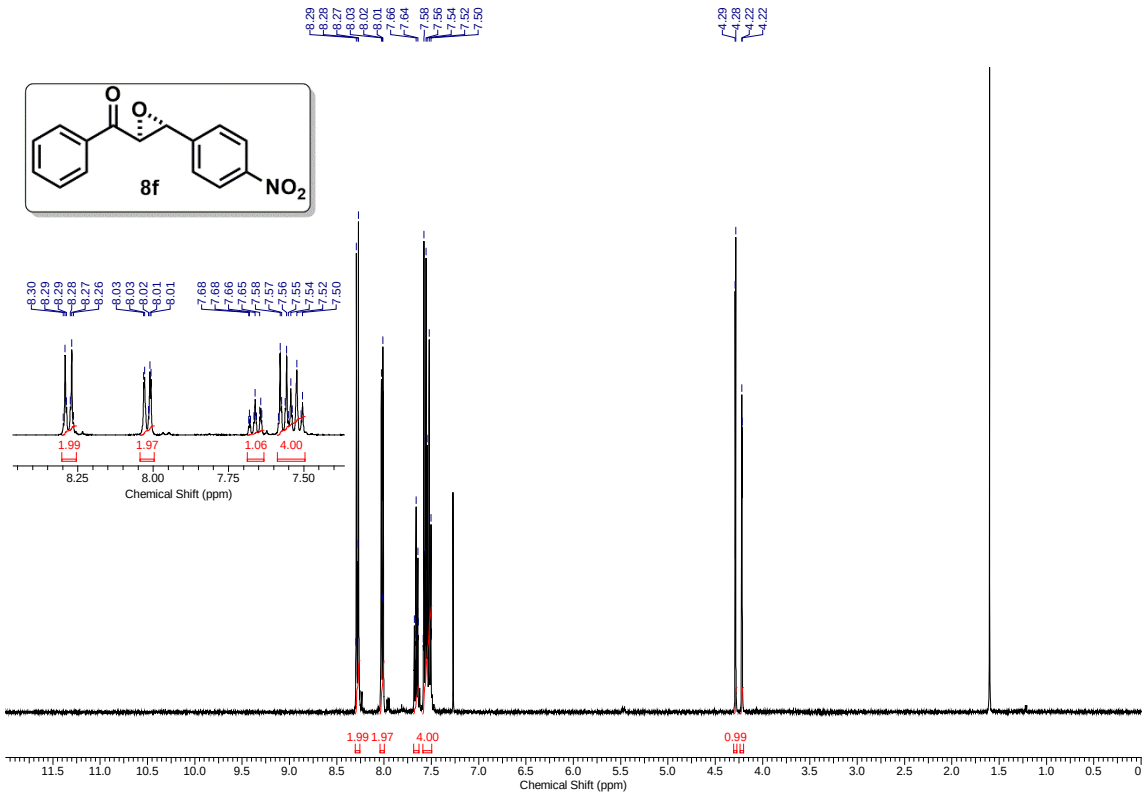
^{13}C NMR of compound **8d**



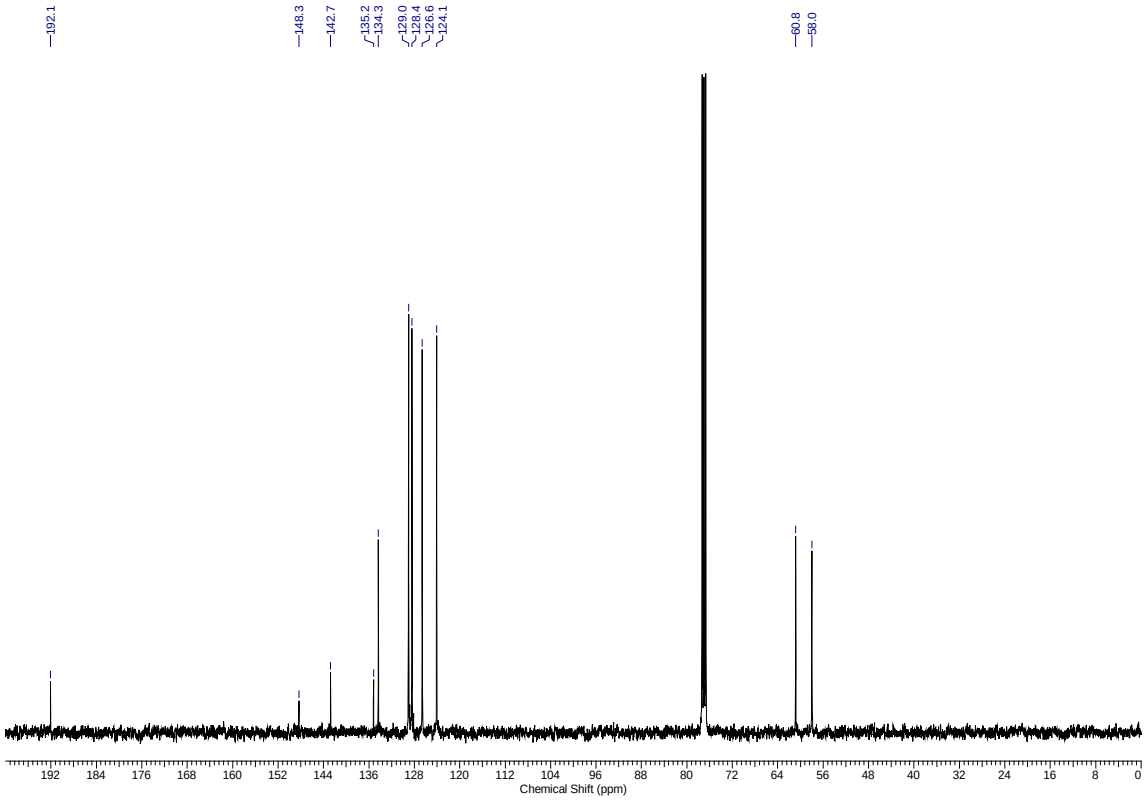
^{1}H NMR of compound **8e**



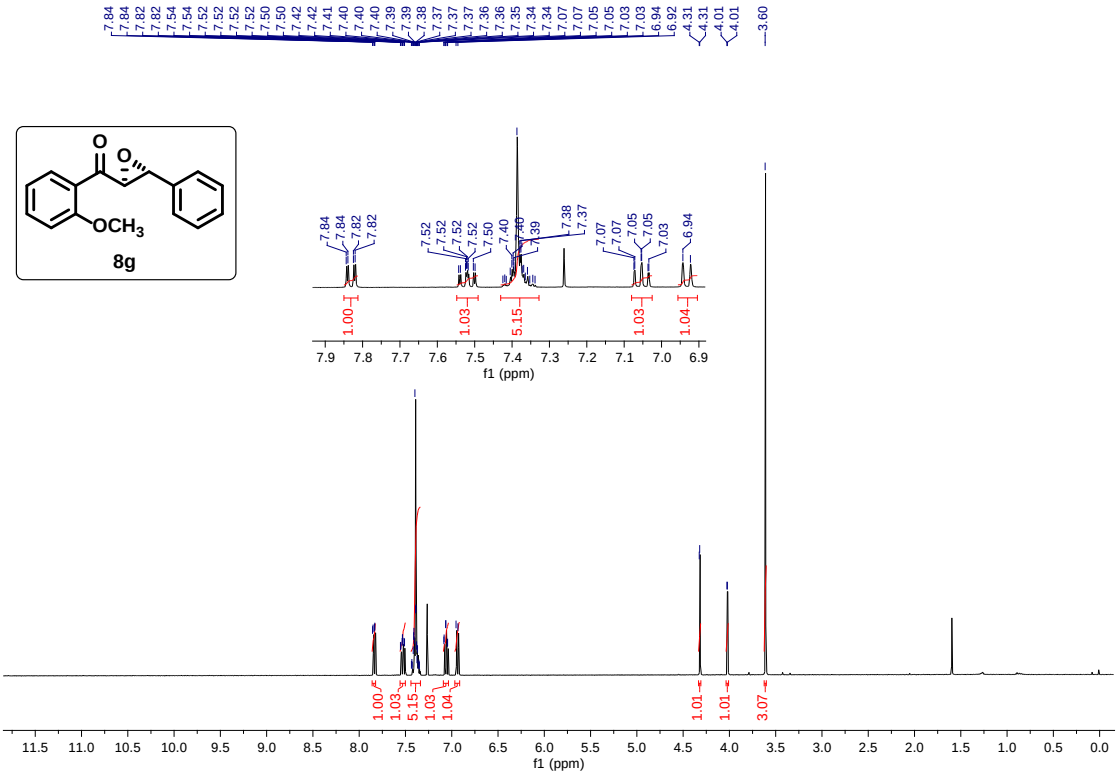
^{13}C NMR of compound **8e**



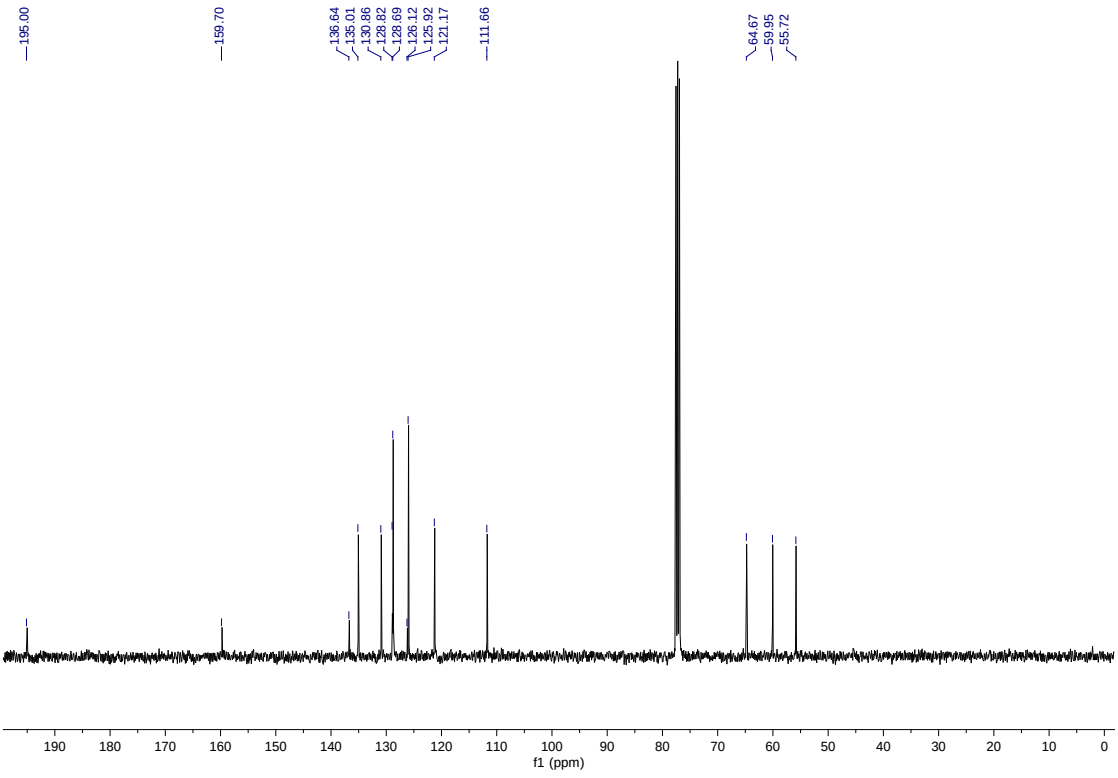
^{1}H NMR of compound **8f**



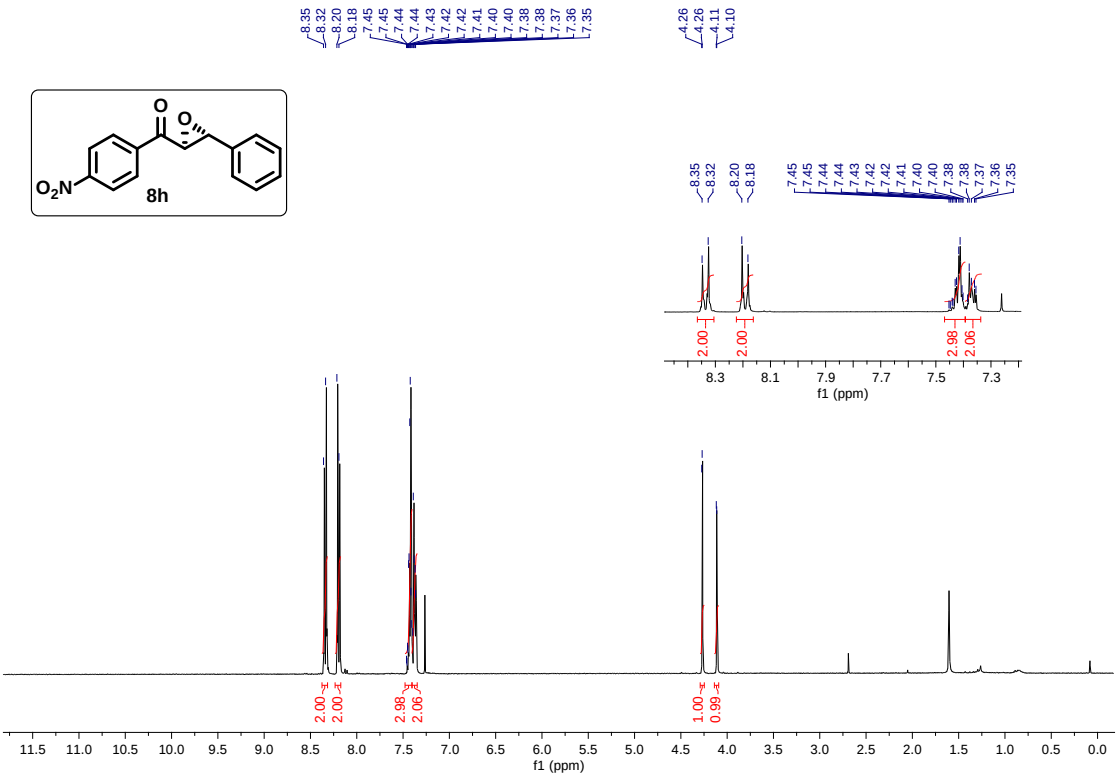
^{13}C NMR of compound **8f**



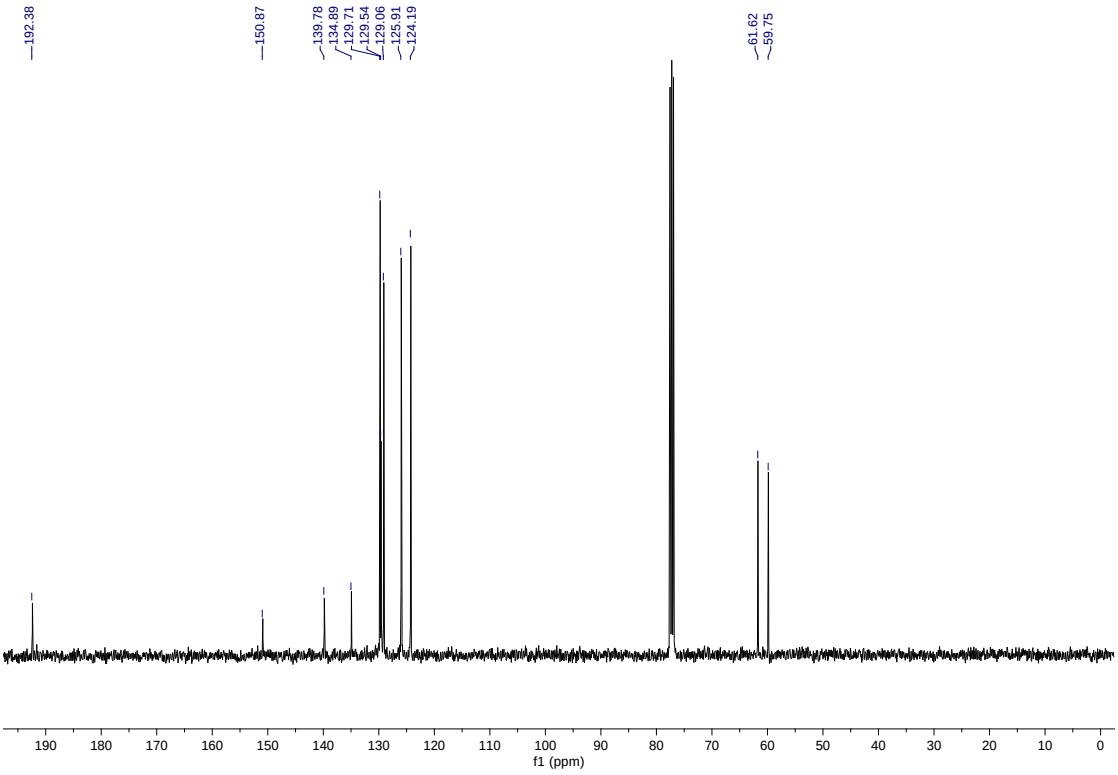
^{1}H NMR of compound **8g**



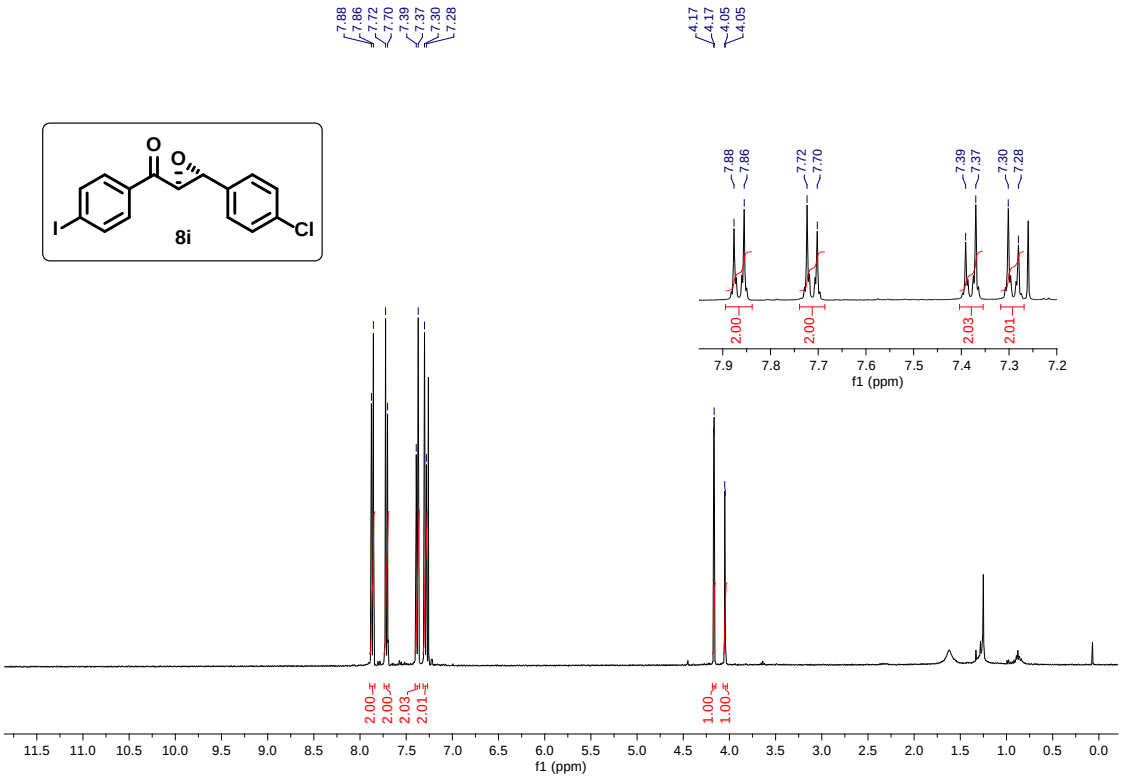
^{13}C NMR of compound **8g**



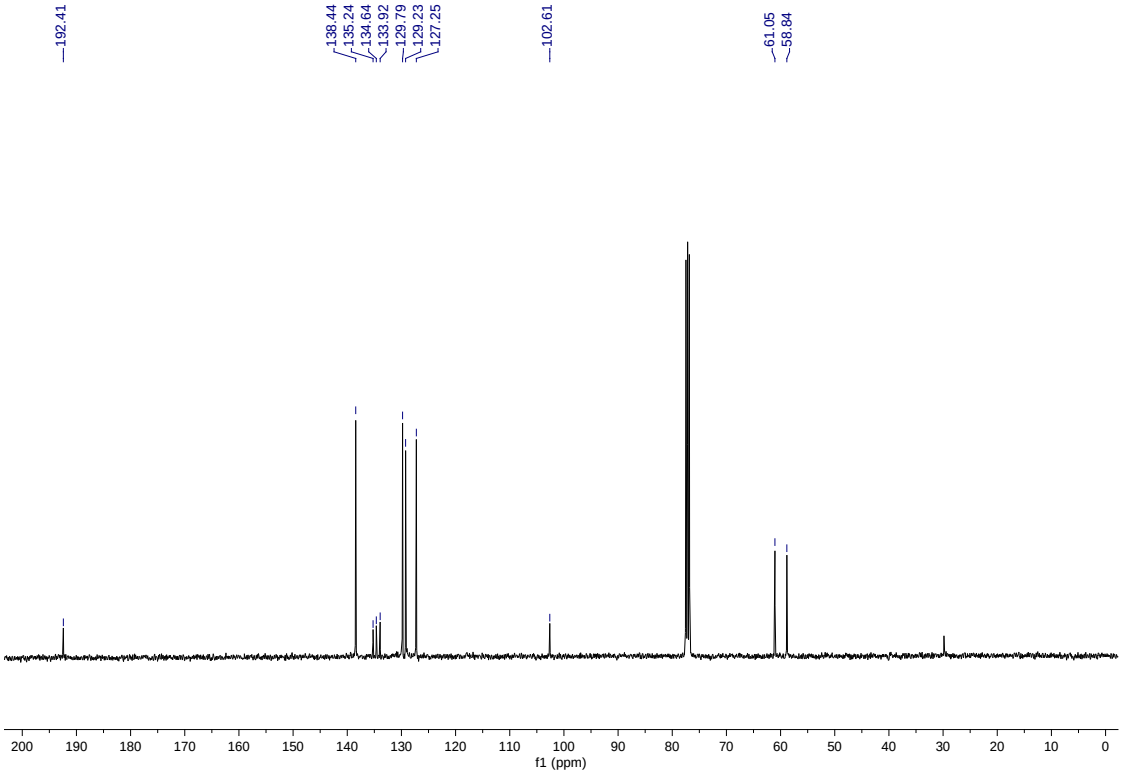
^{1}H NMR of compound **8h**



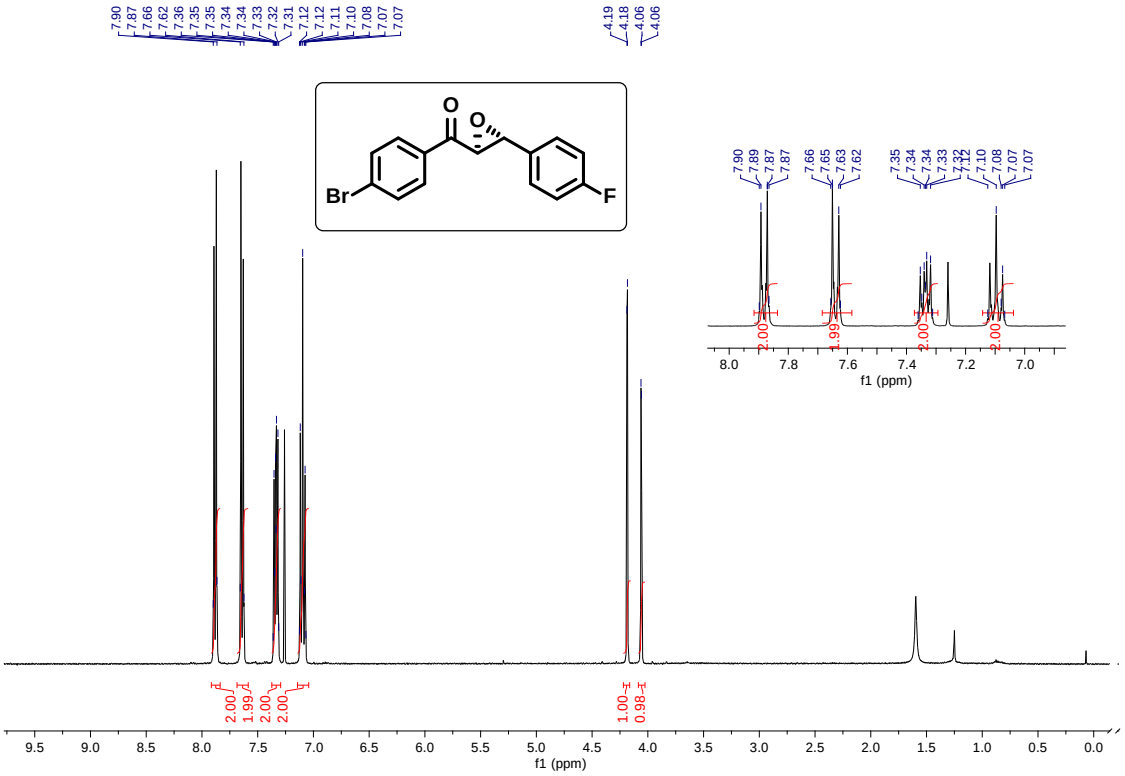
^{13}C NMR of compound **8h**



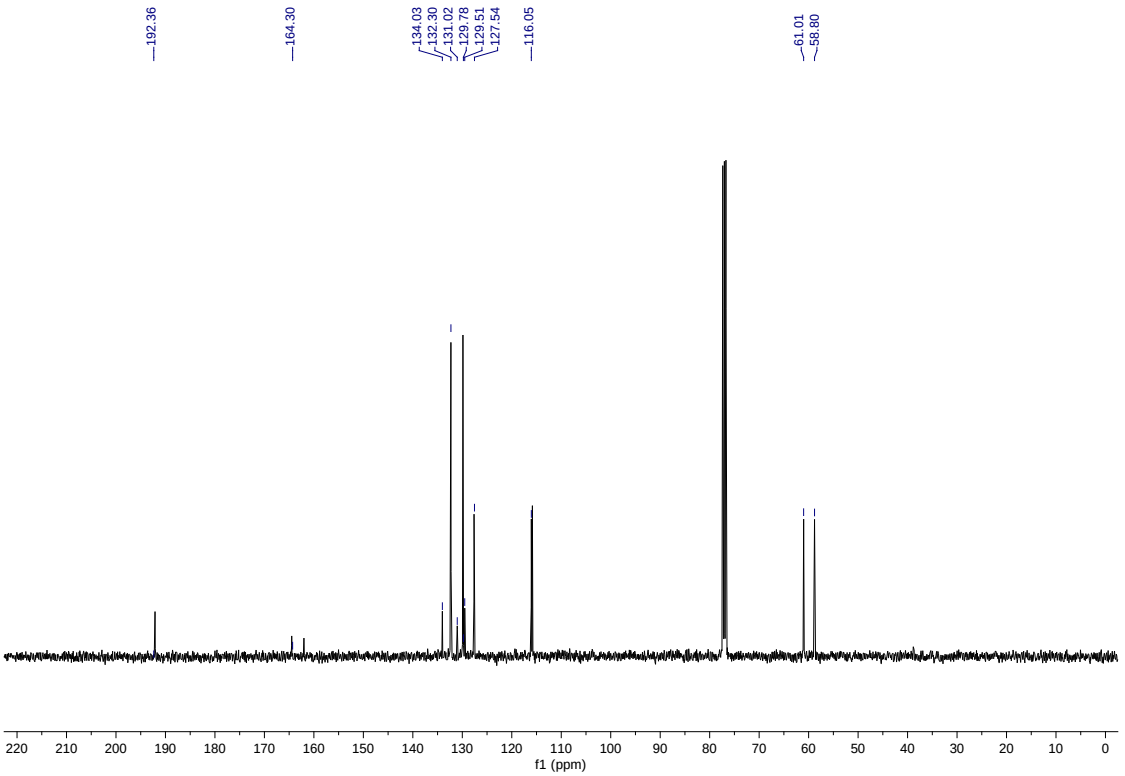
^{1}H NMR of compound **8i**



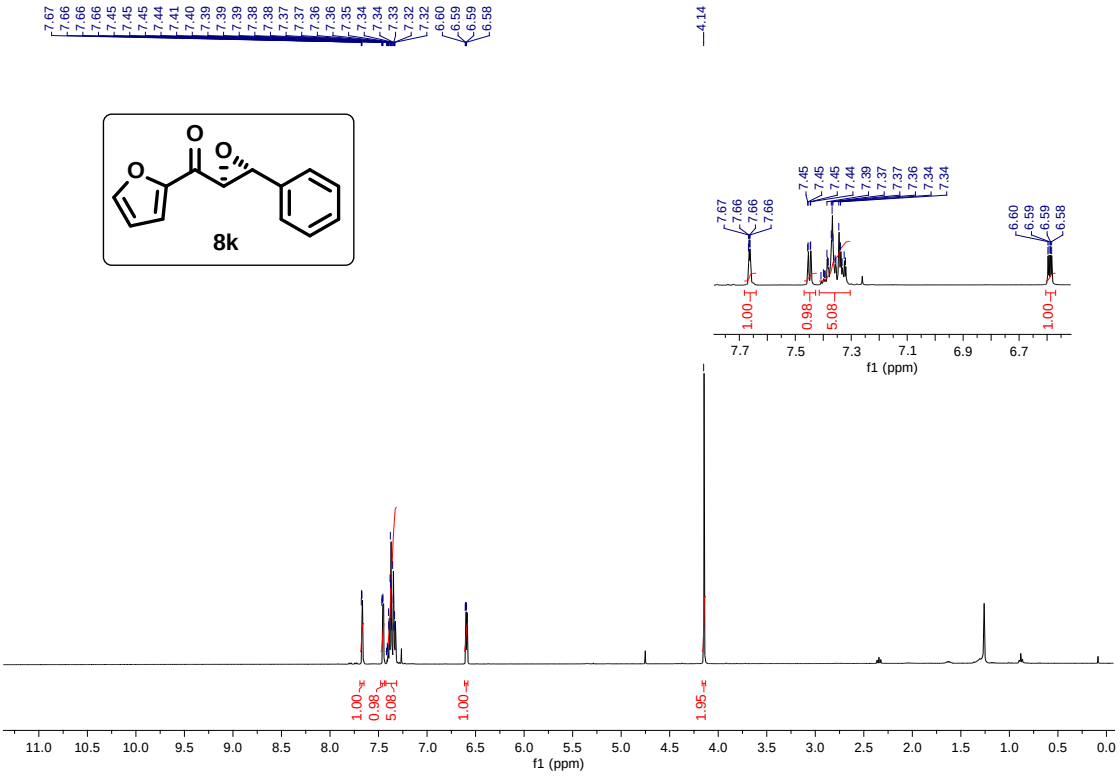
^{13}C NMR of compound **8i**



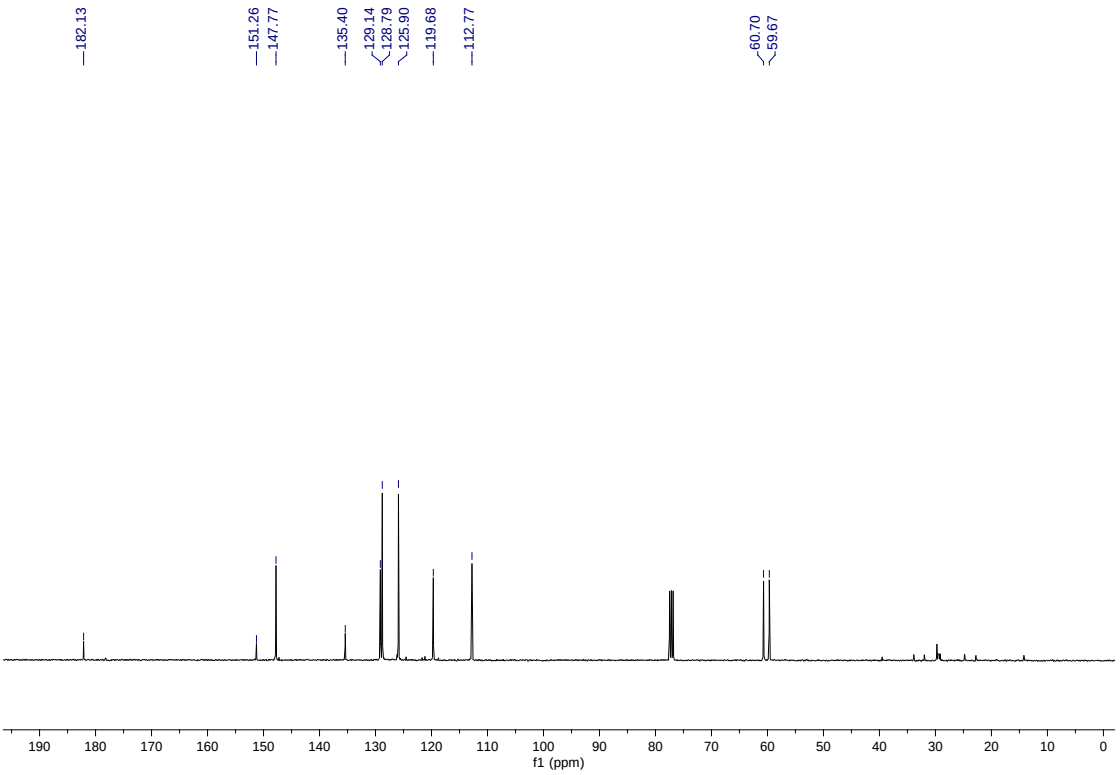
^{1}H NMR of compound **8j**



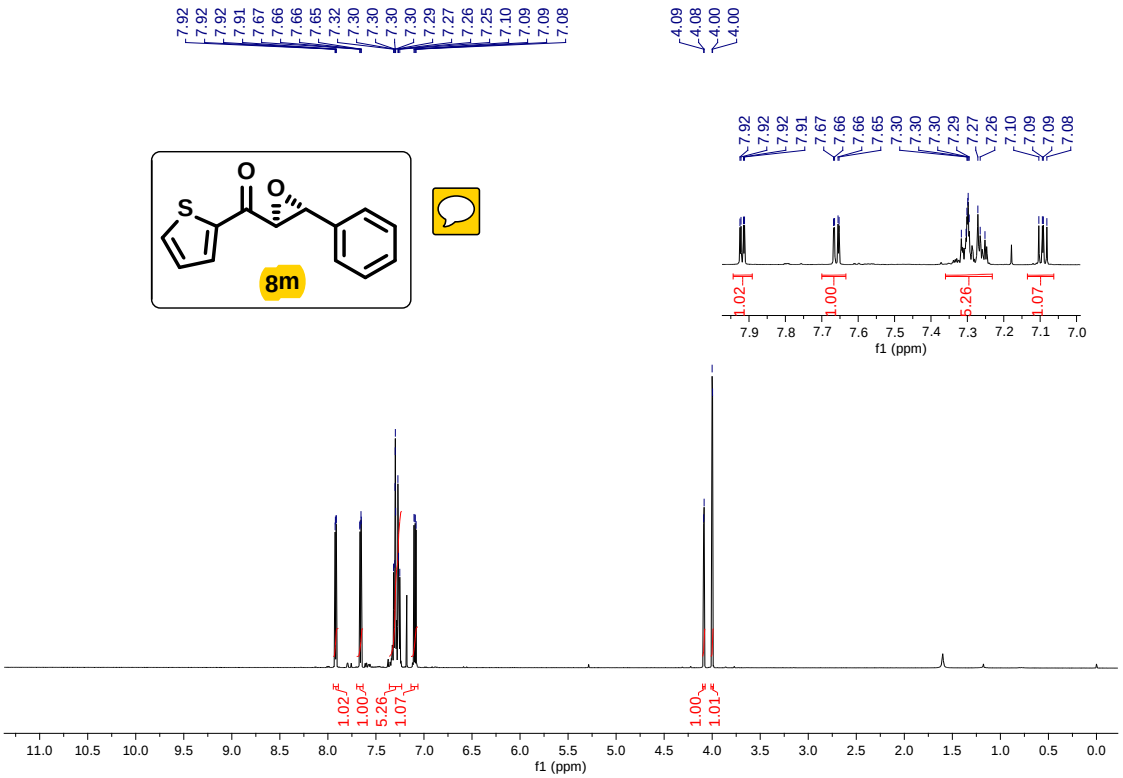
^{13}C NMR of compound **8j**



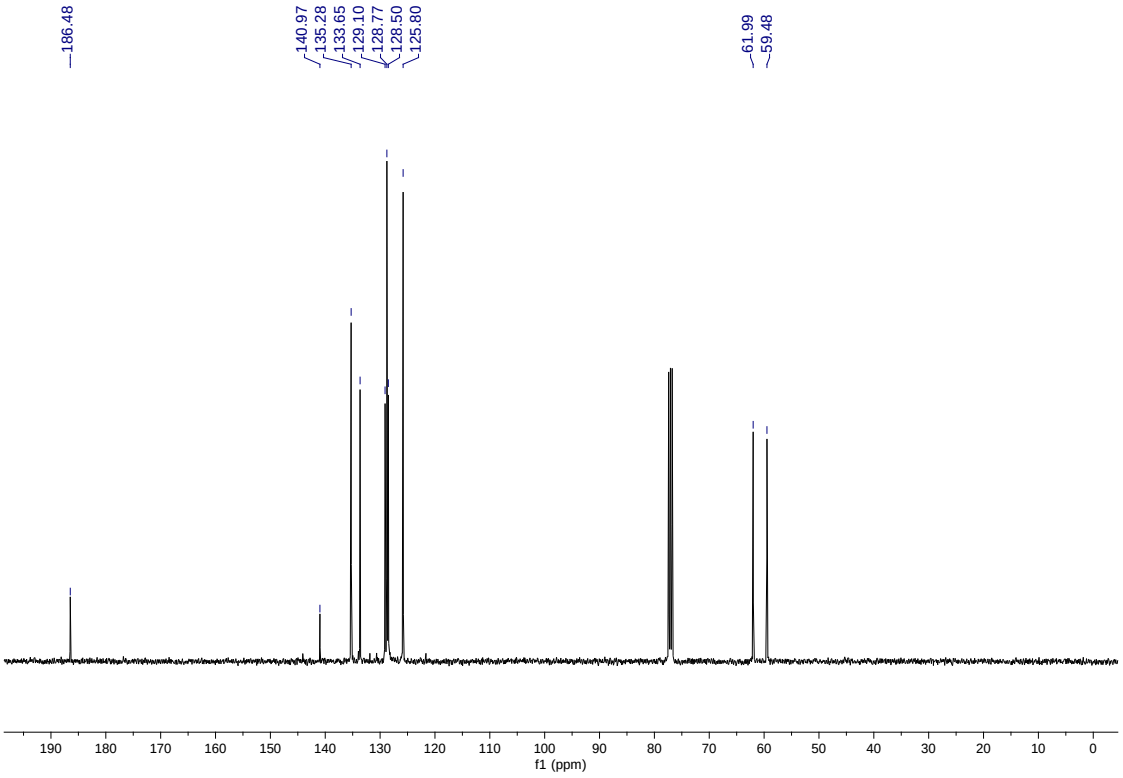
^{1}H NMR of compound **8k**



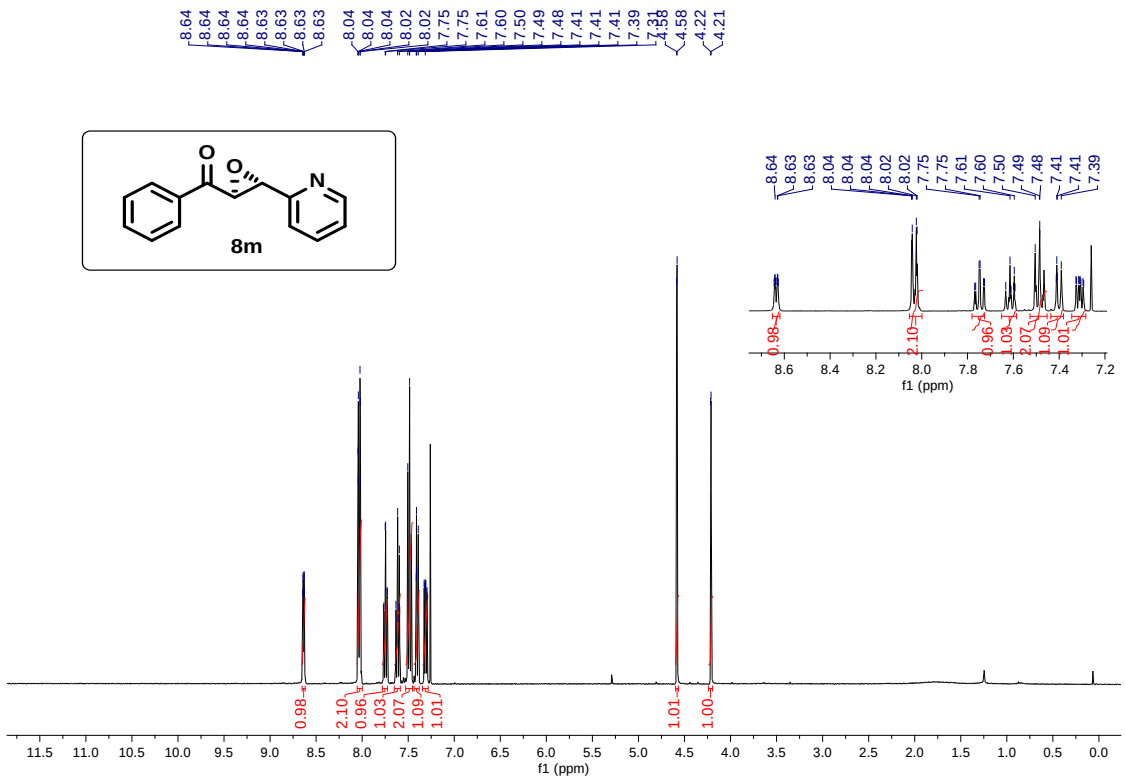
^{13}C NMR of compound **8k**



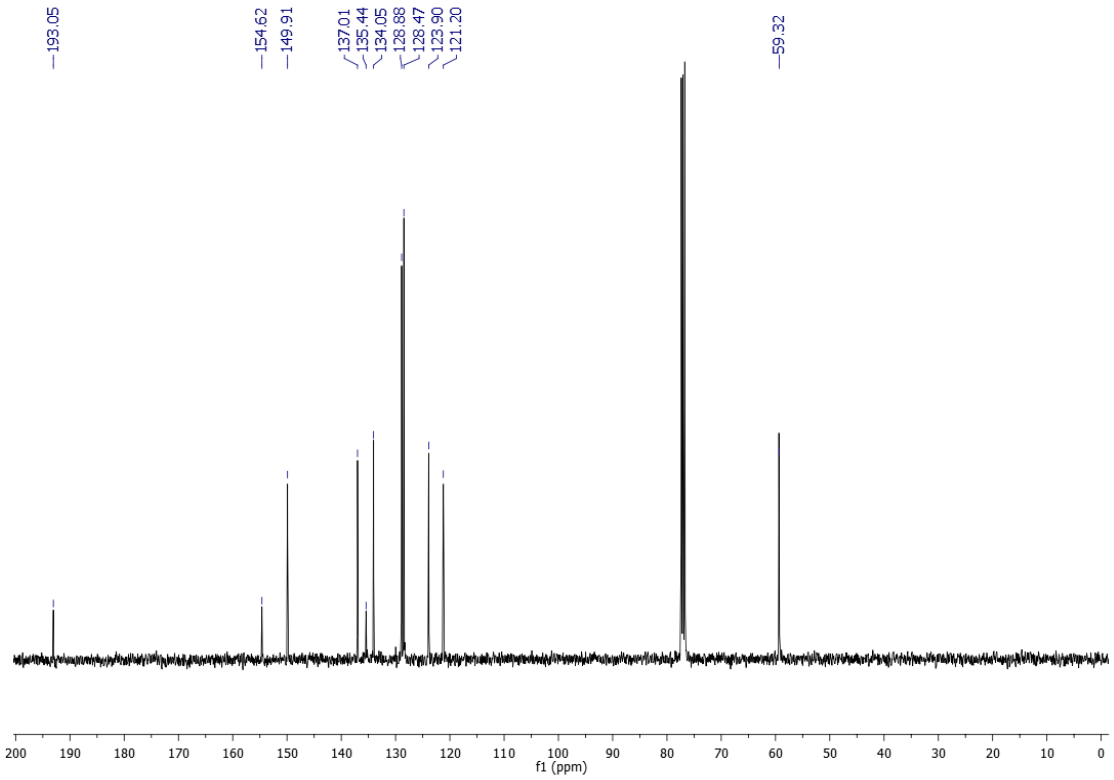
^{1}H NMR of compound **8l**



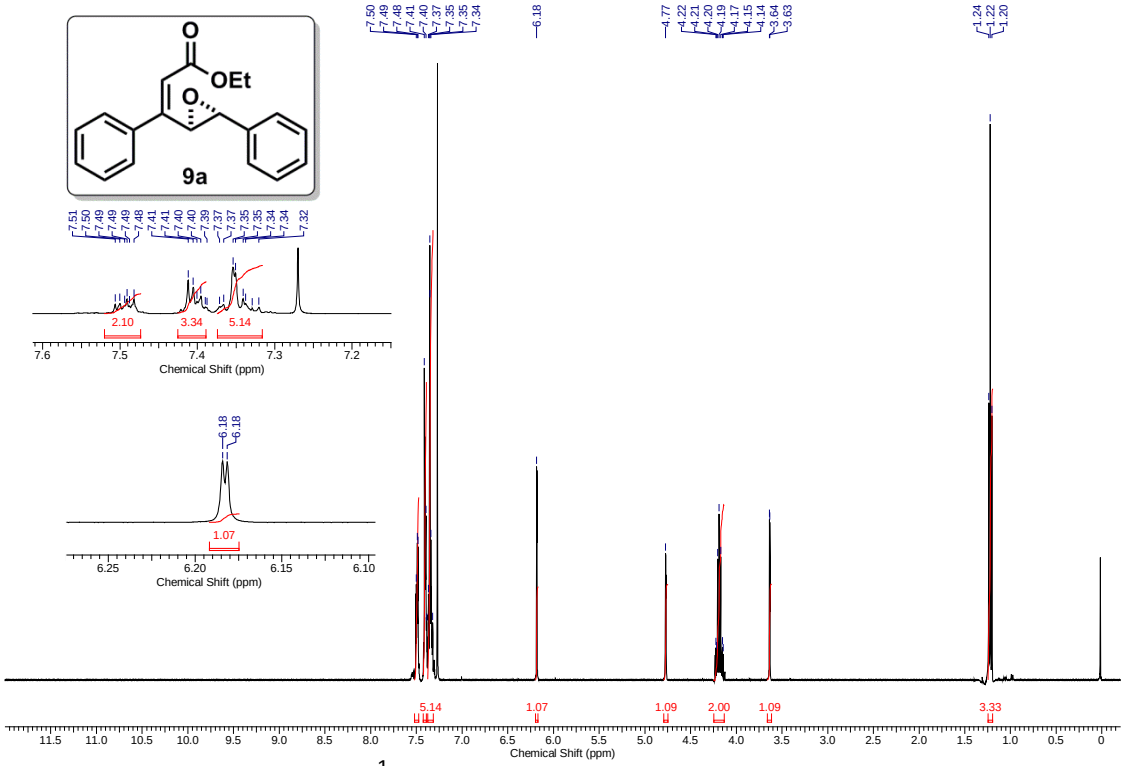
^{13}C NMR of compound **8l**



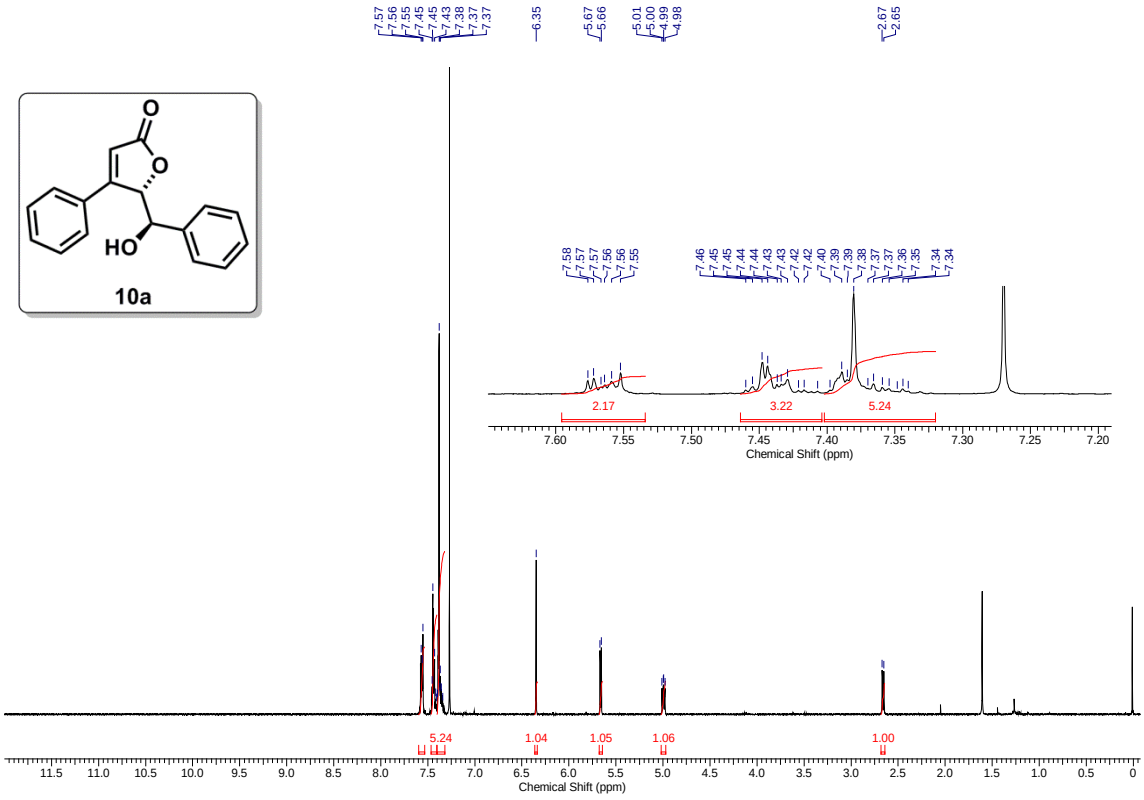
^{1}H NMR of compound **8m**



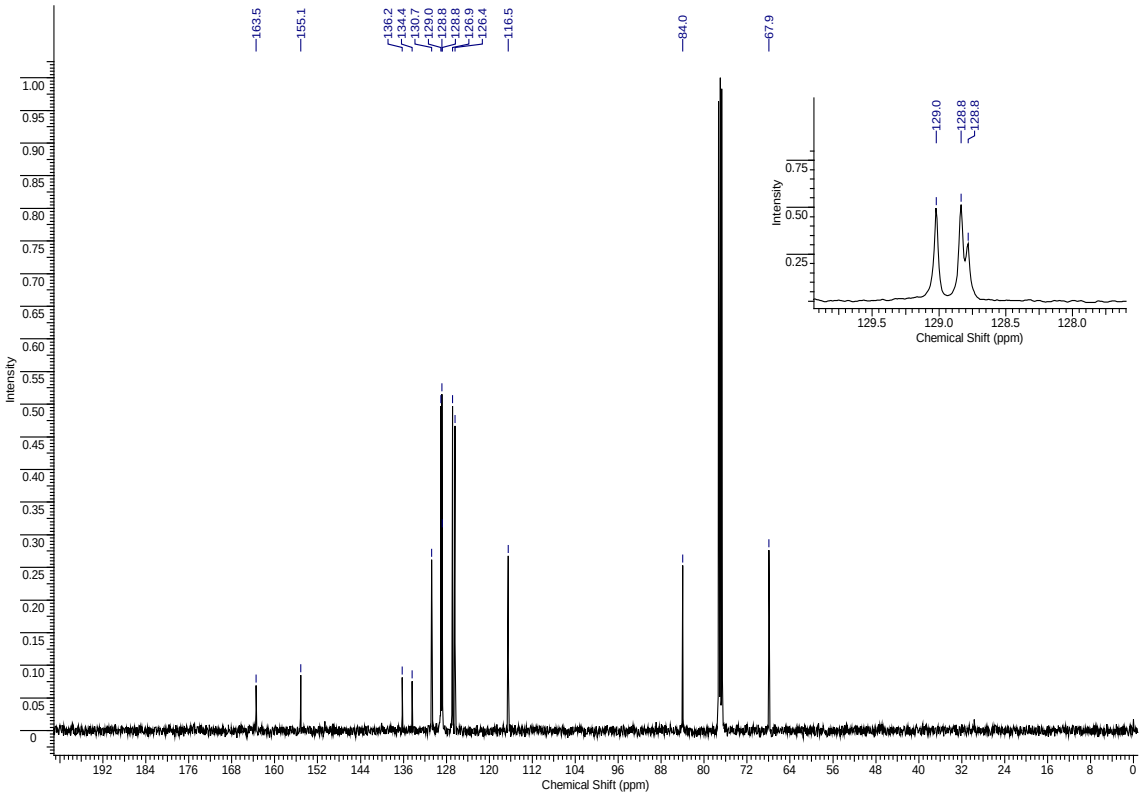
^{13}C NMR of compound **8m**



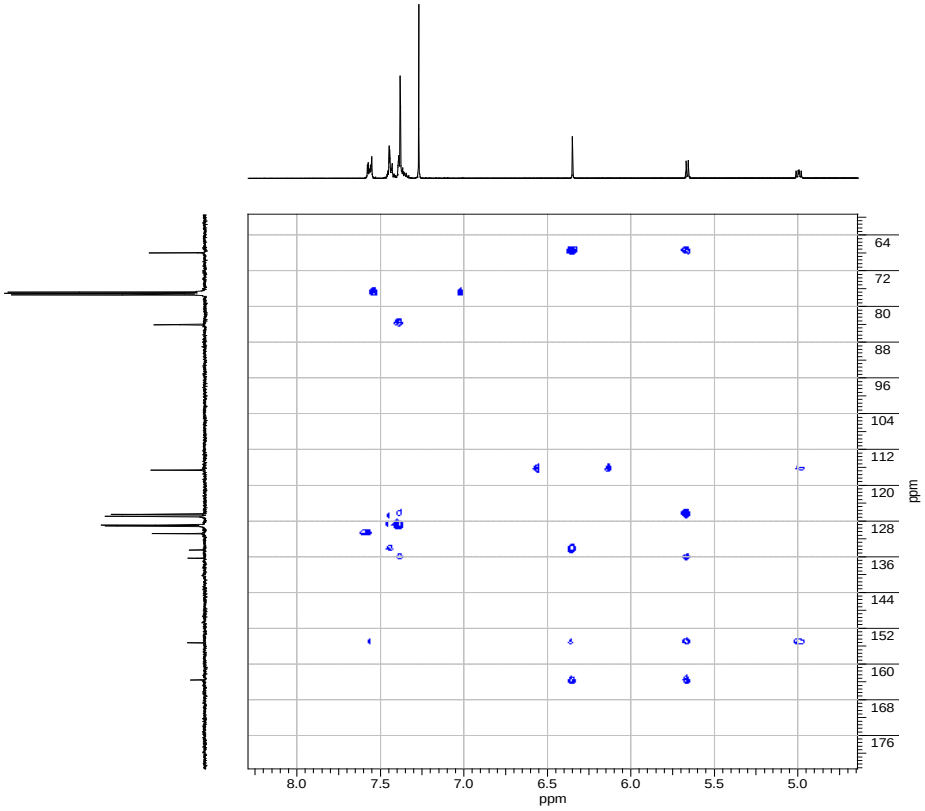
^{1}H NMR of compound **9a**



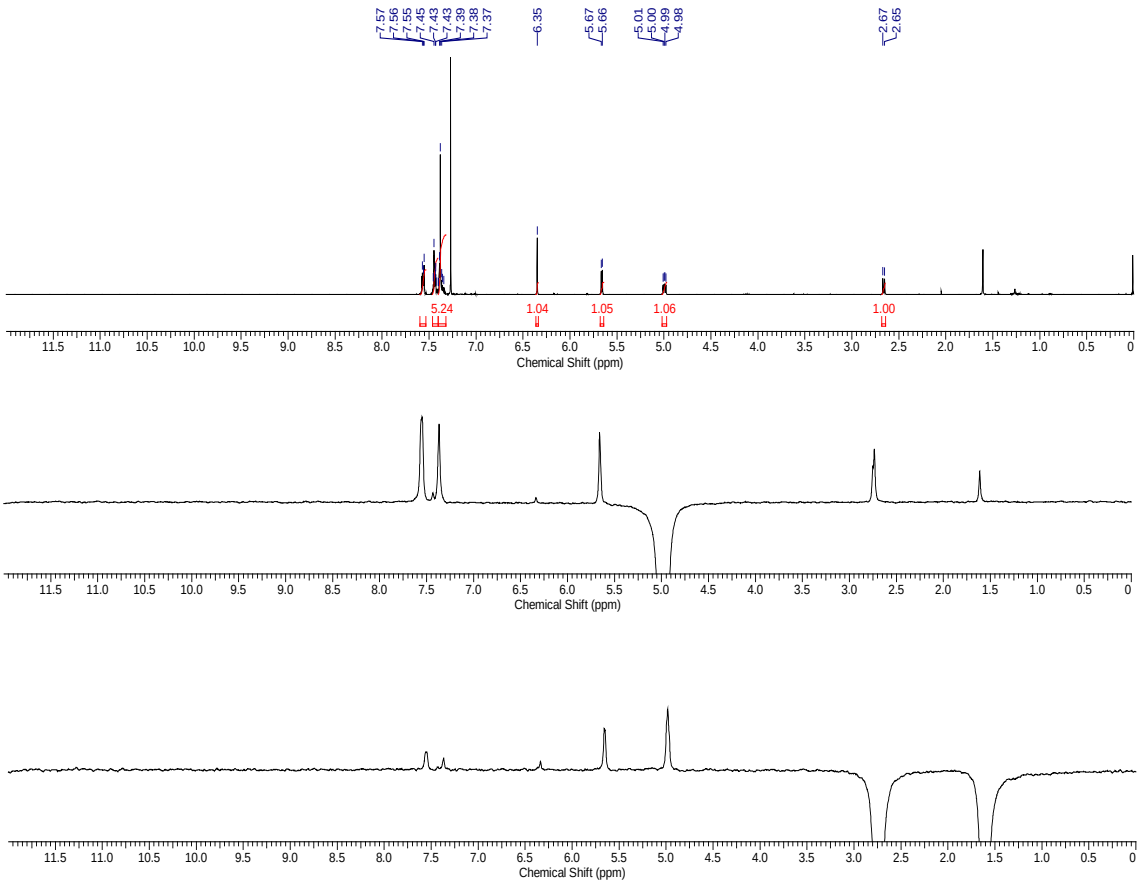
^{1}H NMR of compound **10a**



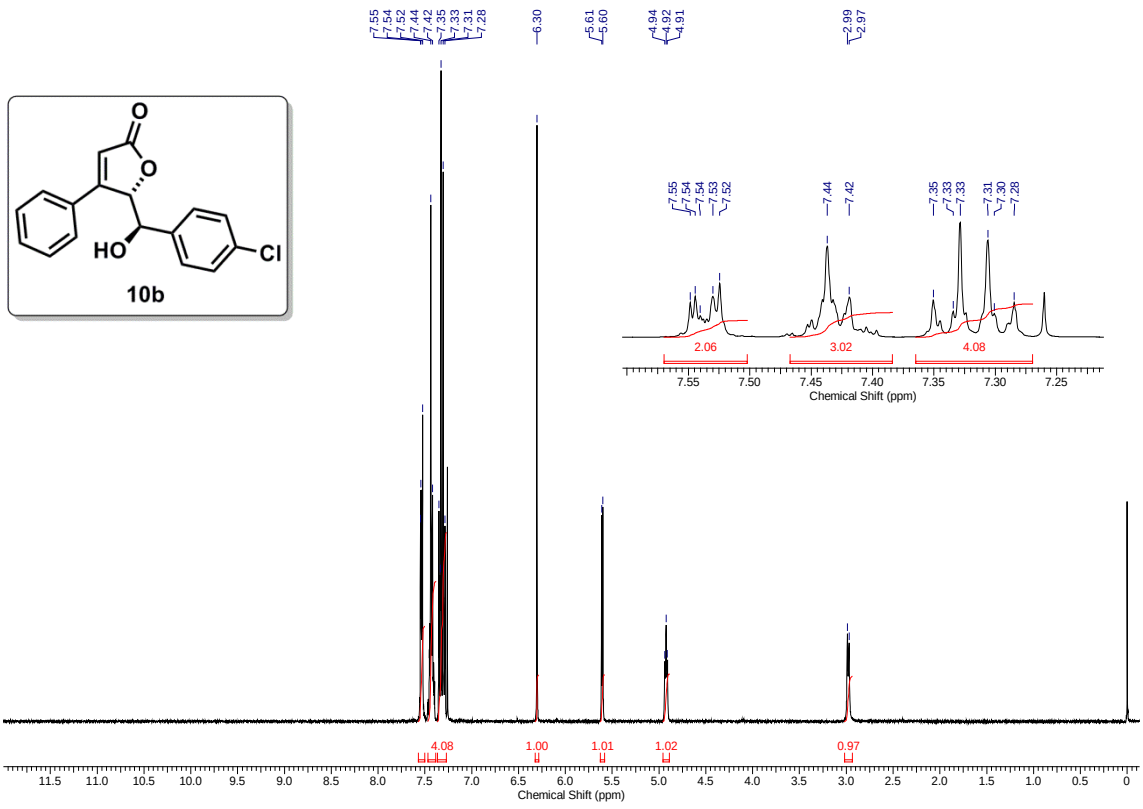
^{13}C NMR of compound **10a**



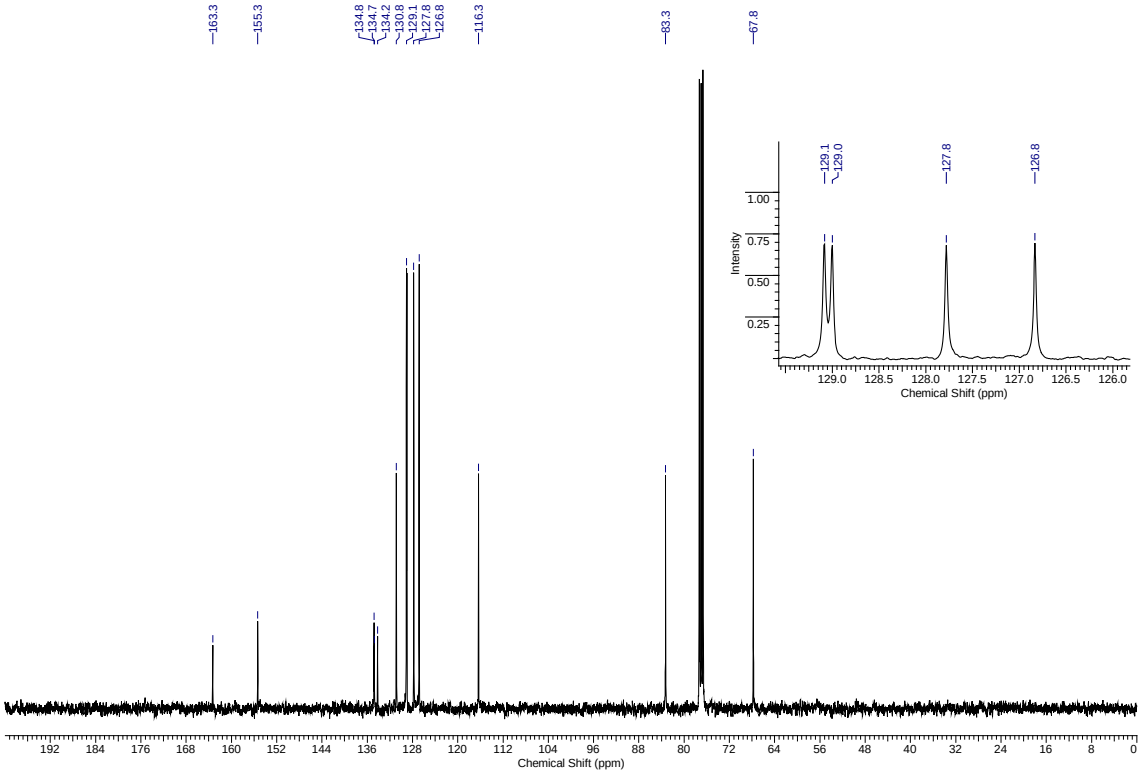
HMBC of compound **10a**



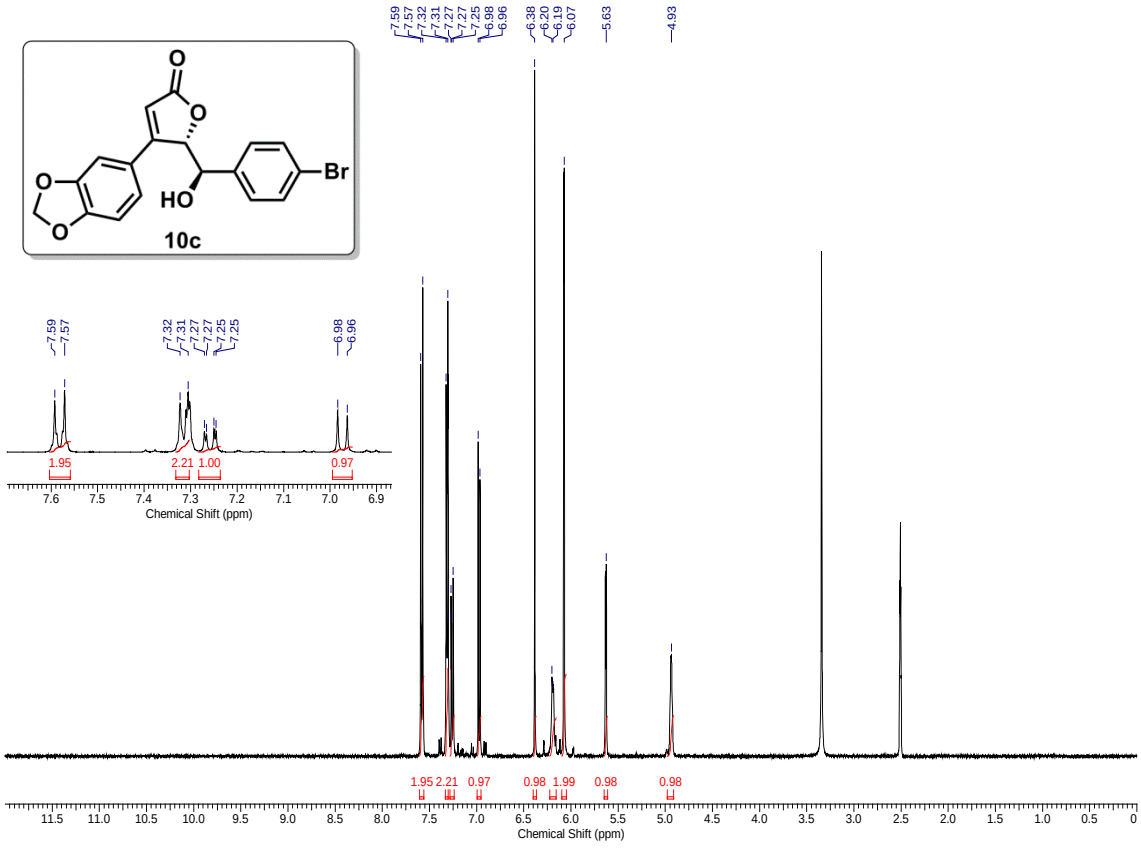
NOESY of compound **10a**



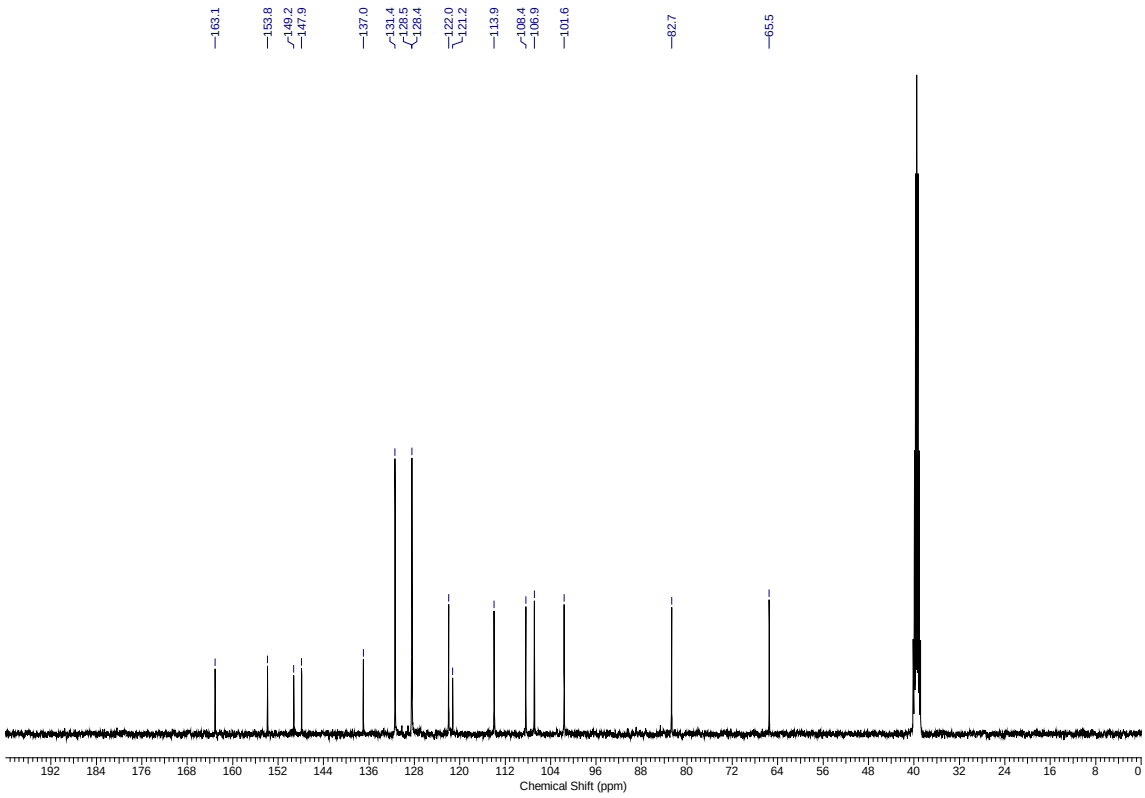
^{1}H NMR of compound **10b**



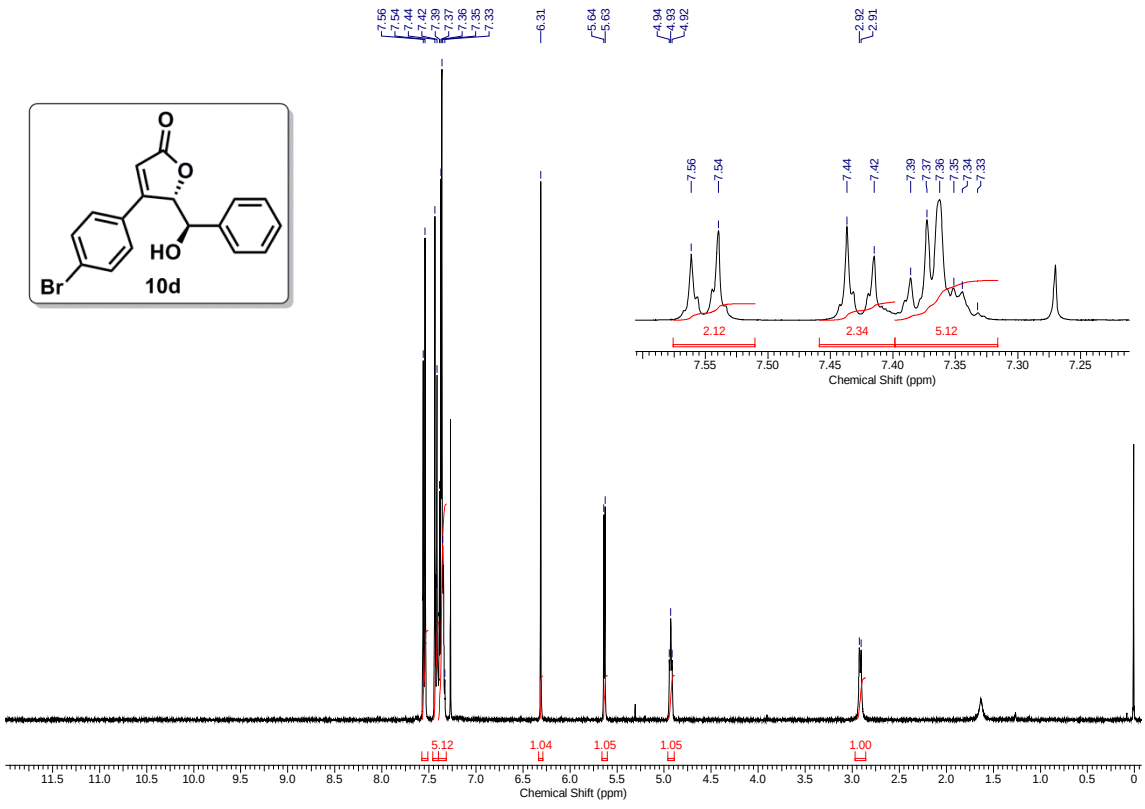
^{13}C NMR of compound **10b**



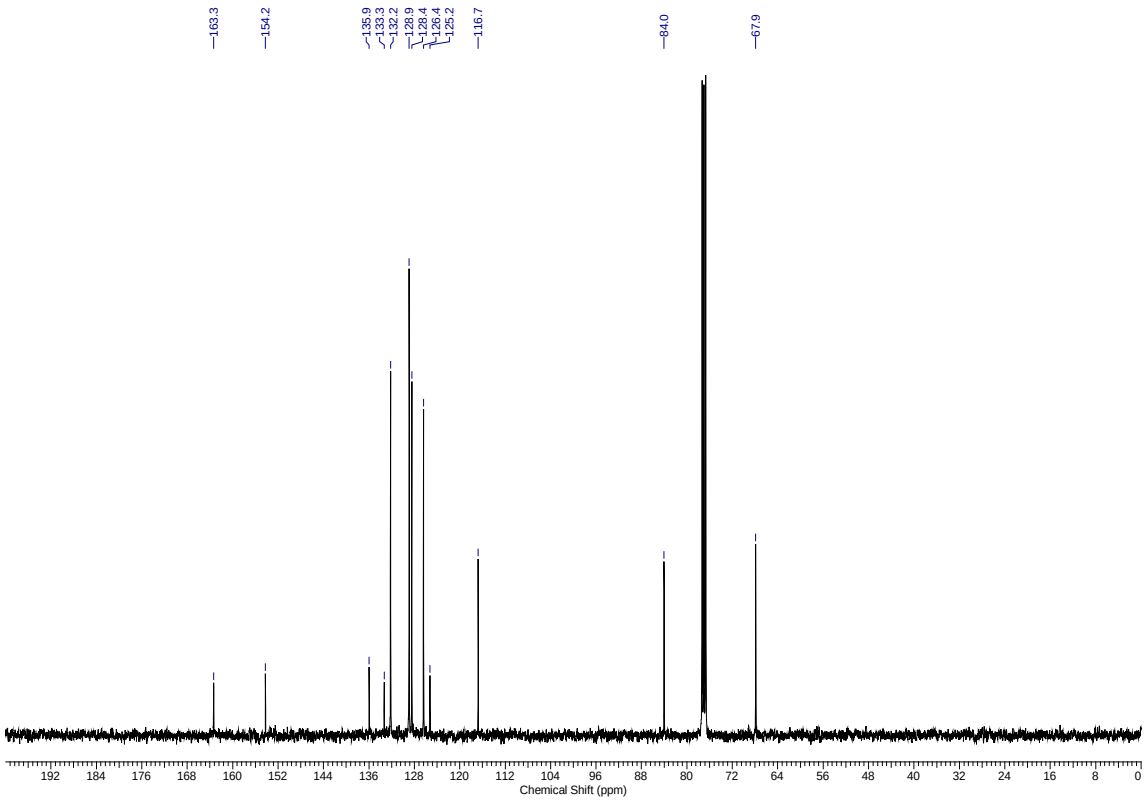
^{1}H NMR of compound **10c**



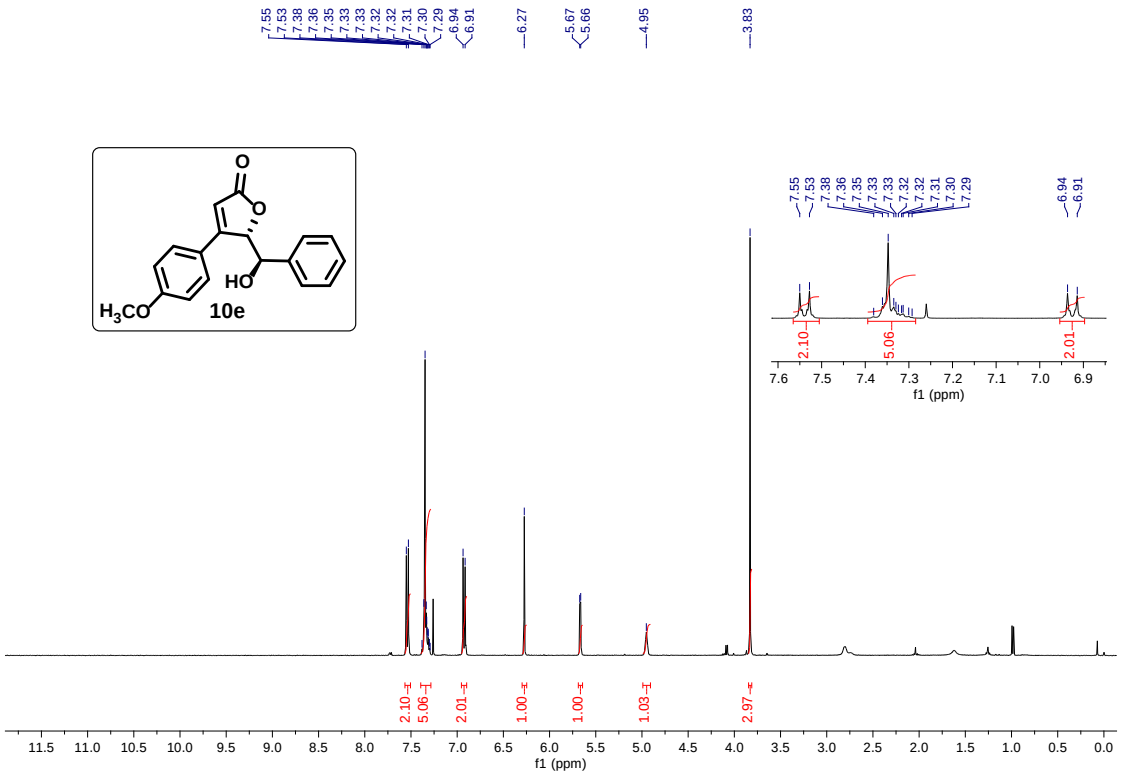
^{13}C NMR of compound **10c**



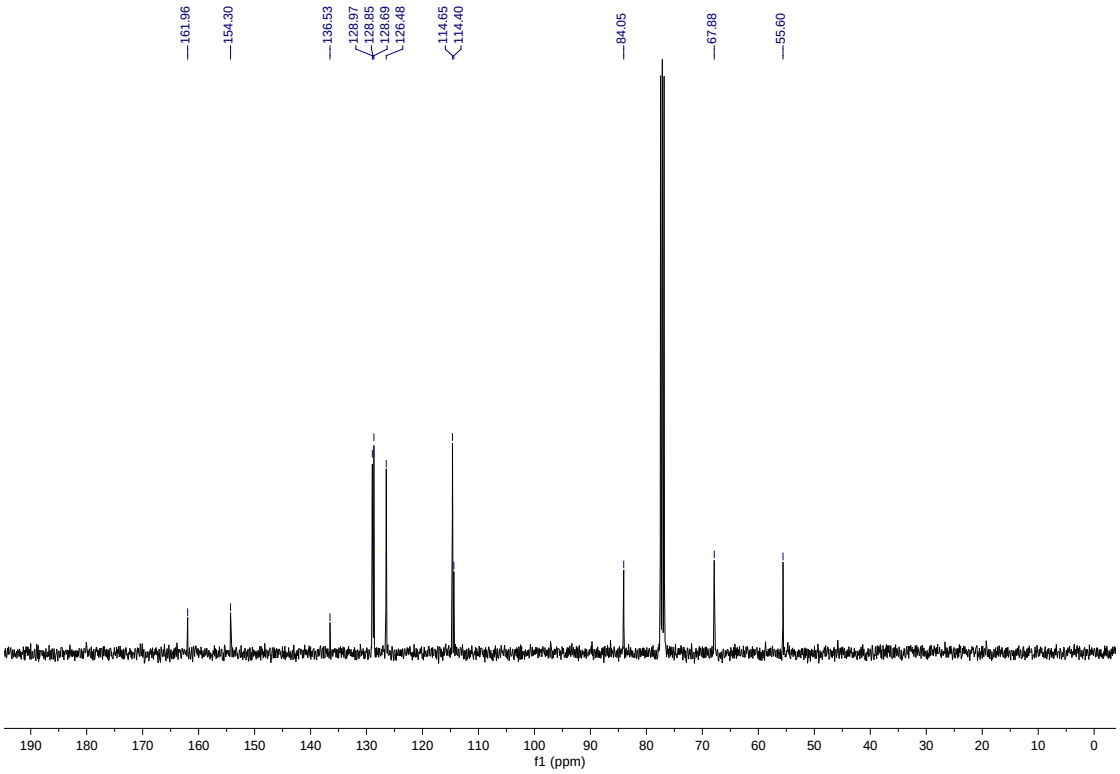
^{1}H NMR of compound **10d**



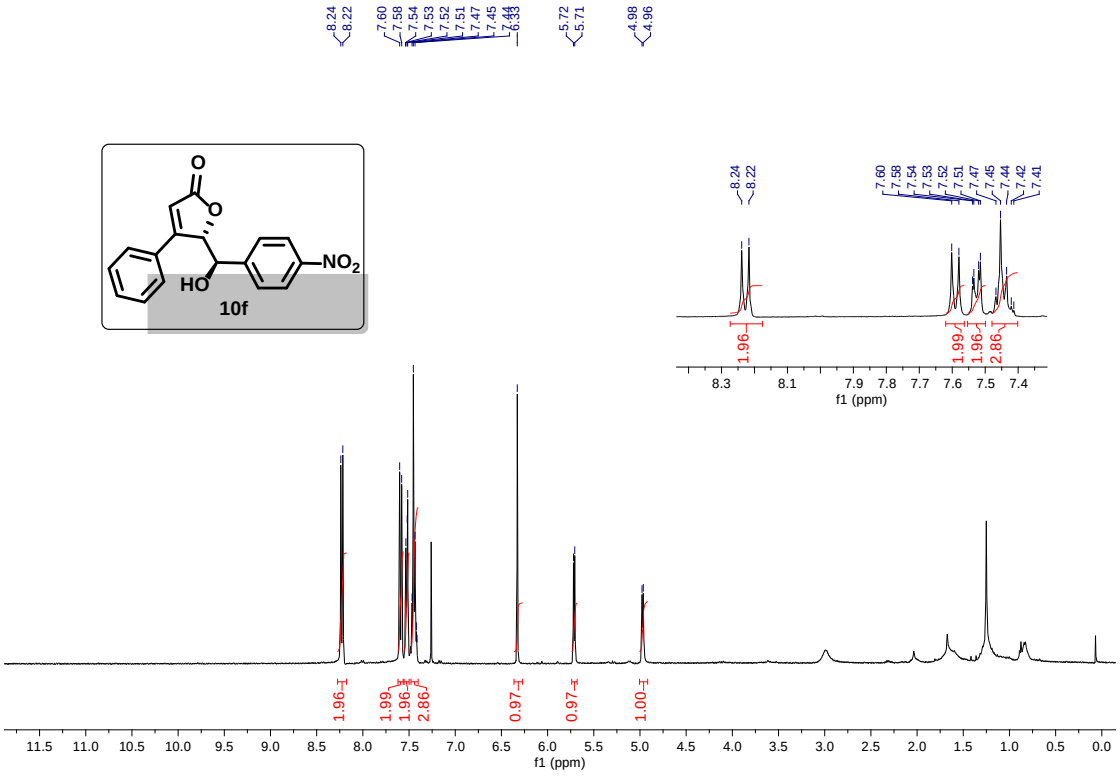
^{13}C NMR of compound **10d**



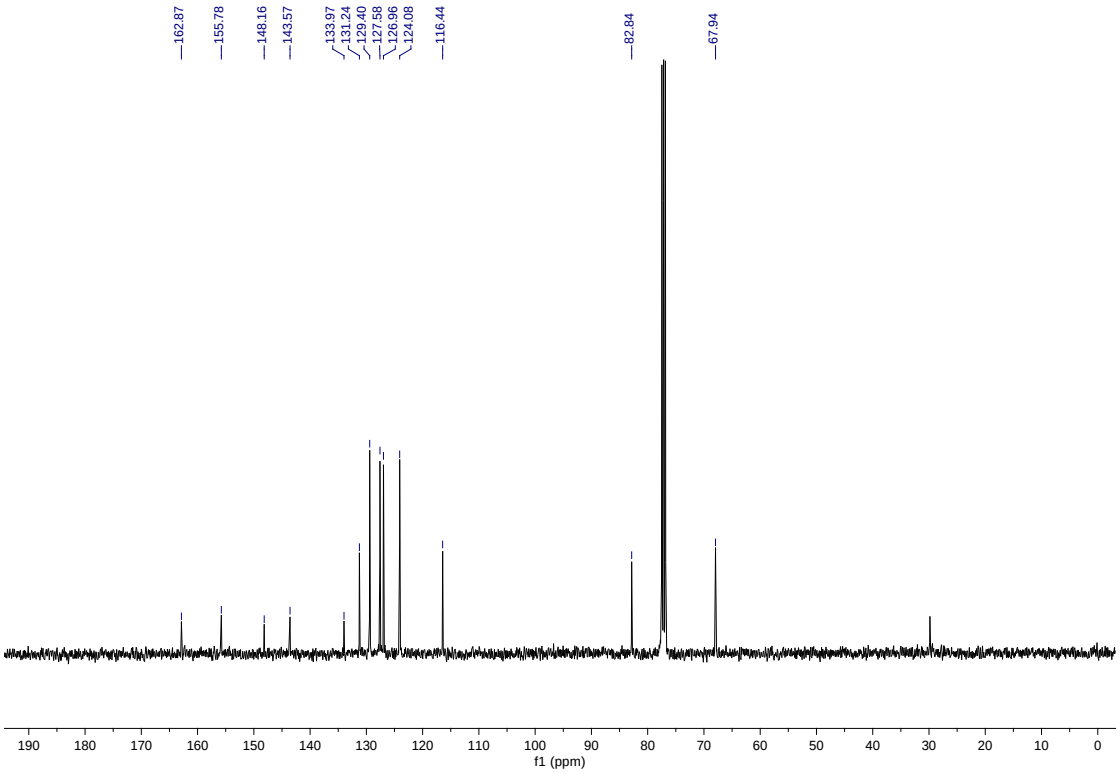
^{1}H NMR of compound **10e**



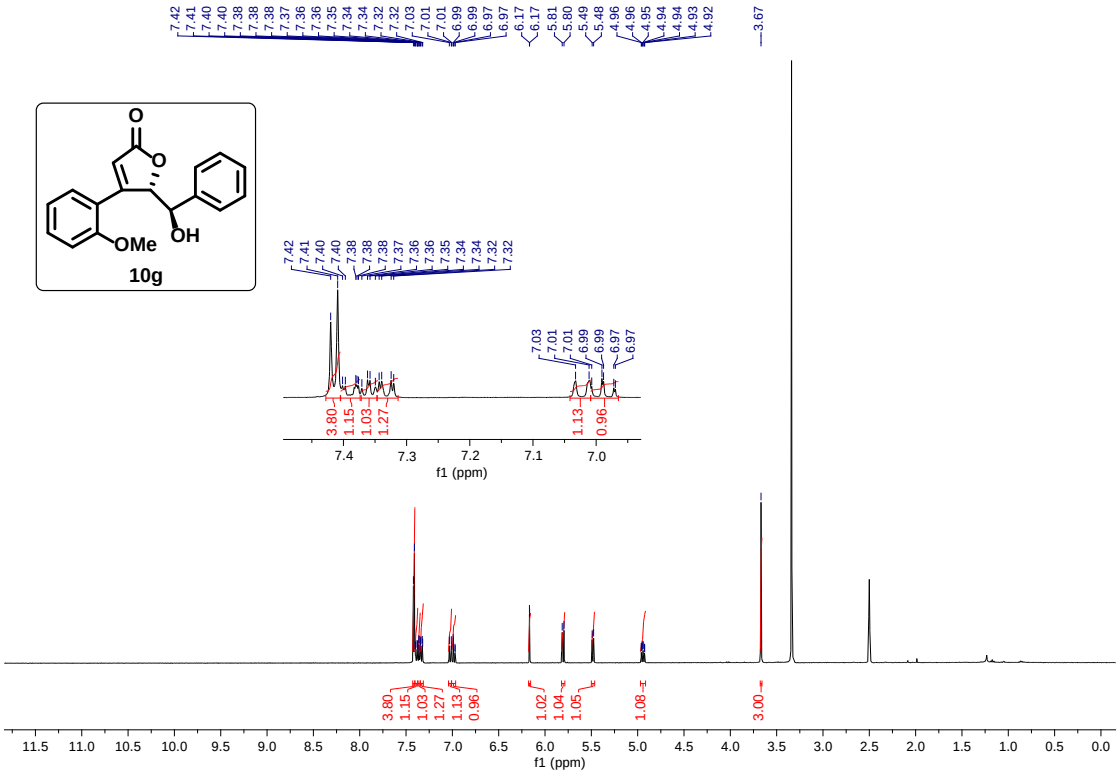
^{13}C NMR of compound **10e**



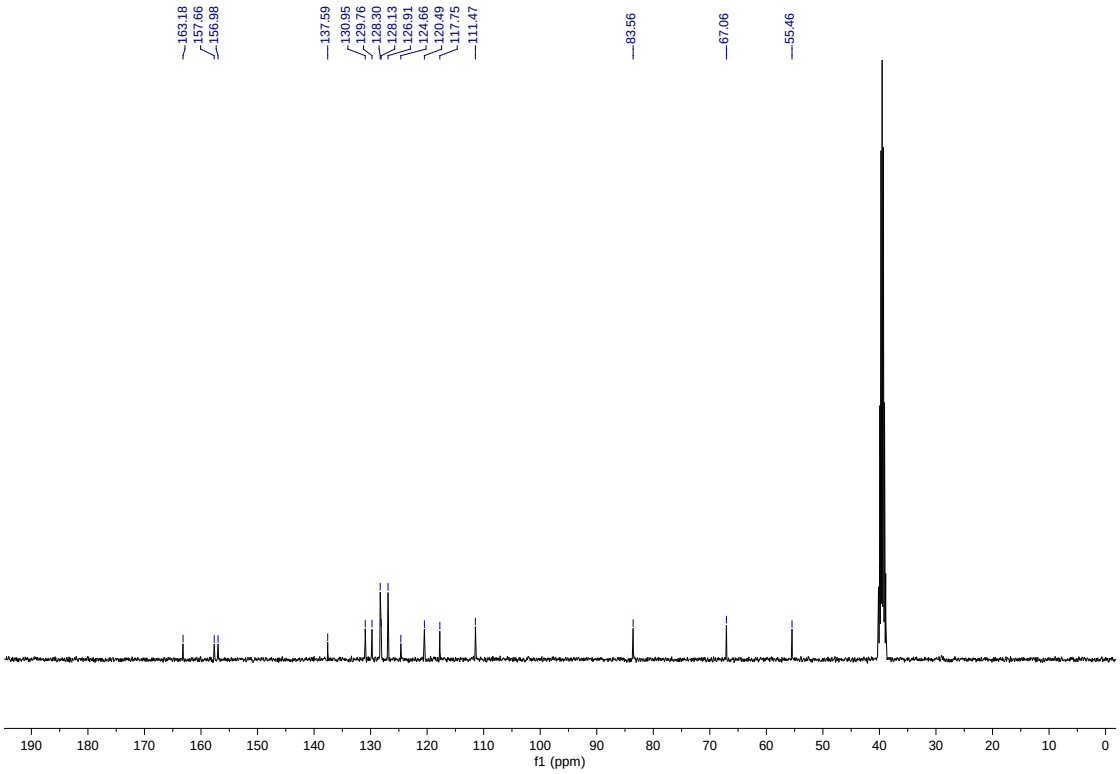
^{1}H NMR of compound **10f**



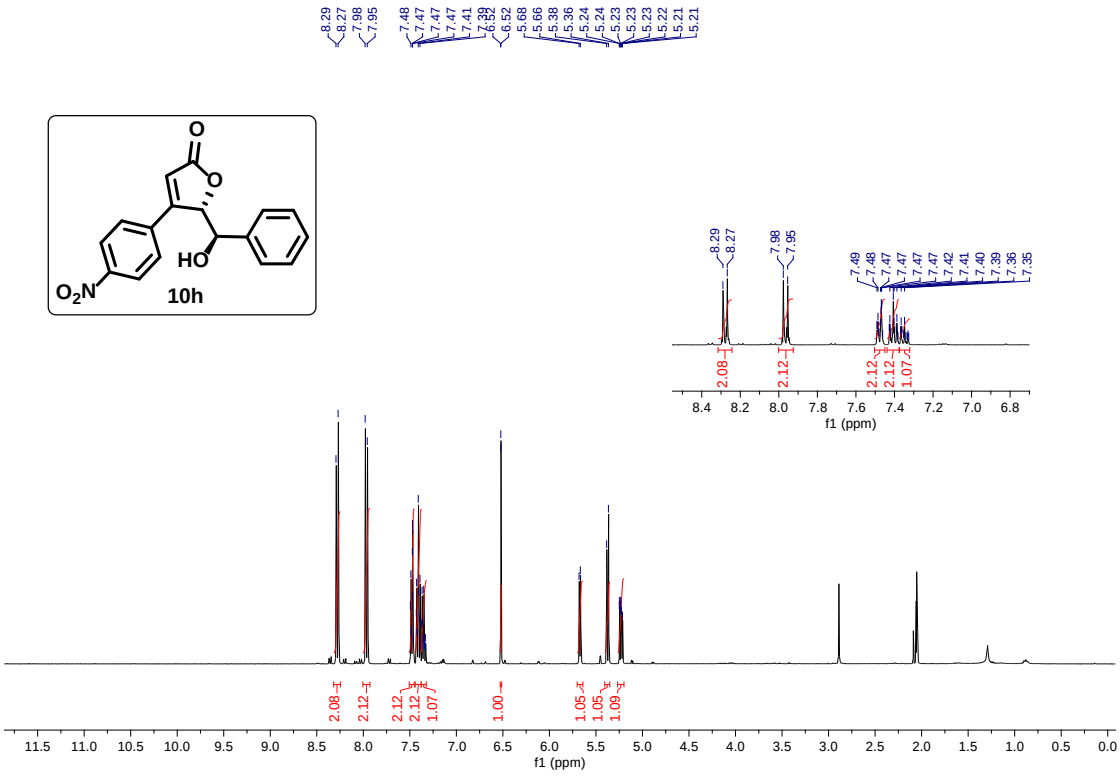
^{13}C NMR of compound **10f**



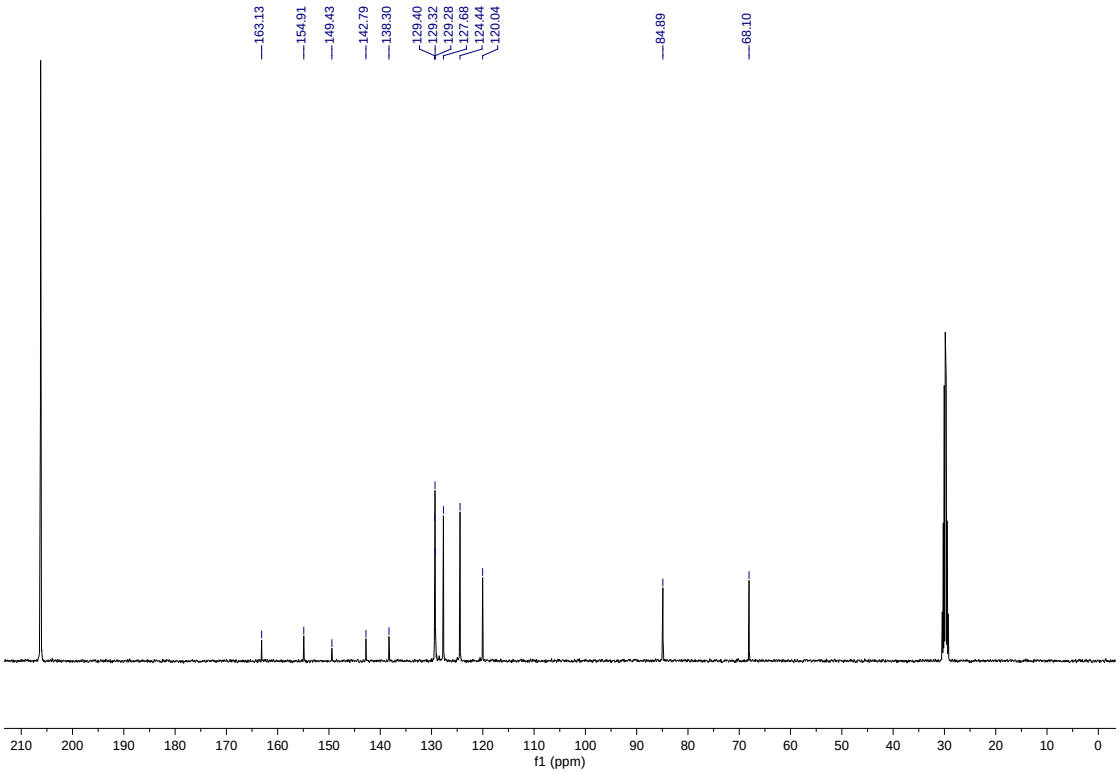
^{1}H NMR of compound **10g**



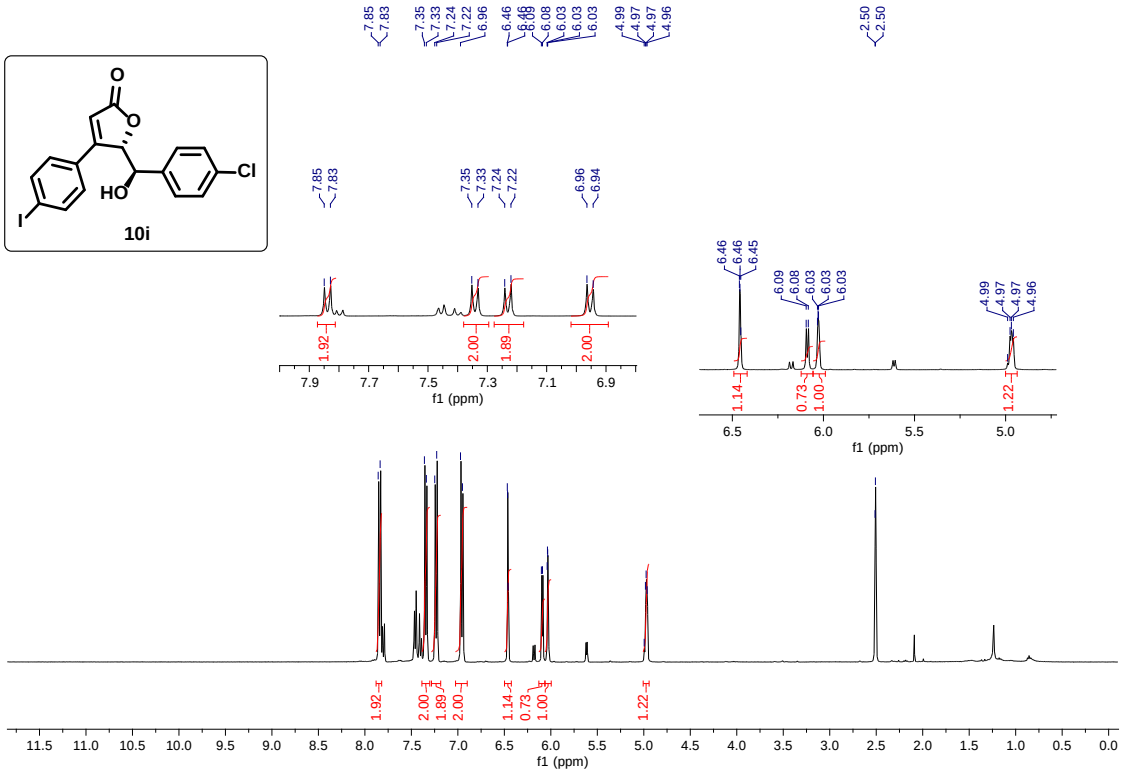
^{13}C NMR of compound **10g**



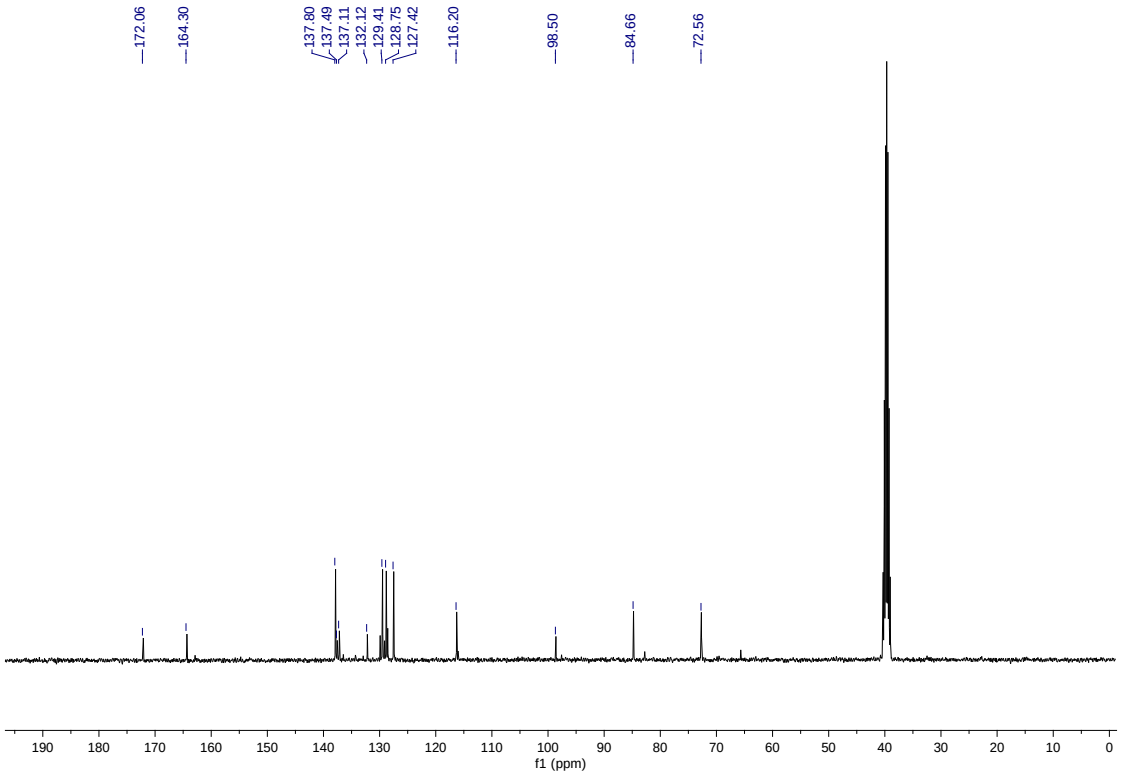
^{1}H NMR of compound **10h**



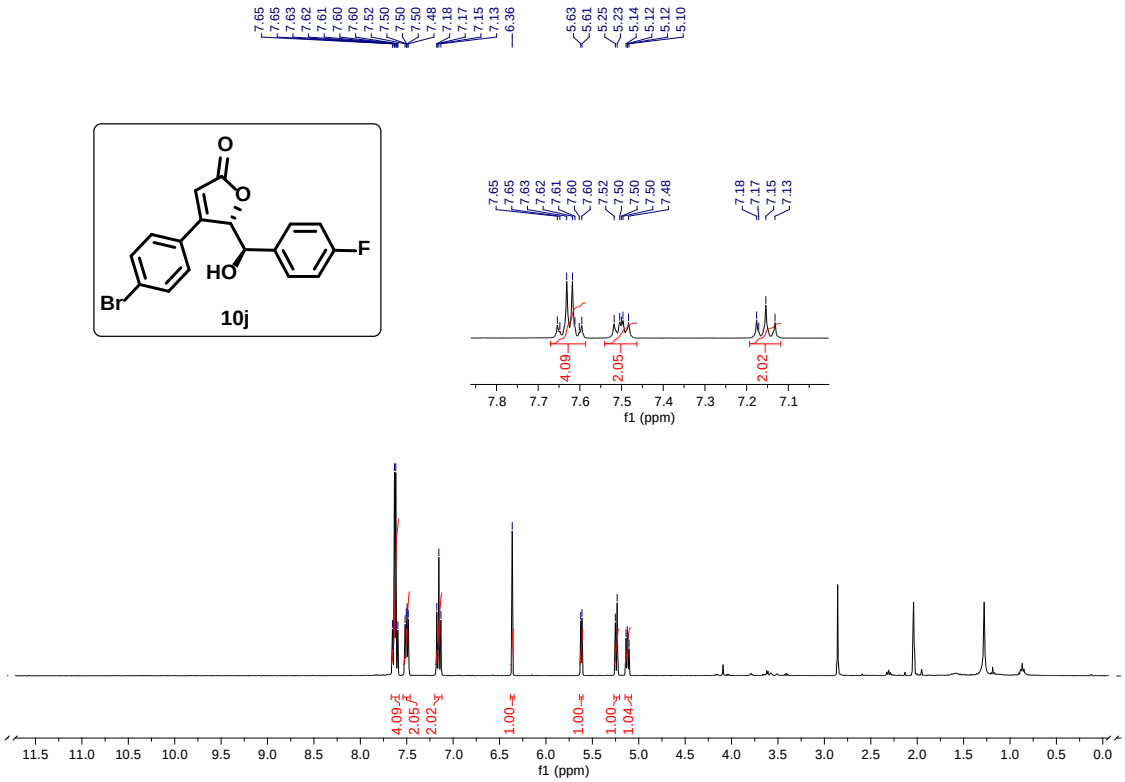
^{13}C NMR of compound **10h**



^{1}H NMR of compound **10i**



^{13}C NMR of compound **10i**



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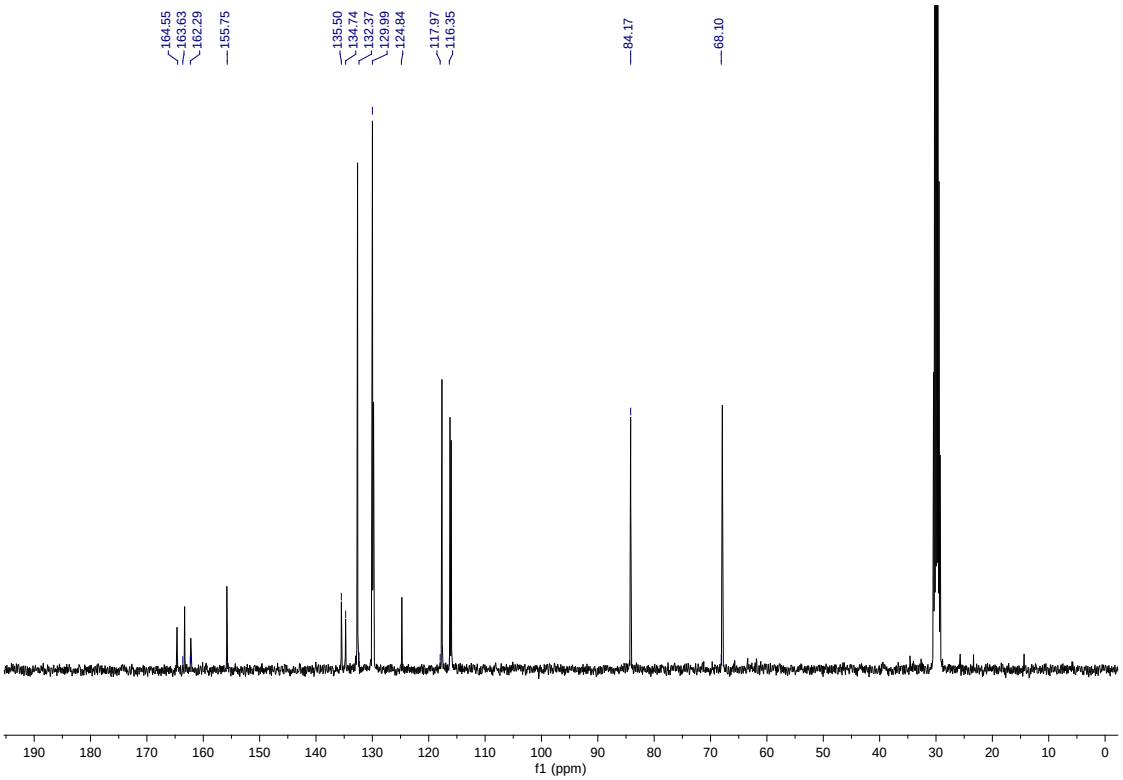

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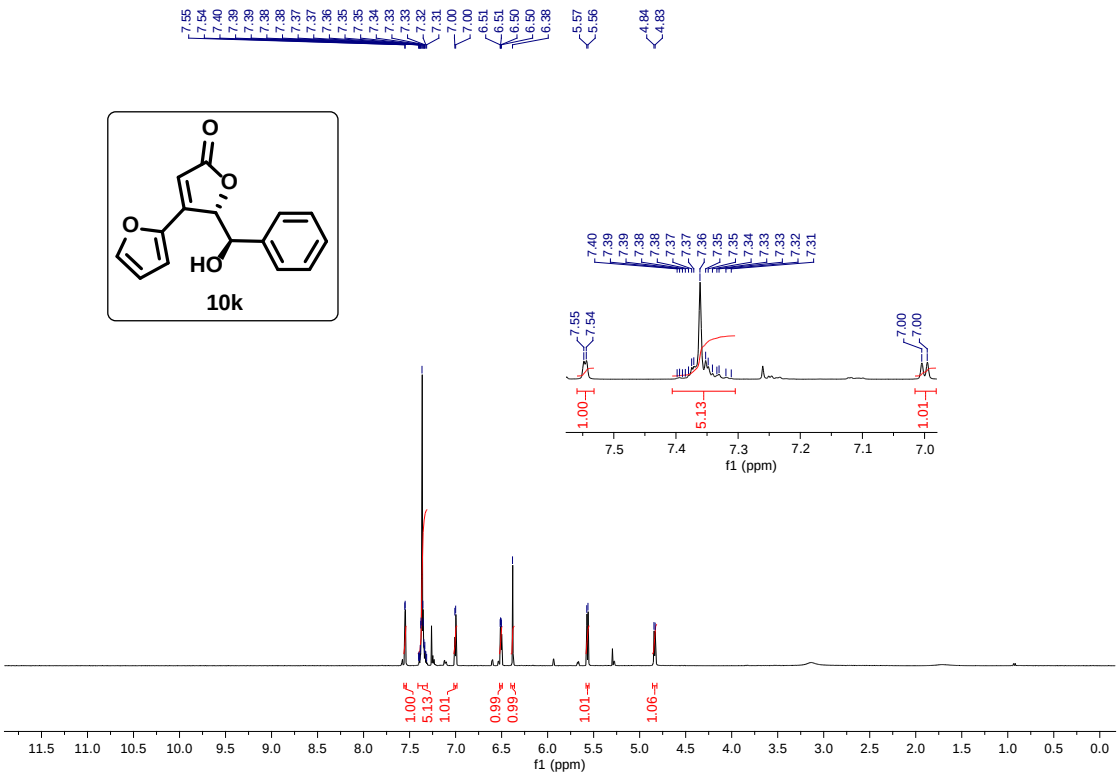
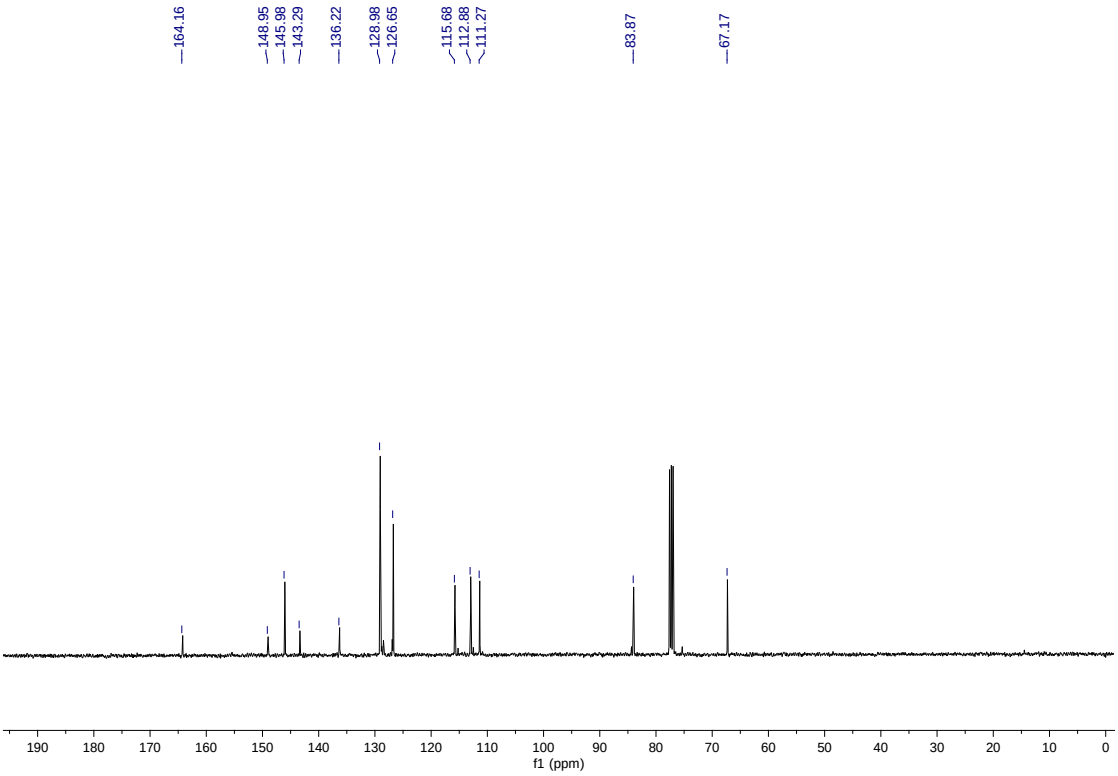


^{1}H NMR of compound **10k**



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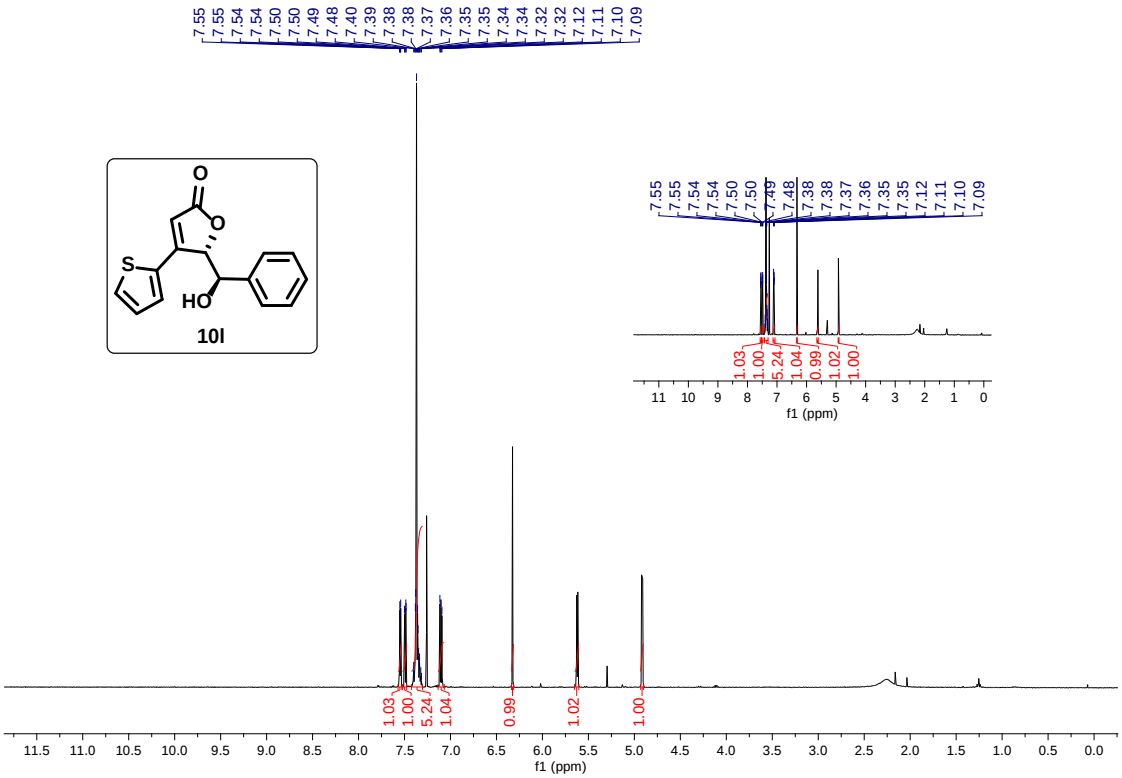

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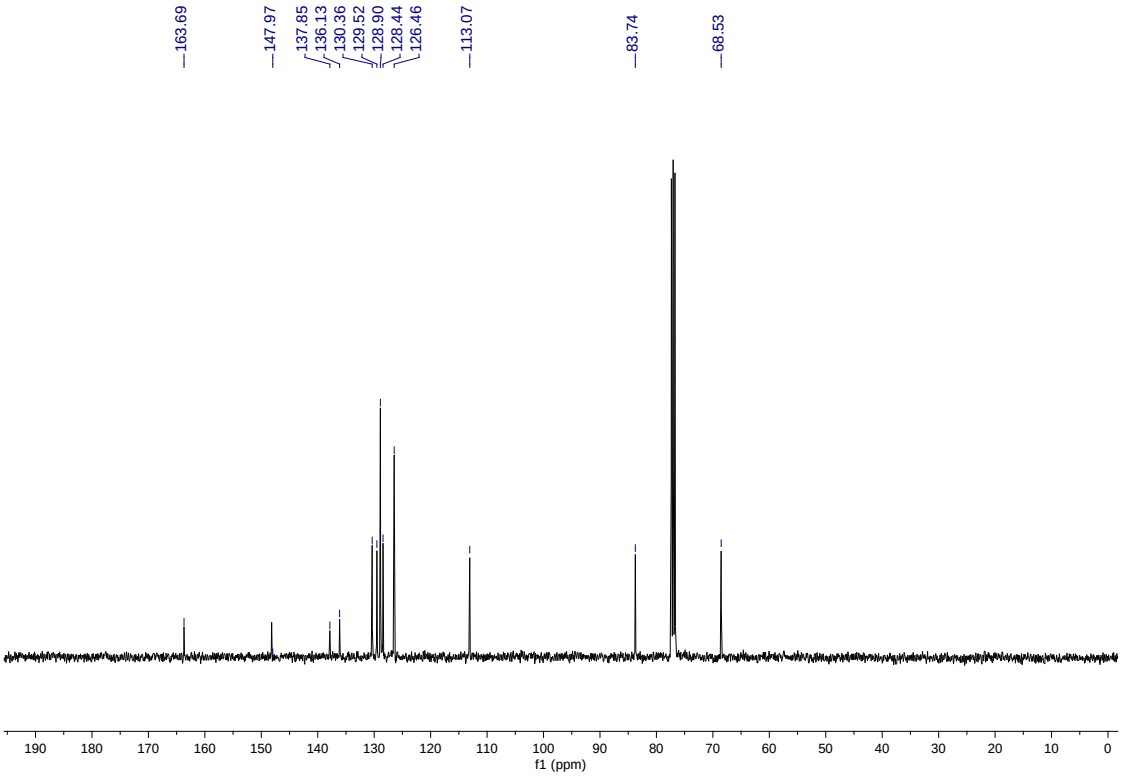
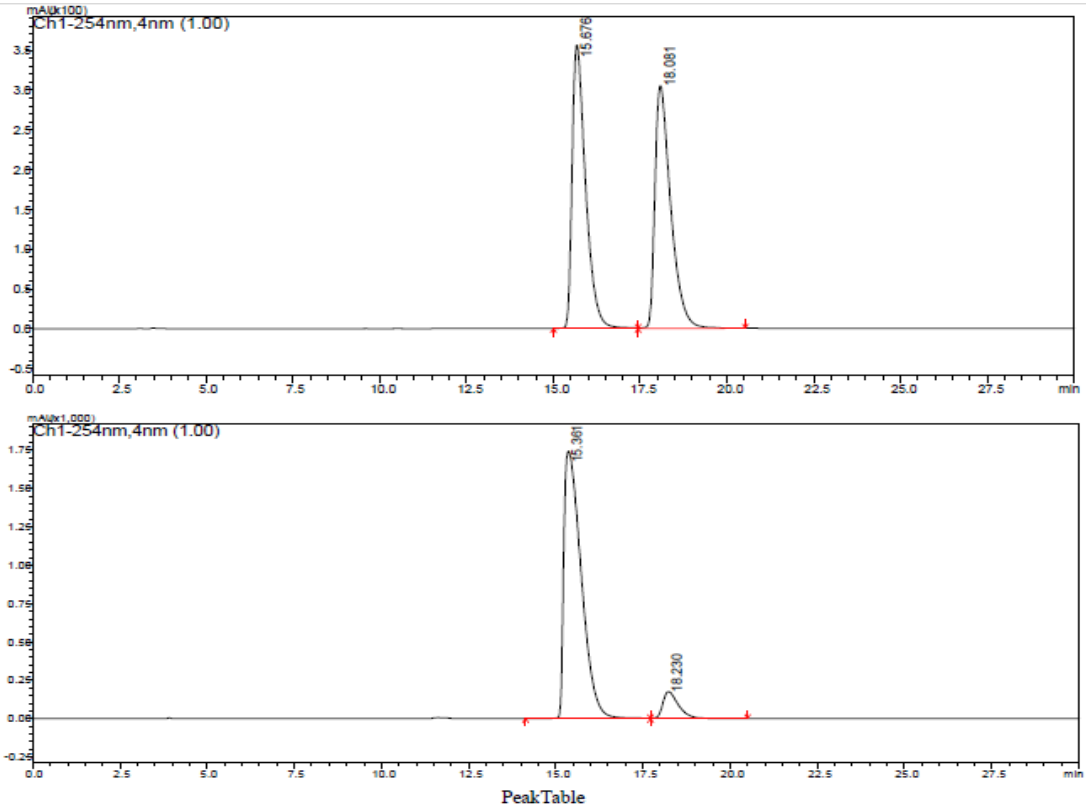


^{13}C NMR of compound **10l**



PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
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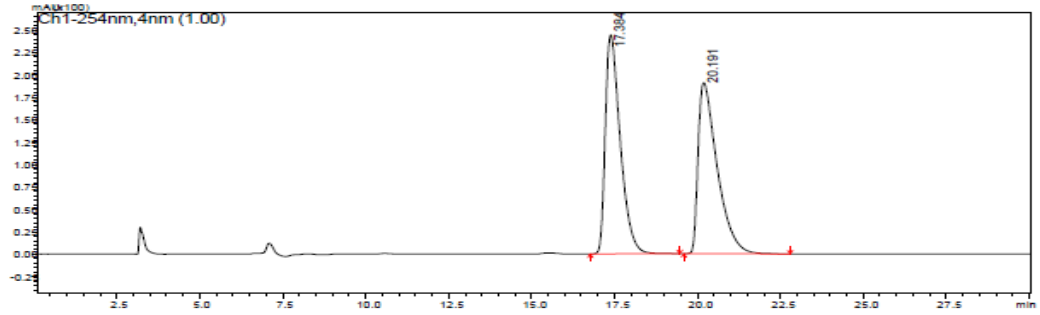
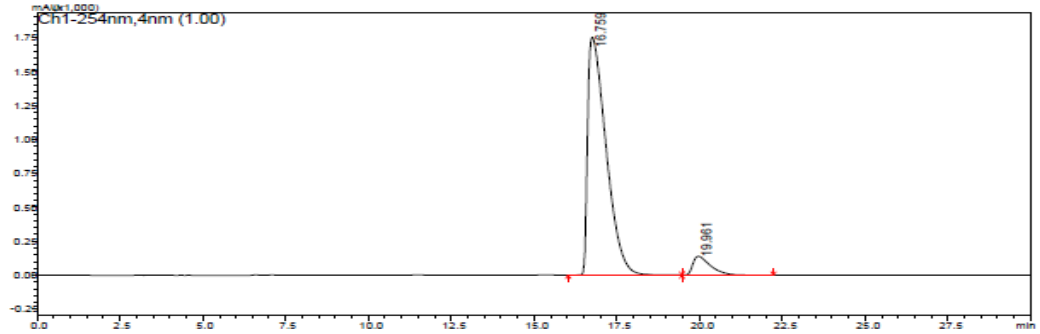
2	18.230	5447696	175186	8.246	9.133
Total		66062688	1918145	100.000	100.000

Chromatogram of compound **8a**





PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
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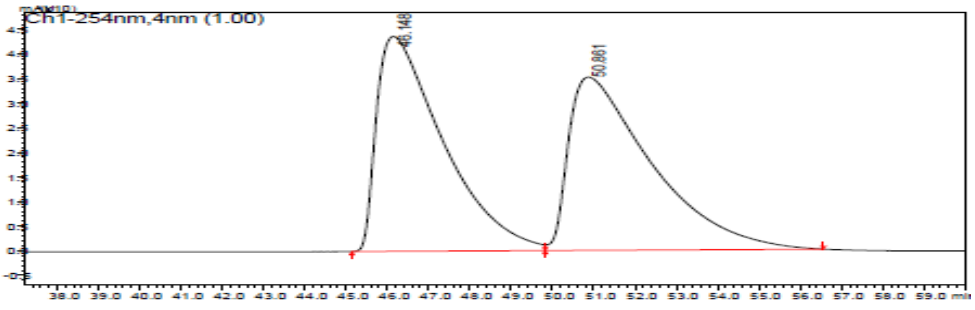
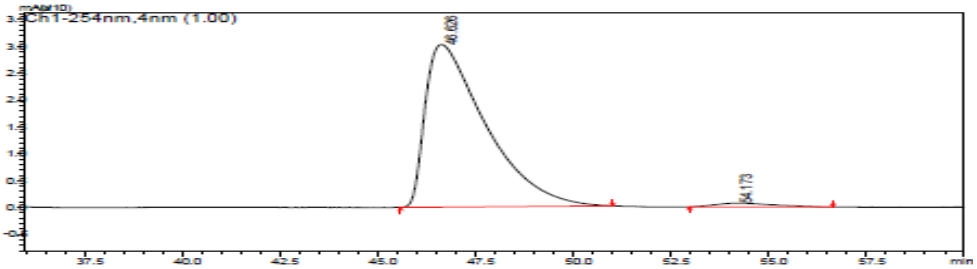
2	19.961	5144905	138706	7.035	7.338
Total		73138169	1890263	100.000	100.000

Chromatogram of compound **8b**



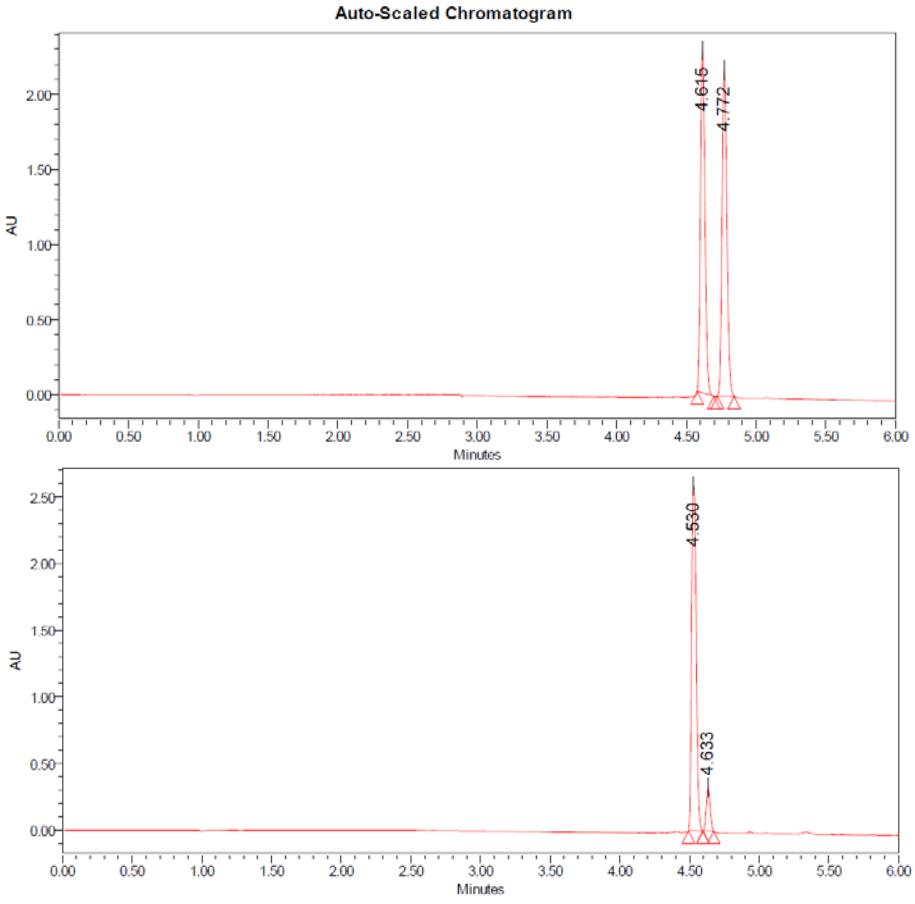


PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	46.626	3254973	30267	97.866	97.735
2	54.173	70967	702	2.134	2.265
Total		3325940	30968	100.000	100.000

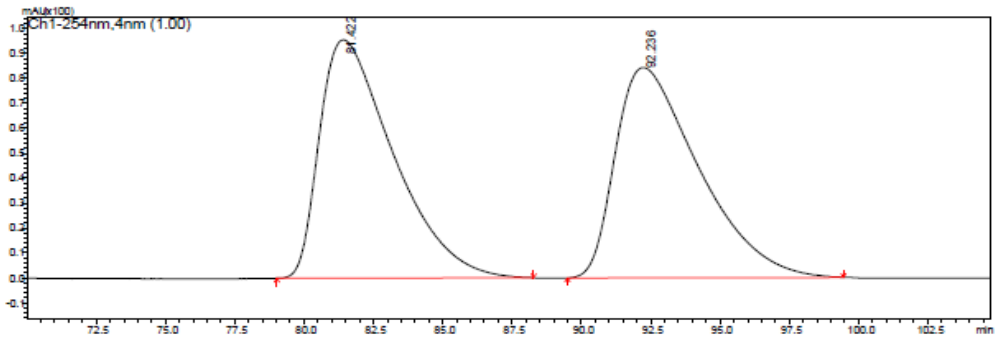
Chromatogram of compound **8c**

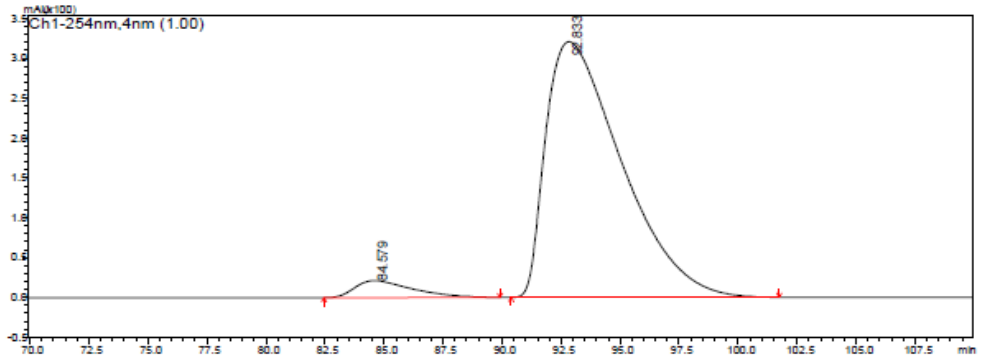


Peak Results

	RT	Area	Height	% Area	% Height
1	4.530	5985136	2587183	90.61	88.96
2	4.633	620059	321103	9.39	11.04

Chromatogram of compound **8d**



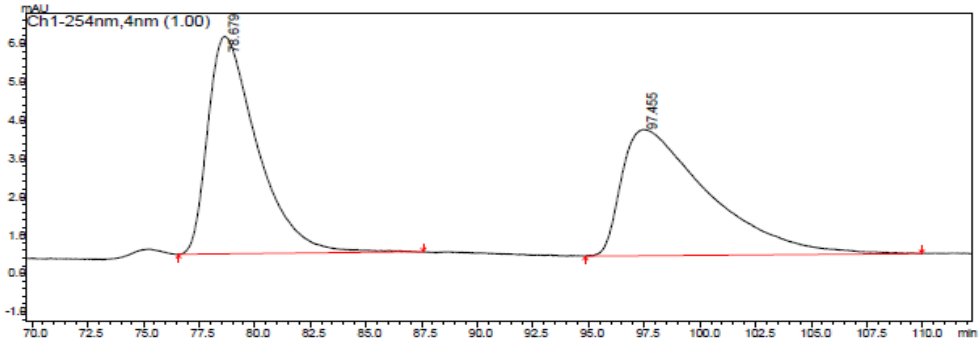


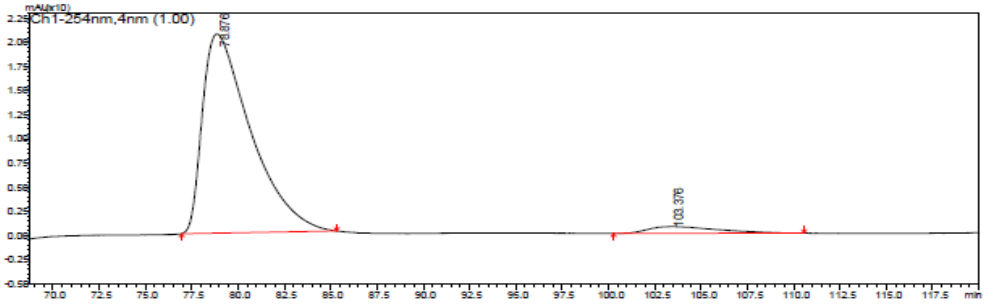
PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	84.579	3596049	21395	4.778	6.250
2	92.833	71670759	320914	95.222	93.750
Total		75266808	342310	100.000	100.000

Chromatogram of compound **8e**



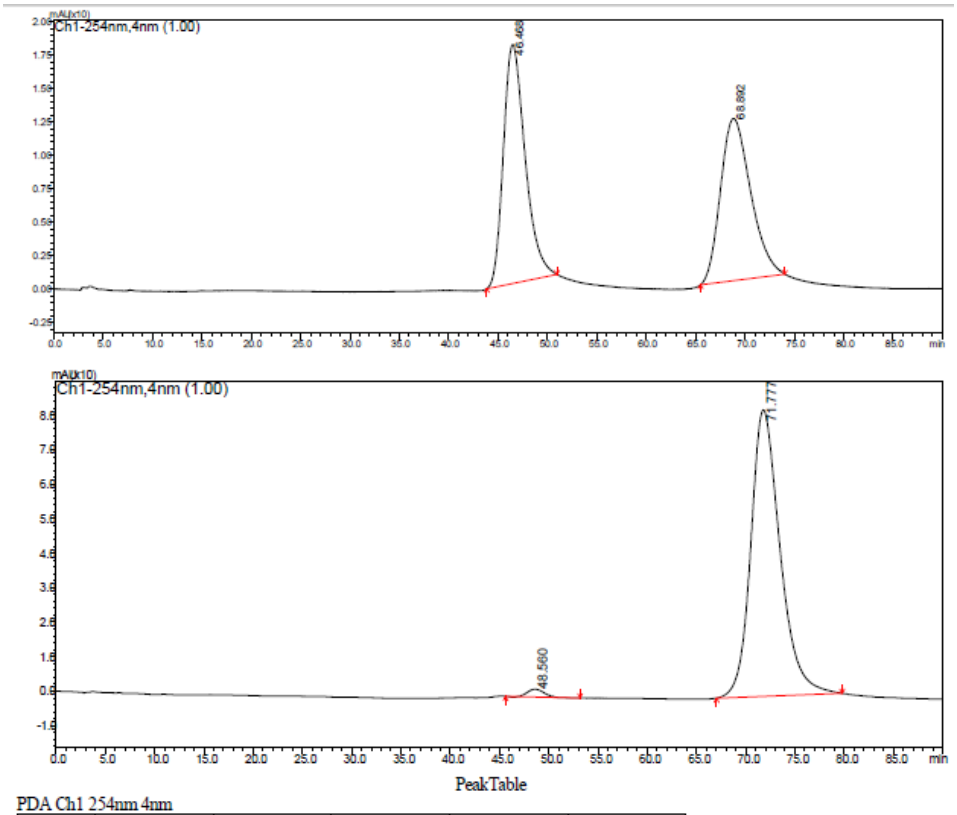


PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	78.876	3743737	20632	95.317	96.657
2	103.376	183913	713	4.683	3.343
Total		3927650	21346	100.000	100.000

Chromatogram of compound **8f**

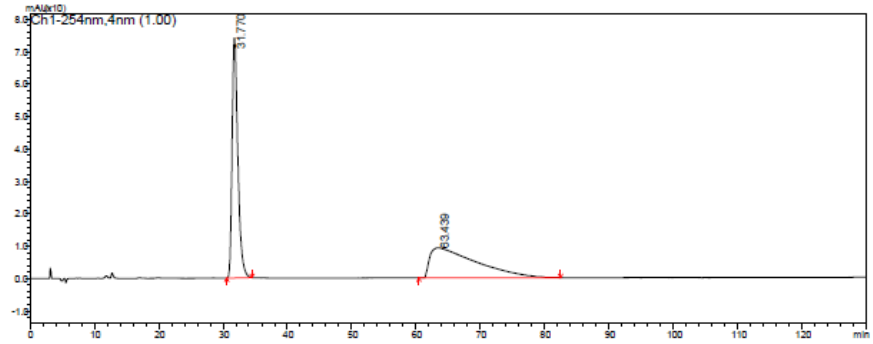


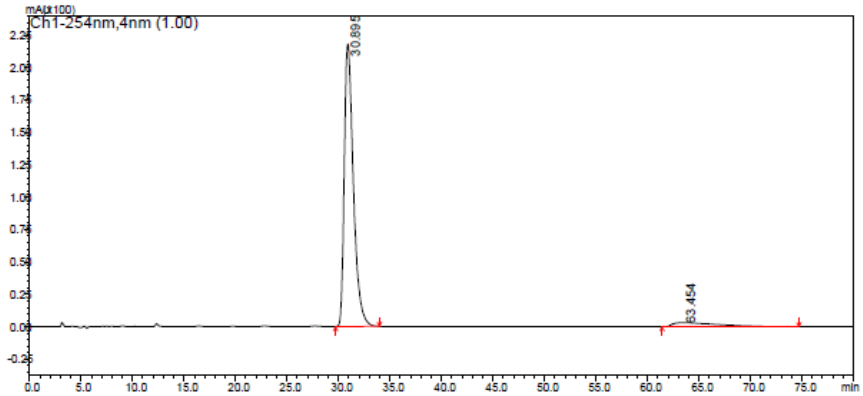
PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	48.560	256198	2280	1.469	2.674
2	71.777	17180528	83000	98.531	97.326
Total		17436726	85280	100.000	100.000

Chromatogram of compound **10a**





PeakTable

PDA Ch1 254nm 4nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	30.895	13382366	218179	93.385	98.586
2	63.454	947891	3129	6.615	1.414
Total		14330257	221308	100.000	100.000

Chromatogram of compound **10b**