

Supporting Information

Enantioselective Total Synthesis of Furofuran Lignans via Pd-Catalyzed Asymmetric Allylic Cycloaddition of Vinylethylene Carbonates with 2-Nitroacrylates

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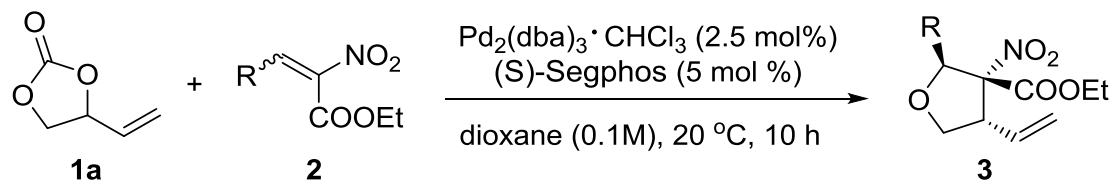
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General Experimental Details

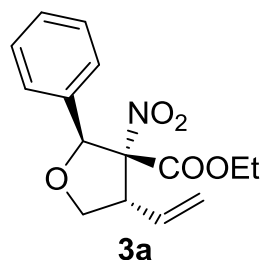
Analytical thin-layer chromatography (TLC) was carried out using 0.2 mm commercial silica gel plates (Yantai Jiangyou Silica Gel Development Co., Ltd., silica gel HSGF 254). Preparative column chromatography employing silica gel (Qingdao Shenghai Fine Silica Gel Chemical Co., Ltd., 200-300 mesh) was performed according to the method of Still. Solvents for the chromatography are listed as volume/volume ratios. High-resolution mass spectra (HRMS) were performed at Instrumental Analysis Center of Shanghai Jiao Tong University using ESI method. Proton nuclear magnetic resonance (^1H NMR) spectra were recorded with a Bruker AVANCE III HD 400 (400MHz) (or Bruker AVANCE III HD 500 (500 MHz)) spectrometer. Chemical shifts are reported in delta (δ) units, parts per million (ppm) downfield from tetramethylsilane or ppm relative to the center of the singlet at 7.26 ppm for deuteriochloroform. Coupling constants are reported in Hertz (Hz). Carbon-13 nuclear magnetic resonance (^{13}C NMR) spectra were recorded with a Bruker AVANCE III HD 400 (100MHz) (or Bruker AVANCE III HD 400 (125 MHz) spectrometer. Chemical shifts are reported in delta (δ) units, ppm relative to the center of the triplet at 77.0 ppm for deuteriochloroform. ^{13}C NMR spectra were routinely run with broadband decoupling. High performance liquid chromatography (HPLC) was performed with Thermo Fisher spectrometers and Shimazu HPLC-16 and 2030 instrument using chiral column as noted for each compound. Optical rotations were measured on a SGW[®]-1 polarimeter. X-ray diffraction data were collected on Bruker SMART Apex- III CMOS-Based X-ray diffractometer with Cu-K α Radiation ($\lambda = 1.54178$). Vinyl ethylene carbonates (H-VEC) was purchased from energy chemical. Dry 1,4-dioxane was purchased from Sigma -Aldrich. $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ was purchased from Sinocompound Co. and used as received. Substituted vinyl ethylene carbonates (VECs) were synthesized according to previous reported procedures.¹⁻² Substrates **2** were facilely synthesized according to the reported literature.³ All other chemicals were used as received from commercial resources.

General Procedure for Pd-Catalyzed Asymmetric Allylic Cycloaddition of Vinyltetrahydrofuran Carbonate **1a** with 2-Nitroacrylates



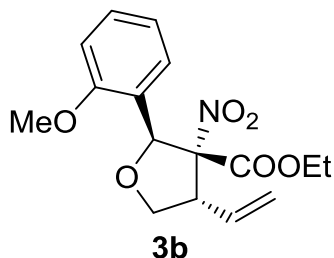
To an oven dried screw-cap reaction tube equipped with a magnetic stir bar, $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (5.2 mg, 0.005 mmol, 2.5 mol%), (*S*)-Segphos (6.1 mg, 0.01 mmol, 5 mol%), **1a** (0.24 mmol) and **2** (0.2 mmol) were added. The reaction tube was sealed with rubber-septum, then evacuated and backfilled with nitrogen (this process was repeated a total of three times). Anhydrous 1,4-dioxane (2 mL) was added sequentially via syringe. The resulting mixture was stirred at 20 °C for 10 hours. The solvent was removed *in vacuo* with the aid of a rotary evaporator. The obtained residue was purified by flash column chromatography on silica gel to afford the corresponding products **3**. Diastereoisomer ratios (d.r.) were determined by ^1H NMR analysis of the reaction mixture. The enantiomeric excesses of the products were determined by HPLC analysis using chiral stationary phases as indicated for each case.

Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-phenyl-4-vinyltetrahydrofuran-3-carboxylate (**3a**)



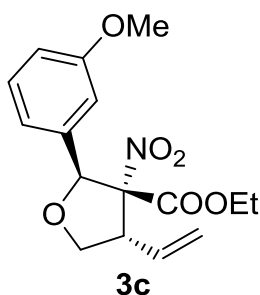
3a was prepared according to the general procedure. Yield: 95% (55.3 mg), d.r. = 6:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.38–7.28 (m, 5H), 5.95 (s, 1H), 5.62 (ddd, $J = 17.2, 10.2, 6.9$ Hz, 1H), 5.38–5.26 (m, 2H), 4.55–4.43 (m, 1H), 4.05–3.93 (m, 2H), 3.89–3.77 (m, 1H), 3.65–3.54 (m, 1H), 0.86 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.4, 136.4, 129.5, 129.0, 128.2, 127.3, 121.4, 103.9, 85.5, 70.6, 62.7, 49.9, 13.1; HRMS (ESI-MS): Calcd. for $\text{C}_{15}\text{H}_{17}\text{NO}_5$ ($\text{M}+\text{Na}$): 314.0999, Found: 314.1003; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 10.60$ min, $t_{\text{major}} = 9.94$ min; 99% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(2-methoxyphenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3b)



3b was prepared according to the general procedure. Yield: 84% (54.0 mg), d.r. = 3:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (500 MHz, Chloroform-*d*) δ 7.31–7.27 (m, 1H), 6.96–6.91 (m, 2H), 6.86–6.79 (m, 1H), 6.40 (s, 1H), 5.58 (ddd, $J = 17.5, 10.2, 7.4$ Hz, 1H), 5.39–5.22 (m, 2H), 4.46–4.31 (m, 1H), 4.17–4.01 (m, 1H), 3.97–3.90 (m, 1H), 3.85–3.79 (m, 1H), 3.78 (s, 3H), 3.60–3.54 (m, 1H), 0.84 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 163.8, 157.0, 143.3, 129.9, 129.2, 128.9, 128.3, 121.5, 120.4, 110.1, 104.1, 70.0, 62.4, 55.2, 51.0, 13.1; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{19}\text{NO}_6$ ($\text{M}+\text{Na}$): 344.1105, Found: 344.1107; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 14.44$ min, $t_{\text{major}} = 12.39$ min; 97% ee.

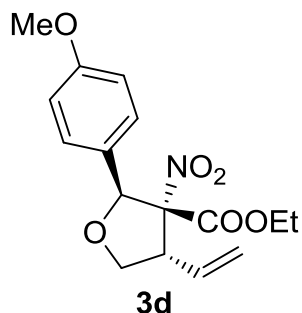
Ethyl (2*S*,3*R*,4*S*)-2-(3-methoxyphenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3c)



3c was prepared according to the general procedure. Yield: 88% (56.5 mg), d.r. = 9:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (500 MHz, Chloroform-*d*) δ 7.26–7.20 (m, 1H), 6.93–6.87 (m, 1H), 6.86–6.80 (m, 2H), 5.92 (s, 1H), 5.61 (ddd, $J = 17.3, 10.2, 7.0$ Hz, 1H), 5.40–5.20 (m, 2H), 4.52–4.44 (m, 1H), 4.03–3.92 (m, 2H), 3.91–3.83 (m, 1H), 3.79 (s, 3H), 3.70–3.61 (m, 1H), 0.89 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 163.4, 159.4, 137.9, 129.5, 129.2, 121.4, 119.6, 114.5, 112.9, 103.9, 85.3,

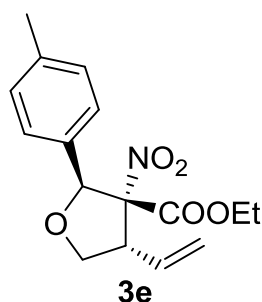
70.6, 62.7, 55.2, 49.9, 13.1; HRMS (ESI-MS): Calcd. for C₁₆H₁₉NO₆ (M+Na): 344.1105, Found: 344.1103; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, *t*_{minor} = 14.27 min, *t*_{major} = 14.95 min; 99% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(4-methoxyphenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3d)



3d was prepared according to the general procedure. Yield: 85% (54.6 mg), d.r. = 9:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ¹H NMR (400 MHz, Chloroform-*d*) δ 7.25–7.19 (m, 2H), 6.88–6.81 (m, 2H), 5.91 (s, 1H), 5.61 (ddd, *J* = 17.2, 10.2, 7.0 Hz, 1H), 5.38–5.25 (m, 2H), 4.52–4.42 (m, 1H), 4.02–3.93 (m, 2H), 3.93–3.83 (m, 1H), 3.81–3.79 (s, 3H), 3.70–3.60 (m, 1H), 0.91 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 163.5, 160.1, 129.5, 128.6, 128.4, 121.3, 113.5, 103.9, 85.3, 70.3, 62.6, 55.2, 49.8, 13.2; HRMS (ESI-MS): Calcd. for C₁₆H₁₉NO₆ (M+Na): 344.1105, Found: 344.1105; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 1/99, *t*_{minor} = 41.74 min, *t*_{major} = 37.95 min; 99% ee.

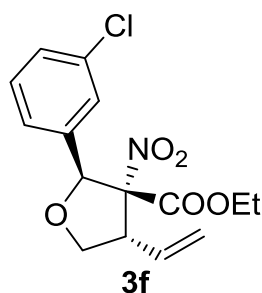
Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-(*p*-tolyl)-4-vinyltetrahydrofuran-3-carboxylate (3e)



3e was prepared according to the general procedure. Yield: 91% (55.5 mg), d.r. = 5:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ¹H NMR (400 MHz, Chloroform-*d*) δ 7.22–7.16 (m, 2H), 7.15–7.10 (m, 2H), 5.92 (s, 1H), 5.61 (ddd, *J* = 17.2, 10.2, 6.9 Hz, 1H),

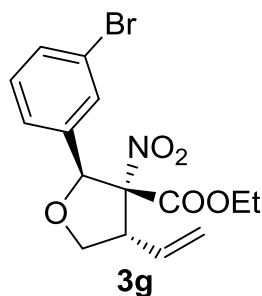
5.34–5.26 (m, 2H), 4.53–4.41 (m, 1H), 4.03–3.92 (m, 2H), 3.90–3.80 (m, 1H), 3.68–3.57 (m, 1H), 2.32 (s, 3H), 0.89 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform- d) δ 163.4, 138.9, 133.4, 129.5, 128.8, 127.2, 121.3, 104.0, 85.5, 70.4, 62.6, 49.8, 21.1, 13.1; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{19}\text{NO}_5$ ($\text{M}+\text{Na}$): 328.1155, Found: 328.1156; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, i -PrOH/hexanes = 5/95, $t_{\text{minor}} = 11.09$ min, $t_{\text{major}} = 9.79$ min; 99% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(3-chlorophenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3f)



3f was prepared according to the general procedure. Yield 94% (61.2 mg), d.r. = 9:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform- d) δ 7.37–7.18 (m, 4H), 5.92 (s, 1H), 5.61 (ddd, $J = 17.2, 10.3, 7.0$ Hz, 1H), 5.39–5.24 (m, 2H), 4.56–4.44 (m, 1H), 4.03–3.93 (m, 2H), 3.94–3.86 (m, 1H), 3.76–3.64 (m, 1H), 0.93 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform- d) δ 163.2, 138.4, 134.2, 129.5, 129.3, 129.1, 127.5, 125.5, 121.7, 103.6, 84.5, 70.8, 62.9, 49.9, 13.1; HRMS (ESI-MS): Calcd. for $\text{C}_{15}\text{H}_{16}\text{ClNO}_5$ ($\text{M}+\text{Na}$): 348.0609, Found: 348.0611; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, i -PrOH/hexanes = 5/95, $t_{\text{minor}} = 9.40$ min, $t_{\text{major}} = 8.88$ min; 98% ee.

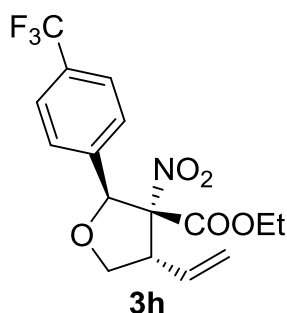
Ethyl (2*S*,3*R*,4*S*)-2-(3-bromophenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3g)



3g was prepared according to the general procedure. Yield 90% (66.6 mg), d.r. = 9:1;

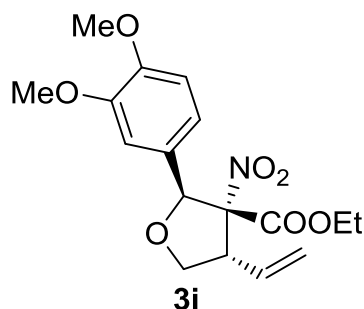
Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.52–7.40 (m, 2H), 7.33–7.17 (m, 2H), 5.91 (s, 1H), 5.61 (ddd, $J = 17.6, 10.3, 7.0$ Hz, 1H), 5.38–5.26 (m, 2H), 4.55–4.44 (m, 1H), 4.03–3.92 (m, 2H), 3.91–3.85 (m, 1H), 3.75–3.65 (m, 1H), 0.94 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.2, 138.6, 132.1, 130.4, 129.8, 129.3, 125.9, 122.2, 121.7, 103.6, 84.4, 70.8, 62.9, 49.9, 13.2; HRMS (ESI-MS): Calcd. for $\text{C}_{15}\text{H}_{16}\text{BrNO}_5$ ($\text{M}+\text{Na}$): 392.0104, Found: 392.0106; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 9.75$ min, $t_{\text{major}} = 9.21$ min; 96% ee.

Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-(4-(trifluoromethyl)phenyl)-4-vinyltetrahydrofuran-3-carboxylate (3h)



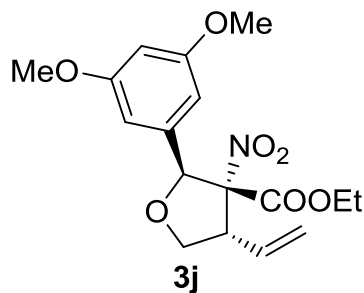
3h was prepared according to the general procedure. Yield 97% (69.7 mg), d.r. = 20:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.65–7.55 (m, 2H), 7.52–7.40 (m, 2H), 6.01 (s, 1H), 5.63 (ddd, $J = 17.3, 10.1, 7.0$ Hz, 1H), 5.39–5.19 (m, 2H), 4.61–4.41 (m, 1H), 4.05–3.91 (m, 2H), 3.92–3.77 (m, 1H), 3.70–3.51 (m, 1H), 0.83 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.3, 140.3, 129.4, 129.4, 127.7, 125.1, 125.1, 121.8, 103.5, 84.4, 71.0, 62.9, 50.2, 13.0; ^{19}F NMR (376 MHz, Chloroform-*d*) δ -62.77; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{16}\text{F}_3\text{NO}_5$ ($\text{M}+\text{Na}$): 382.0873, Found: 382.0872; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 8.53$ min, $t_{\text{major}} = 8.23$ min; 99% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(3,4-dimethoxyphenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3i)



3i was prepared according to the general procedure. Yield 86% (60.4 mg), d.r. = 8:1; Purification: 2:10 EtOAc : Petroleum ether; white solid; ¹H NMR (500 MHz, Chloroform-*d*) δ 6.94–6.87 (m, 1H), 6.85–6.78 (m, 2H), 5.90 (s, 1H), 5.62 (ddd, *J* = 17.4, 10.3, 7.0 Hz, 1H), 5.39–5.25 (m, 2H), 4.52–4.44 (m, 1H), 4.03–3.92 (m, 3H), 3.87 (s, 6H), 3.70–3.60 (m, 1H), 0.90 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 163.6, 149.5, 148.6, 129.6, 128.6, 121.4, 120.0, 110.6, 110.2, 103.9, 85.4, 70.4, 62.7, 55.9, 50.0, 13.3; HRMS (ESI-MS): Calcd. for C₁₇H₂₁NO₇ (M+Na): 374.1210, Found: 374.1208; HPLC conditions: Chiralcel AD-H column, 220 nm, flow rate: 1 mL/min, *i*-PrOH/hexanes = 2/98, *t*_{minor} = 29.92 min, *t*_{major} = 36.46 min; >99% ee.

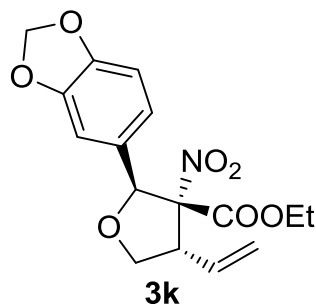
Ethyl (2*S*,3*R*,4*S*)-2-(3,5-dimethoxyphenyl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3j)



3j was prepared according to the general procedure. Yield 81% (56.9 mg), d.r. = 8:1; Purification: 1:10 EtOAc : Petroleum ether; colorless oil; ¹H NMR (500 MHz, Chloroform-*d*) δ 6.50–6.44 (m, 2H), 6.42–6.38 (m, 1H), 5.88 (s, 1H), 5.61 (ddd, *J* = 17.4, 10.2, 7.0 Hz, 1H), 5.34–5.25 (m, 2H), 4.51–4.44 (m, 1H), 4.01–3.94 (m, 2H), 3.94–3.87 (m, 1H), 3.77 (s, 6H), 3.75–3.67 (m, 1H), 0.93 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 163.4, 160.6, 138.6, 129.5, 121.4, 105.3, 103.8, 100.9, 85.3, 70.6, 62.7, 55.3, 49.9, 13.2; HRMS (ESI-MS): Calcd. for C₁₇H₂₁NO₇ (M+Na): 374.1210, Found: 374.1207; HPLC conditions:

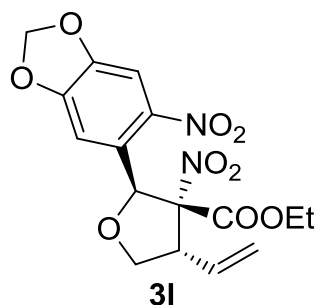
Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 22.20$ min, $t_{\text{major}} = 36.70$ min; 98% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(benzo[*d*][1,3]dioxol-5-yl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3k)



3k was prepared according to the general procedure. Yield 91% (61.0 mg), d.r. = 10:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (500 MHz, Chloroform-*d*) δ 6.83–6.73 (m, 3H), 5.95 (s, 2H), 5.85 (s, 1H), 5.60 (ddd, $J = 17.2, 10.3, 7.0$ Hz, 1H), 5.38–5.26 (m, 2H), 4.49–4.42 (m, 1H), 4.01–3.87 (m, 3H), 3.82–3.70 (m, 1H), 0.98 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 163.4, 148.0, 147.5, 130.1, 129.4, 121.4, 121.2, 107.9, 107.6, 103.8, 101.2, 85.2, 70.3, 62.7, 49.7, 13.3; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{17}\text{NO}_7$ ($\text{M}+\text{Na}$): 358.0897, Found: 358.0896; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 20.74$ min, $t_{\text{major}} = 19.39$ min; 97% ee.

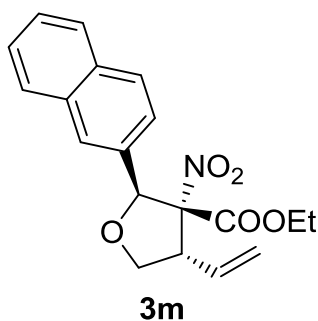
Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-(6-nitrobenzo[*d*][1,3]dioxol-5-yl)-4-vinyltetrahydrofuran-3-carboxylate (3l)



3l was prepared according to the general procedure. Yield 86% (65.4 mg), d.r. = 6:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (500 MHz, Chloroform-*d*) δ 7.62 (s, 1H), 7.12 (s, 1H), 6.82 (s, 1H), 6.15 (s, 2H), 5.55 (ddd, $J = 17.0, 10.4, 6.7$ Hz, 1H),

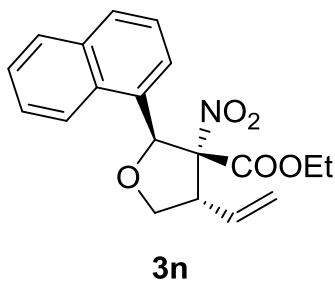
5.41–5.24 (m, 2H), 4.51–4.33 (m, 1H), 4.07–3.88 (m, 3H), 3.80–3.65 (m, 1H), 0.96 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (125 MHz, Chloroform- d) δ 163.4, 152.2, 148.1, 142.2, 129.7, 128.2, 122.3, 107.6, 105.4, 103.6, 103.3, 81.9, 69.7, 63.0, 51.6, 13.2; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{16}\text{N}_2\text{O}_9$ (M+Na): 403.0748, Found: 403.0753; HPLC conditions: Chiralcel OD-H column, 220 nm, flow rate: 1 mL/min, i -PrOH/hexanes = 8/92, $t_{\text{minor}} = 20.17$ min, $t_{\text{major}} = 15.72$ min; 98% ee.

Ethyl (2*S*,3*R*,4*S*)-2-(naphthalen-2-yl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3m)



3m was prepared according to the general procedure. Yield 93% (63.5 mg), d.r. = 13:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform- d) δ 7.88–7.75 (m, 4H), 7.53–7.45 (m, 2H), 7.43–7.35 (m, 1H), 6.13 (s, 1H), 5.65 (ddd, $J = 17.2, 10.3, 6.8$ Hz, 1H), 5.41–5.28 (m, 2H), 4.63–4.50 (m, 1H), 4.14–3.98 (m, 2H), 3.80–3.65 (m, 1H), 3.50–3.40 (m, 1H), 0.66 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform- d) δ 163.4, 133.7, 133.5, 132.7, 129.5, 128.0, 127.9, 127.6, 126.9, 126.6, 126.4, 124.4, 121.5, 103.9, 85.6, 70.7, 62.6, 50.0, 12.9; HRMS (ESI-MS): Calcd. for $\text{C}_{19}\text{H}_{19}\text{NO}_5$ (M+Na): 364.1155, Found: 364.1157; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, i -PrOH/hexanes = 5/95, $t_{\text{minor}} = 13.80$ min, $t_{\text{major}} = 12.26$ min; 99% ee.

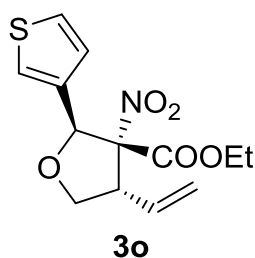
Ethyl (2*S*,3*R*,4*S*)-2-(naphthalen-1-yl)-3-nitro-4-vinyltetrahydrofuran-3-carboxylate (3n)



3n was prepared according to the general procedure. Yield 83% (58.7 mg), d.r. = 2.2:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; Major-diastereomer: ^1H NMR (400

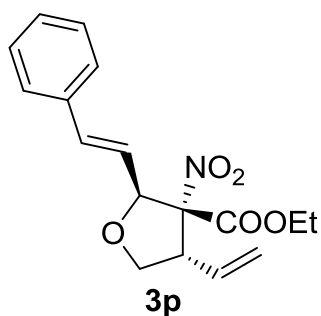
MHz, Chloroform-*d*) δ 7.95 (d, $J = 8.2$ Hz, 1H), 7.88–7.78 (overlapped, 2H), 7.64–7.57 (m, 1H), 7.54–7.42 (overlapped, 3H), 6.96 (s, 1H), 5.61 (ddd, $J = 17.4, 10.3, 7.0$ Hz, 1H), 5.42–5.26 (overlapped, 2H), 4.54–4.43 (m, 2H), 4.05 (dd, $J = 11.5, 8.6$ Hz, 1H), 3.60–3.40 (overlapped, 1H), 3.05–2.87 (m, 1H), 0.20 (t, $J = 7.1$ Hz, 3H); Minor-diastereomer: ^1H NMR (400 MHz, Chloroform-*d*) δ 8.17 (d, $J = 8.4$ Hz, 1H), 7.88–7.78 (overlapped, 2H), 7.64–7.57 (m, 1H), 7.54–7.42 (overlapped, 3H), 6.94 (s, 1H), 6.15 (ddd, $J = 17.4, 8.8, 7.5$ Hz, 1H), 5.42–5.26 (overlapped, 2H), 4.20–4.12 (m, 2H), 3.85–3.76 (m, 1H), 3.60–3.40 (overlapped, 1H), 3.25–3.15 (m, 1H), 0.40 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 133.3, 132.6, 131.2, 130.7, 129.4, 129.3, 128.9, 128.6, 126.4, 125.7, 125.7, 125.4, 125.1, 125.0, 124.9, 123.5, 123.4, 121.6, 121.4, 104.7, 82.5, 82.0, 72.7, 69.9, 62.3, 62.2, 56.2, 51.0, 12.6, 12.2; HRMS (ESI-MS): Calcd. for $\text{C}_{19}\text{H}_{19}\text{NO}_5$ ($\text{M}+\text{Na}$): 364.1155, Found: 364.1157; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 10.46$ min, $t_{\text{major}} = 10.04$ min; 97% ee.

Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-(thiophen-3-yl)-4-vinyltetrahydrofuran-3-carboxylate (3o)



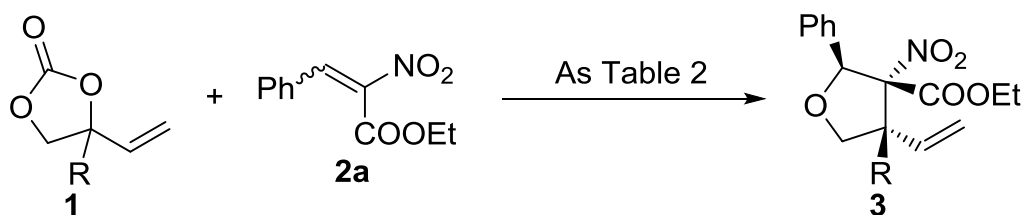
3o was prepared according to the general procedure. Yield 86% (51.1 mg), d.r. = 9:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.35–7.19 (m, 2H), 7.01 (dd, $J = 5.0, 1.4$ Hz, 1H), 6.02 (s, 1H), 5.63 (ddd, $J = 17.4, 10.2, 7.1$ Hz, 1H), 5.42–5.23 (m, 2H), 4.55–4.40 (m, 1H), 4.06–3.84 (m, 3H), 3.83–3.65 (m, 1H), 0.97 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.5, 137.5, 129.6, 126.2, 125.9, 124.1, 121.4, 103.2, 81.5, 70.4, 62.8, 49.7, 13.3; HRMS (ESI-APCI): Calcd. for $\text{C}_{13}\text{H}_{15}\text{NO}_5\text{S}$ ($\text{M}+\text{Na}$): 320.0563, Found: 320.0565; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 12.85$ min, $t_{\text{major}} = 11.66$ min; 98% ee.

Ethyl (2*S*,3*R*,4*S*)-3-nitro-2-((*E*)-styryl)-4-vinyltetrahydrofuran-3-carboxylate (3p)



3p was prepared according to the general procedure. Yield 87% (55.2 mg), d.r. = 20:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.44–7.29 (m, 5H), 6.77 (dd, $J = 15.8, 1.3$ Hz, 1H), 6.03 (dd, $J = 15.8, 7.0$ Hz, 1H), 5.65 (ddd, $J = 17.4, 10.3, 7.2$ Hz, 1H), 5.50 (dd, $J = 7.1, 1.2$ Hz, 1H), 5.41–5.26 (m, 2H), 4.47–4.34 (m, 1H), 4.22 (q, $J = 7.2$ Hz, 2H), 3.98–3.82 (m, 2H), 1.18 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.4, 135.5, 134.8, 129.5, 128.6, 128.4, 126.7, 122.9, 121.4, 102.6, 83.4, 70.2, 63.0, 49.2, 13.8; HRMS (ESI-MS): Calcd. for $\text{C}_{17}\text{H}_{19}\text{NO}_5$ (M+Na): 340.1155, Found: 340.1165; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 12.35$ min, $t_{\text{major}} = 11.13$ min; 99% ee.

General Procedure for Pd-Catalyzed Asymmetric Allylic Cycloaddition of Substituted Vinylethylene Carbonates **1 with 2-Nitroacrylate **2a****



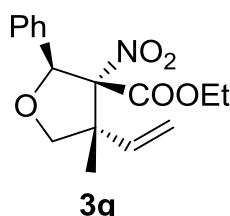
3q, R = Me, 78% yield, 20:1 dr, 95% ee

3r, R = Ph, 73% yield, 20:1 dr, 96% ee

To an oven dried screw-cap reaction tube equipped with a magnetic stir bar, $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (5.2 mg, 0.005 mmol, 2.5 mol%), (*S*)-Segphos (6.1 mg, 0.01 mmol, 5 mol%), **1** (0.24 mmol) and **2a** (0.2 mmol) were added. The reaction tube was sealed with rubber-septum, then evacuated and backfilled with nitrogen (this process was repeated a total of three times). Anhydrous 1,4-dioxane (2 mL) was added sequentially via syringe. The resulting mixture was stirred at 20 °C for 20 hours. The solvent was removed *in vacuo* with the aid of a rotary

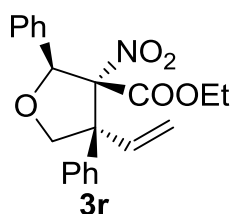
evaporator. The obtained residue was purified by flash column chromatography on silica gel to afford the corresponding products **3**. Diastereoisomer ratios (d.r.) were determined by ^1H NMR analysis of the reaction mixture. The enantiomeric excesses of the products were determined by HPLC analysis using chiral stationary phases as indicated for each case.

Ethyl (2*S*,3*R*,4*S*)-4-methyl-3-nitro-2-phenyl-4-vinyltetrahydrofuran-3-carboxylate (3q**)**



3q was prepared according to the general procedure. Yield: 78% (47.6 mg), d.r. = 20:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.56–7.47 (m, 2H), 7.34–7.27 (m, 3H), 6.05 (s, 1H), 5.99 (dd, $J = 17.3, 10.7$ Hz, 1H), 5.55–5.33 (m, 2H), 4.62 (d, $J = 8.2$ Hz, 1H), 4.24 (d, $J = 8.2$ Hz, 1H), 3.79–3.70 (m, 1H), 3.67–3.53 (m, 1H), 1.51 (s, 3H), 0.78 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.2, 138.5, 136.4, 128.5, 127.9, 127.0, 118.0, 103.7, 81.9, 77.5, 62.5, 53.0, 16.3, 13.2; HRMS (ESI-MS): Calcd. for $\text{C}_{16}\text{H}_{19}\text{NO}_5$ ($\text{M}+\text{Na}$): 328.1155, Found: 328.1156; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, $t_{\text{minor}} = 6.29$ min, $t_{\text{major}} = 8.00$ min; 95% ee.

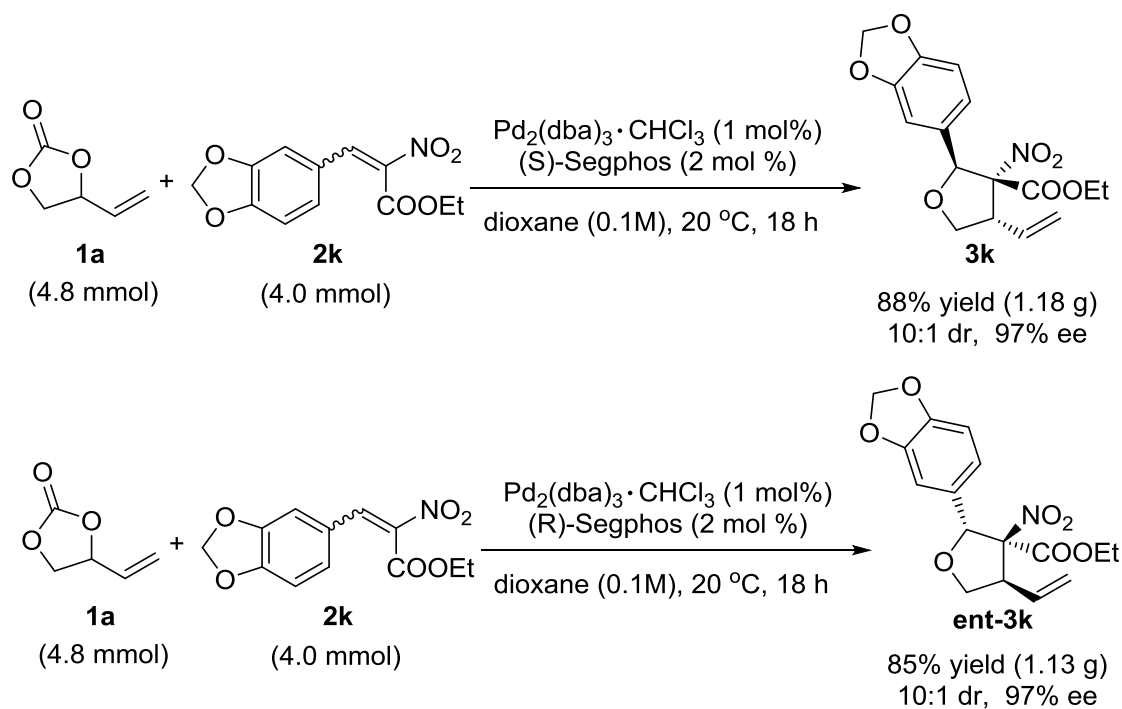
Ethyl (2*S*,3*R*,4*R*)-3-nitro-2,4-diphenyl-4-vinyltetrahydrofuran-3-carboxylate (3r**)**



3r was prepared according to the general procedure. Yield: 73% (53.6 mg), d.r. = 20:1; Purification: 2:98 EtOAc : Petroleum ether; colorless oil; ^1H NMR (400 MHz, Chloroform-*d*) δ 7.57–7.50 (m, 2H), 7.46–7.39 (m, 2H), 7.36–7.22 (m, 6H), 6.40 (s, 1H), 6.22 (dd, $J = 17.1, 10.5$ Hz, 1H), 5.34 (d, $J = 10.6$ Hz, 1H), 5.16 (d, $J = 17.1$ Hz, 1H), 5.04 (d, $J = 8.2$ Hz, 1H), 4.82 (d, $J = 8.3$ Hz, 1H), 3.58–3.47 (m, 2H), 0.65 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR (100 MHz, Chloroform-*d*) δ 163.5, 139.4, 138.5, 136.5, 128.5, 128.3, 128.0, 127.6, 127.2, 126.7, 118.6,

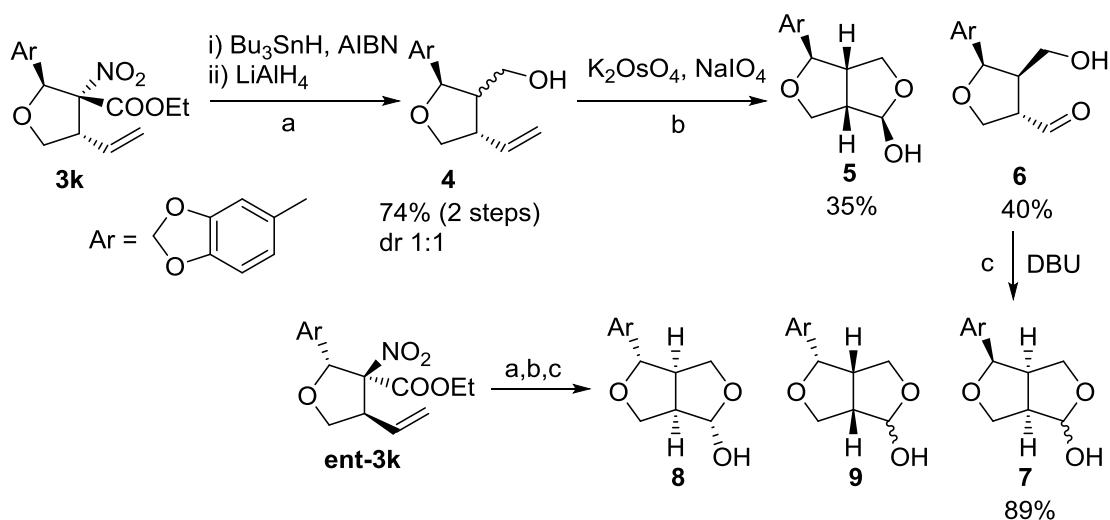
106.2, 83.8, 78.9, 62.6, 61.7, 12.9; HRMS (ESI-MS): Calcd. for C₂₁H₂₁NO₅ (M+Na): 390.1312, Found: 390.1307; HPLC conditions: Chiralcel Lux 5u Cellulose-2 column, 220 nm, flow rate: 0.5 mL/min, *i*-PrOH/hexanes = 5/95, *t*_{minor} = 12.14 min, *t*_{major} = 11.46 min; 96% ee.

Scale-up Transformation



To an oven dried screw-cap reaction tube equipped with a magnetic stir bar, Pd₂(dba)₃·CHCl₃ (41.6 mg, 0.04 mmol, 1 mol%), (S)-Segphos (48.8 mg, 0.08 mmol, 2 mol%), **1a** (4.8 mmol) and **2k** (4 mmol) were added. The reaction tube was sealed with rubber-septum, then evacuated and backfilled with nitrogen (this process was repeated a total of three times). Anhydrous 1,4-dioxane (40 mL) was added sequentially via syringe. The resulting mixture was stirred at 20 °C for 18 hours. The solvent was removed *in vacuo* with the aid of a rotary evaporator. The obtained residue was purified by flash column chromatography on silica gel to afford the corresponding product **3k** in 88% yield (1.18 g) with 10:1 d.r. and 97% ee. When (R)-Segphos was used in this reaction system, the desired product **ent-3k** was provided in 85% yield (1.13 g) with 10:1 d.r. and 97% ee.

The Elaboration of Product **3k** and **ent-3k** into Furofuran Lignans



Procedure a: i) According to the literature⁴, to a stirred solution of the product **3k** (402 mg, 1.2 mmol) and tributyltin hydride (640 μ L, 2.4 mmol) in PhMe (12 mL), AIBN (236.8 mg, 0.7 mmol) were added at room temperature. After being stirred at 80 °C for 20 min, the reaction mixture was cooled to room temperature and 6 mL CCl_4 were added. After being stirred at room temperature for 20 min, sat. KF aq. solution (50 mL) was added to the reaction mixture and the mixture was extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4 . After removal of Na_2SO_4 by a filtration, the solution was concentrated under reduced pressure to get the crude oil.

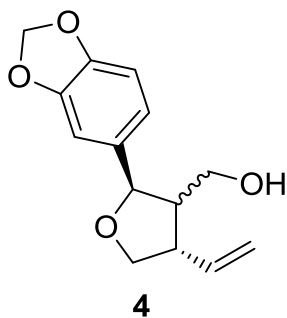
ii) According to the literature⁵, LiAlH_4 (3.6 mmol, 3 equiv.) was carefully added to a stirred solution of the above-mentioned crude oil in THF (20 mL) at 0 °C. After being stirred for 75 minutes at room temperature, the reaction mixture was diluted at 0 °C by the careful addition of saturated aqueous NH_4Cl solution. The phases were then separated, the aqueous layer was extracted with ethyl acetate, and the combined organic phases were dried over anhydrous Na_2SO_4 . After removal of Na_2SO_4 by a filtration, the solution was concentrated at reduced pressure. Purification by chromatography (petroleum ether/ethyl acetate, 10/2) provided the compound **4** (220 mg, d.r. = 1:1, 74% (2 steps)) as a colorless oil.

Procedure b: According to the literature⁶, in a two-neck round-bottom flask equipped with a magnetic stir bar and glass stoppers, compound **4** (129 mg, 0.52 mmol, 1 equiv.) was dissolved in t BuOH/ H_2O /THF (v/v = 1:1:1, 24 mL). To this solution, $\text{K}_2\text{OsO}_4 \cdot 2\text{H}_2\text{O}$ (10 mg, 0.026 mmol, 5 mol%), and 4-methyl morpholine N-oxide (NMO) (183 mg, 1.56 mmol, 3

equiv.) were sequentially added. The resulting mixture was stirred at 35 °C for 40 h. The reaction mixture was quenched with saturated aqueous Na₂SO₃ (16 mL) and stirred at room temperature for 1h. Then, the aqueous phase was extracted with EtOAc (3 × 10 mL). The organic layers combined and washed with aqueous KOH (1 M, 2 × 16 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The obtained crude was then dissolved in acetone/H₂O (v/v = 3:1, 16 mL), and NaIO₄ (334 mg, 1.56 mmol, 3 equiv.) was added. The reaction mixture was stirred at room temperature for 1 h and subsequently quenched by the addition of brine (20 mL). The obtained mixture was extracted with EtOAc, the organic layers dried over Na₂SO₄ and after removal of Na₂SO₄ by a filtration, the solution was concentrated under reduced pressure. Purification by a short column chromatography on silica (petroleum ether /ethyl acetate 10/3) afforded the hemiacetal product **5** [(-)-samin] (colorless needles, 45 mg, 35% yield) and aldehyde **6** (52 mg, 40% yield). When **ent-3k** was used in this reaction system, the enantiomer product hemiacetal product **8** [(+)-samin] (colorless needles) and aldehyde **ent-6** were provided with the same results.

Procedure c: According to the literature⁷, the aldehyde **6** was dissolved in toluene (5 mL), 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) (2 equiv.) was added at room temperature. The reaction mixture was stirred at room temperature for 3 h, removed the solvent under reduced pressure. Purification by a short column chromatography on silica (petroleum ether /ethyl acetate 10/3) afforded hemiacetal product **7** (46 mg, 89% yield). When aldehyde **ent-6** was used in this reaction system, the enantiomer product hemiacetal product **9** was provided with the same results.

((2R,4S)-2-(benzo[d][1,3]dioxol-5-yl)-4-vinyltetrahydrofuran-3-yl)methanol (4)

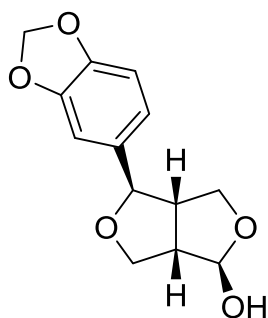


¹H NMR (500 MHz, Chloroform-*d*): First-diastereomer : δ 6.86–6.78 (overlapped, 1H), 6.78–

6.71 (overlapped, 3H), 5.96–5.92 (overlapped, 2H), 5.92–5.86 (overlapped, 1H), 5.13–5.04 (m, 2H), 4.66 (d, $J = 7.5$ Hz, 1H), 4.20 (dd, $J = 8.6, 6.7$ Hz, 1H), 3.80 (dd, $J = 8.5, 5.5$ Hz, 1H), 3.74–3.67 (m, 1H), 3.67–3.56 (overlapped, 1H), 3.15–3.04 (m, 1H), 2.35–2.25 (m, 1H), 1.96 (overlapped, 1H); Second-diastereomer : δ 6.86–6.78 (overlapped, 1H), 6.78–6.71 (overlapped, 3H), 5.96–5.92 (overlapped, 2H), 5.75 (ddd, $J = 18.0, 9.5, 8.0$ Hz, 1H), 5.22–5.14 (m, 3H), 4.26 (t, $J = 8.5$ Hz, 1H), 3.67–3.56 (overlapped, 1H), 3.36 (dd, $J = 11.5, 5.5$ Hz, 1H), 3.30–3.20 (m, 1H), 2.74 (p, $J = 8.5$ Hz, 1H), 2.43–2.38 (m, 1H), 1.96 (overlapped, 1H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 147.7, 146.8, 137.3, 136.3, 135.4, 133.5, 119.3, 119.2, 117.3, 116.8, 108.0, 107.9, 106.8, 106.2, 100.9, 100.8, 82.4, 82.0, 72.6, 72.4, 61.6, 60.6, 53.6, 51.5, 45.9, 45.6; HRMS (ESI-MS): Calcd. for $\text{C}_{14}\text{H}_{16}\text{O}_4$ ($\text{M}+\text{Na}$): 271.0941, Found: 271.0943.

(3a*S*,4*R*,6a*S*)-4-(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan-1-ol (5)

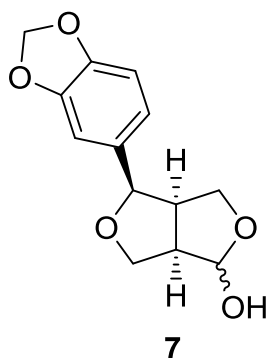
[(-)-samin]



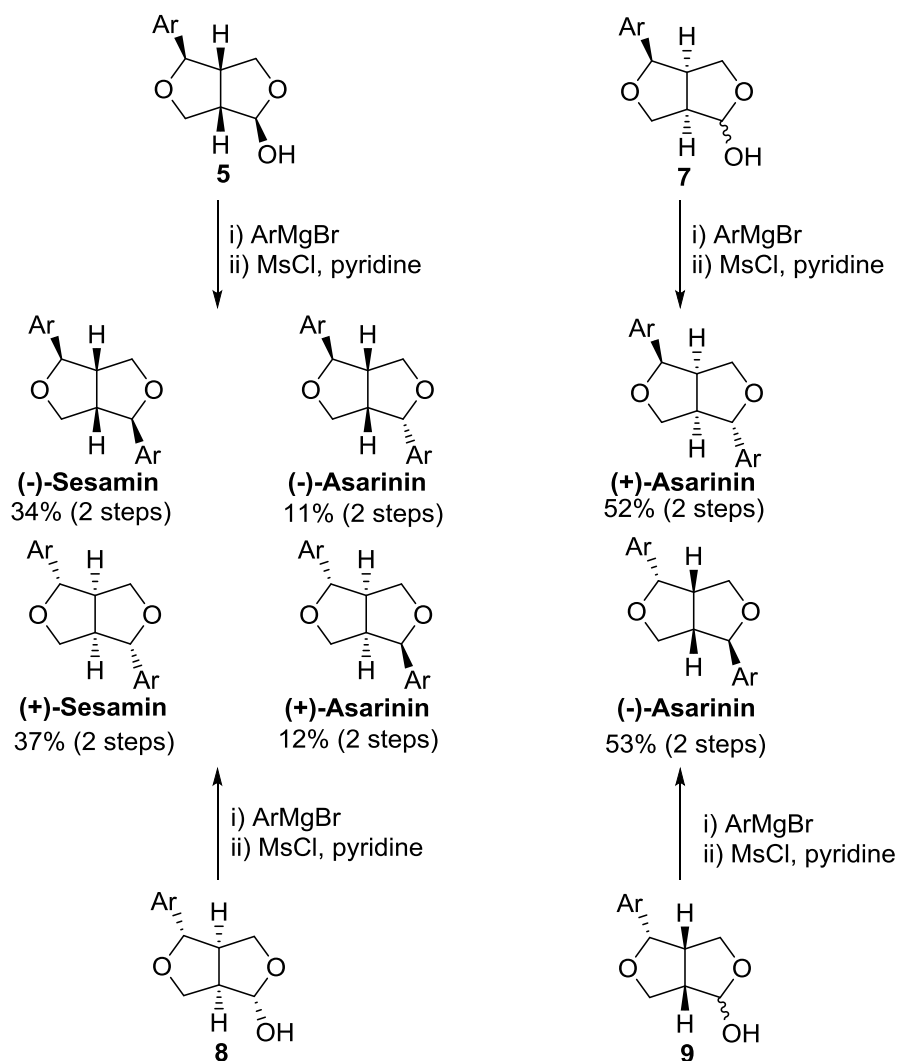
(-)-samin

^1H NMR (500 MHz, Chloroform-*d*) δ 6.86 (d, $J = 1.6$ Hz, 1H), 6.83–6.74 (m, 2H), 5.95 (s, 2H), 5.38 (s, 1H), 4.46–4.31 (m, 2H), 4.17 (dd, $J = 9.1, 6.0$ Hz, 1H), 3.91 (dd, $J = 9.1, 1.4$ Hz, 1H), 3.57 (dd, $J = 9.2, 7.4$ Hz, 1H), 3.07 (q, $J = 8.9$ Hz, 1H), 2.95–2.82 (m, 1H), 1.69 (s, 1H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 147.9, 147.2, 134.5, 119.6, 108.1, 106.5, 102.2, 101.0, 86.8, 71.2, 69.3, 53.6, 52.7; HRMS (ESI-MS): Calcd. for $\text{C}_{13}\text{H}_{14}\text{O}_5$ ($\text{M}+\text{Na}$): 273.0733, Found: 273.0736.

(3a*R*,4*R*,6a*R*)-4-(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan-1-ol (7)



^1H NMR (500 MHz, Chloroform-*d*) δ 6.85–6.81 (m, 1H), 6.80–6.70 (m, 2H), 5.94 (s, 2H), 5.38 (s, 1H), 4.81 (d, $J = 5.8$ Hz, 1H), 4.04 (dd, $J = 9.5, 2.7$ Hz, 1H), 3.95–3.84 (m, 1H), 3.81 (dd, $J = 9.4, 7.6$ Hz, 1H), 3.51 (dd, $J = 9.3, 3.2$ Hz, 1H), 3.17–3.10 (m, 1H), 3.00–2.90 (m, 1H); ^{13}C NMR (125 MHz, Chloroform-*d*) δ 147.5, 146.5, 132.4, 119.1, 108.0, 106.6, 104.2, 100.8, 83.4, 70.8, 67.6, 52.0, 47.3; HRMS (ESI-MS): Calcd. for $\text{C}_{13}\text{H}_{14}\text{O}_5$ ($\text{M}+\text{Na}$): 273.0733, Found: 273.0731.



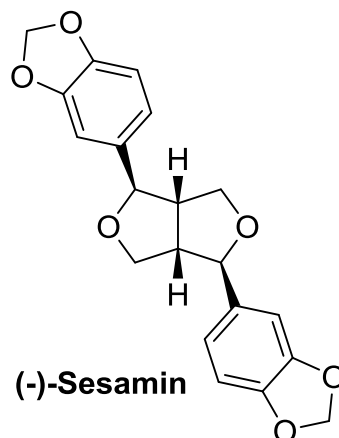
General procedure: According to the literature⁸, the compound **5** (50 mg, 0.2 mmol) was dissolved in THF (5 mL) under nitrogen, then the freshly prepared 3,4-methylenedioxyphenylmagnesium bromide (3 equiv., 1 mol/mL in THF) was added dropwise, the mixture was stirred at 40 °C overnight. The reaction mixture was quenched at 0 °C by the careful addition of saturated aqueous NH₄Cl solution. The phases were then separated, the aqueous layer was extracted with ethyl acetate, and the combined organic phases were dried and concentrated at reduced pressure to provide the crude diol.

According to the literature⁹, to a solution of crude diol in CH₂Cl₂ (0.4 mL) and pyridine (0.2 mL) at 0 °C was added MsCl (80 μL, 1.03 mmol) and the reaction warmed to room temperature and stirred for 1 day. The mixture was pipetted onto 1 N HCl (5 mL) and diluted with CH₂Cl₂ (8 mL). The organic layer was separated and the aqueous layer extracted with CH₂Cl₂ (3 × 10 mL). The combined organic layers were washed with 1 N HCl (10 mL) and

brine (15 mL), dried with MgSO₄, and concentrated in vacuo and purification by a short column chromatography on silica (petroleum ether/ethyl acetate, 10/1) afforded desired natural product (-)-Sesamin (white solid) and(-)-Asarinin (white solid) respectively.

(1*R*,3*aS*,4*R*,6*aS*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

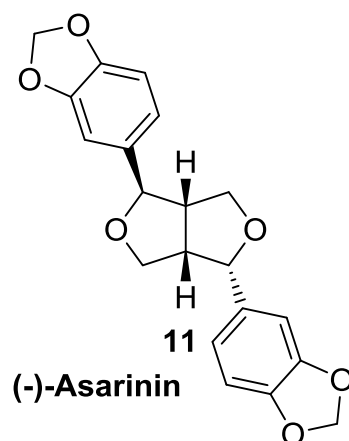
(-)-Sesamin



According to the above procedure, (-)-Sesamin was afforded (24.0 mg) (yield 34% in 2 steps) as a white solid; m.p. = 120-121 °C, $[\alpha]_D^{25} = -63.24$ ($c = 0.740$, CH₂Cl₂) {lit.¹⁰ m.p. = 123-124.5 °C, $[\alpha]_D^{25} = -64.24$ ($c = 1.08$, CHCl₃)}; ¹H NMR (500 MHz, Chloroform-*d*) δ 6.87–6.83(m, 2H), 6.82–6.75 (m, 4H), 5.94 (s, 4H), 4.71 (d, $J = 4.4$ Hz, 2H), 4.30–4.16 (m, 2H), 3.86 (dd, $J = 9.2, 3.5$ Hz, 2H), 3.13–2.99 (m, 2H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 147.9, 147.0, 135.0, 119.3, 108.1, 106.4, 101.0, 85.7, 71.6, 54.2; HRMS (ESI-MS): Calcd. for C₂₀H₁₈O₆ (M+Na): 377.0996, Found: 377.0999.

(1*R*,3*aS*,4*S*,6*aS*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

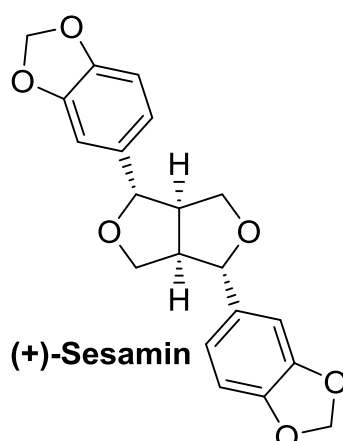
(-)-Asarinin



According to the above procedure, (-)-Asarinin was afforded (7.8 mg) (yield 11% in 2 steps) as a white solid; m.p. = 123-124 °C, $[\alpha]_D^{25} = -70.00$ ($c = 0.200$, CH_2Cl_2) {lit.¹¹ m.p. = 122-123 °C, $[\alpha]_D^{26} = -71.90$ ($c = 0.19$, CHCl_3)}; ^1H NMR (400 MHz, Chloroform-*d*) δ 6.90–6.85 (m, 2H), 6.84–6.75 (m, 4H), 5.96 (s, 2H), 5.95 (s, 2H), 4.83 (d, $J = 5.3$ Hz, 1H), 4.39 (d, $J = 7.1$ Hz, 1H), 4.10 (d, $J = 9.4$ Hz, 1H), 3.99–3.77 (m, 2H), 3.40–3.21 (m, 2H), 2.95–2.75 (m, 1H); ^{13}C NMR (125MHz, Chloroform-*d*) δ 147.9, 147.6, 147.1, 146.5, 135.0, 132.2, 119.5, 118.6, 108.1, 106.5, 106.3, 101.0, 100.9, 87.6, 82.0, 70.8, 69.6, 54.6, 52.5, 50.1; HRMS (ESI-MS): Calcd. for $\text{C}_{20}\text{H}_{18}\text{O}_6$ ($\text{M}+\text{Na}$): 377.0996, Found: 377.0996.

(1*S*,3*aR*,4*S*,6*aR*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

(+)-Sesamin

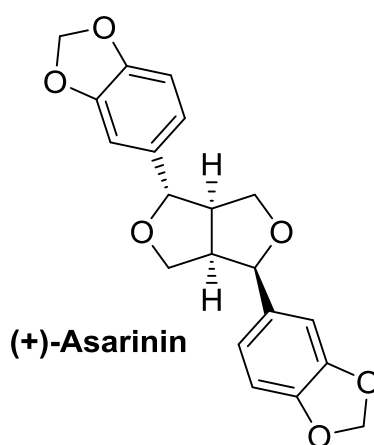


According to the above procedures, compound **7** was used as starting material, (+)-Sesamin was afforded (26.2 mg) (yield 37% in 2 steps) as a white solid; m.p. = 120-121 °C $[\alpha]_D^{25} =$

+60.54 ($c = 0.740$, CH_2Cl_2) {lit.¹² m.p. = 122 °C, $[\alpha]^{20.4}_{\text{D}} = +61.5$ ($c = 0.58$, CH_2Cl_2)}; ^1H NMR (500 MHz, Chloroform- d) δ 6.87–6.83(m, 2H), 6.82–6.75 (m, 4H), 5.94 (s, 4H), 4.71 (d, $J = 4.5$ Hz, 2H), 4.30–4.16 (m, 2H), 3.86 (dd, $J = 9.0, 3.5$ Hz, 2H), 3.13–2.99 (m, 2H); ^{13}C NMR (125 MHz, Chloroform- d) δ 147.9, 147.0, 135.0, 119.3, 108.1, 106.4, 101.0, 85.7, 71.6, 54.2; HRMS (ESI-MS): Calcd. for $\text{C}_{20}\text{H}_{18}\text{O}_6$ (M+Na): 377.0996, Found: 377.0994.

(1*R*,3*aR*,4*S*,6*aR*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

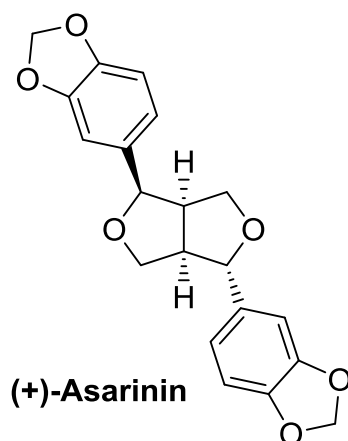
(+)-Asarinin



According to the above procedure, compound **7** was used as starting material, (+)-Asarinin was afforded (8.5 mg) (yield 12% in 2 steps) as a white solid; m.p. = 120-121 °C $[\alpha]^{25}_{\text{D}} = +61$ ($c = 0.160$, CH_2Cl_2) {lit.¹³ m.p. = 123 °C, $[\alpha]^{25}_{\text{D}} = +77.8$ ($c = 0.45$, CHCl_3)}; ^1H NMR (400 MHz, Chloroform- d) δ 6.90–6.85 (m, 2H), 6.8–6.75 (m, 4H), 5.96 (s, 2H), 5.95 (s, 2H), 4.83 (d, $J = 5.3$ Hz, 1H), 4.39 (d, $J = 7.1$ Hz, 1H), 4.10 (d, $J = 9.4$ Hz, 1H), 3.99–3.77 (m, 2H), 3.40–3.21 (m, 2H), 2.95–2.75 (m, 1H); ^{13}C NMR (125 MHz, Chloroform- d) δ 147.9, 147.6, 147.1, 146.5, 135.0, 132.2, 119.5, 118.6, 108.1, 106.5, 106.3, 101.0, 100.9, 87.6, 82.0, 70.8, 69.6, 54.6, 52.5, 50.1; HRMS (ESI-MS): Calcd. for $\text{C}_{20}\text{H}_{18}\text{O}_6$ (M+Na): 377.0996, Found: 377.0993.

(1*R*,3*aR*,4*S*,6*aR*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

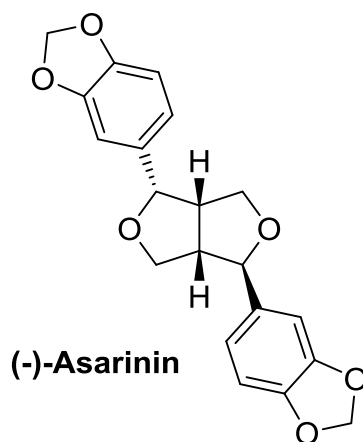
(+)-Asarinin



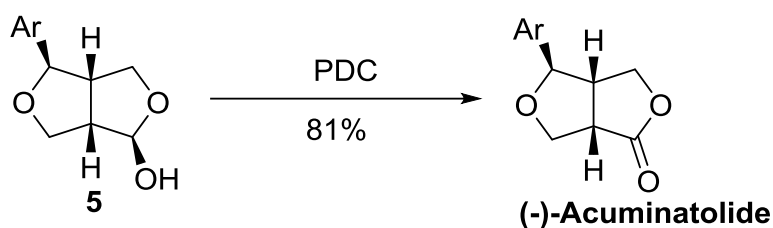
According to the above procedures, compound **8** was used as starting material, (+)-Asarinin was afforded (36.8 mg) (yield 52% in 2 steps) as a white solid; m.p. = 122-123 °C, $[\alpha]^{25}_{\text{D}} = +90$ ($c = 0.240$, CH_2Cl_2) {lit.¹³ m.p. = 123 °C, $[\alpha]^{25}_{\text{D}} = +77.8$ ($c = 0.45$, CHCl_3)}; ¹H NMR (400 MHz, Chloroform-*d*) δ 6.90–6.85 (m, 2H), 6.84–6.75 (m, 4H), 5.96 (s, 2H), 5.95 (s, 2H), 4.83 (d, $J = 5.3$ Hz, 1H), 4.39 (d, $J = 7.1$ Hz, 1H), 4.10 (d, $J = 9.4$ Hz, 1H), 3.99–3.77 (m, 2H), 3.40–3.21 (m, 2H), 2.95–2.75 (m, 1H); ¹³C NMR (125MHz, Chloroform-*d*) δ 147.9, 147.6, 147.1, 146.5, 135.0, 132.2, 119.5, 118.6, 108.1, 106.5, 106.3, 101.0, 100.9, 87.6, 82.0, 70.8, 69.6, 54.6, 52.5, 50.1; HRMS (ESI-MS): Calcd. for $\text{C}_{20}\text{H}_{18}\text{O}_6$ (M+Na): 377.0996, Found: 377.0999.

(1*R*,3*aS*,4*S*,6*aS*)-1,4-bis(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan

(-)-Asarinin

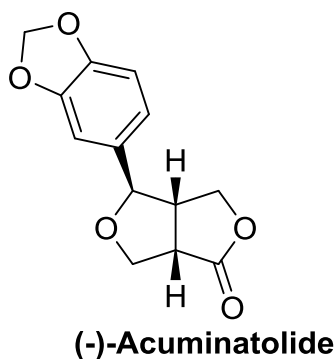


According to the above procedures, compound **9** was used as starting material, (-)-Asarinin was afforded (41.46 mg) (yield 53% in 2 steps) as a white solid; m.p. = 122-123 °C [α]²⁵_D = -82 (*c* = 0.200, CH₂Cl₂) {lit.¹¹ m.p. = 122-123 °C, [α]²⁶_D = -71.9 (*c* = 0.19, CHCl₃)}. ¹H NMR (400 MHz, Chloroform-*d*) δ 6.90–6.85 (m, 2H), 6.84–6.75 (m, 4H), 5.96 (s, 2H), 5.95 (s, 2H), 4.83 (d, *J* = 5.3 Hz, 1H), 4.39 (d, *J* = 7.1 Hz, 1H), 4.10 (d, *J* = 9.4 Hz, 1H), 3.99–3.77 (m, 2H), 3.40–3.21 (m, 2H), 2.95–2.75 (m, 1H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 147.9, 147.6, 147.1, 146.5, 135.0, 132.2, 119.5, 118.6, 108.1, 106.5, 106.3, 101.0, 100.9, 87.6, 82.0, 70.8, 69.6, 54.6, 52.5, 50.1; HRMS (ESI-MS): Calcd. for C₂₀H₁₈O₆ (M+Na): 377.0996, Found: 377.0998.



(3a*S*,4*R*,6a*S*)-4-(benzo[*d*][1,3]dioxol-5-yl)tetrahydro-1*H*,3*H*-furo[3,4-*c*]furan-1-one

(-)-Acuminatolide



According to the literature¹⁴, to a solution of compound **5** (0.32 mmol) in dry CH₂Cl₂ was added pyridinium dichromate (PDC) (4 equiv., 481 mg), AcOH (1 equiv., 20 μ L), and 4Å molecular sieves (500 mg). The resulting suspension was stirred for 6 h at room temperature, then filtrated through a plug of silica gel and the filtrate was evaporated in vacuo to give a yellow solid and purification by a short column chromatography on silica (petroleum ether/ethyl acetate, 10/2) afforded (-)-Acuminatolide as a white solid in 81% yield (64.3 mg);

mp 118–119 °C; ¹H NMR (500 MHz, Chloroform-*d*) δ 6.87–6.83 (m, 1H), 6.82–6.75 (m, 2H), 5.97 (s, 2H), 4.61 (d, *J* = 6.8 Hz, 1H), 4.49 (dd, *J* = 9.8, 6.9 Hz, 1H), 4.39–4.28 (m, 2H), 4.19 (dd, *J* = 9.3, 3.8 Hz, 1H), 3.44 (td, *J* = 8.9, 3.8 Hz, 1H), 3.15–3.05 (m, 1H); ¹³C NMR (125 MHz, Chloroform-*d*) δ 178.0, 148.2, 147.7, 132.7, 119.6, 108.3, 106.3, 101.2, 86.0, 70.0, 69.7, 48.3, 45.9; HRMS (ESI-MS): Calcd. for C₁₃H₁₂O₅ (M+Na): 271.0577, Found: 271.0579.

X-rays crystallography of **3i** (CCDC2015920) and (-)-Acuminatolide (CCDC2015921)

Single crystal of **3i** and (-)-Acuminatolide were obtained from THF /n-Hexane solvent at room temperature. Diffraction data were collected on Bruker SMART Apex-III CMOS-Based X-ray diffractometer with Cu-Kα. Radiation ($\lambda = 1.54178$). The empirical absorption correction was applied by using the SADABS program. The structure was solved using direct method, and refined by full matrix least-squares on F² (G.M Sheldrick, SHELXTL2014, program of crystal structure refinement, University of Göttingen, Germany).

Table S1. Crystal Data and Structure Refinement for 3i

Identification code	3i
Empirical formula	C ₁₇ H ₂₁ N O ₇
Formula weight	351.35
Temperature	296(2) K
Wavelength	1.54178 Å
Crystal system, space group	Orthorhombic, P2(1)2(1)2(1)
Unit cell dimensions	a = 6.921(6) Å alpha = 90 deg. b = 10.91(3) Å beta = 90 deg. c = 24.068(19) Å gamma = 90 deg.
Volume	1817(5) Å ³
Z, Calculated density	4, 1.285 Mg/m ³
Absorption coefficient	0.846 mm ⁻¹
F(000)	744
Crystal size	0.180 x 0.160 x 0.120 mm
Theta range for data collection	3.673 to 65.128 deg.
Limiting indices	-7<=h<=8, -12<=k<=12, -28<=l<=28

Reflections collected / unique	21728 / 3094 [R(int) = 0.0442]
Completeness to theta = 65.128	99.7 %
Refinement method	Full-matrix least-squares on F ²
Data / restraints / parameters	3094 / 0 / 230
Goodness-of-fit on F ²	1.020
Final R indices [I>2sigma(I)]	R1 = 0.0378, wR2 = 0.1043
R indices (all data)	R1 = 0.0452, wR2 = 0.1131
Absolute structure parameter	0.04(8)
Extinction coefficient	0.0051(9)
Largest diff. peak and hole	0.149 and -0.094 e.Å ⁻³

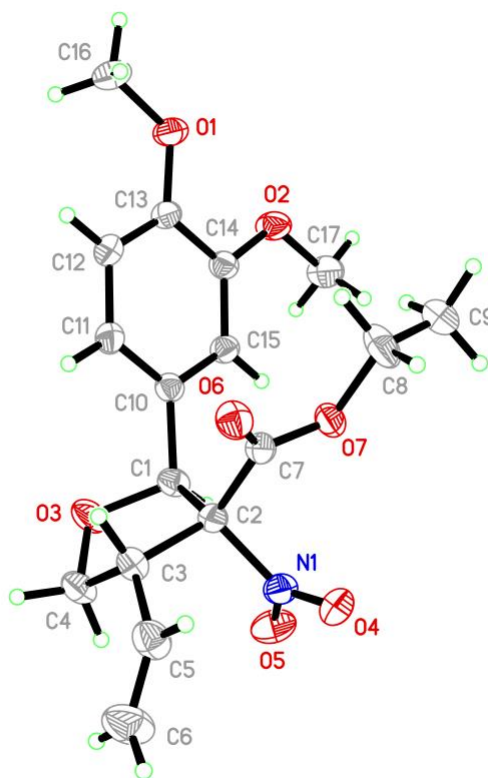


Figure S1: Molecular structure of **3i**

Table S2. Crystal Data and Structure Refinement for (-)-Acuminatolide

Identification code	(-)-Acuminatolide
Empirical formula	C ₁₃ H ₁₂ O ₅
Formula weight	248.23

Temperature	298(2) K
Wavelength	1.54178 Å
Crystal system, space group	Orthorhombic, P2(1)2(1)2(1)
Unit cell dimensions	a = 6.6885(3) Å alpha = 90 deg. b = 7.1093(3) Å beta = 90 deg. c = 24.1880(9) Å gamma = 90 deg.
Volume	1150.15(8) Å ³
Z, Calculated density	4, 1.434 Mg/m ³
Absorption coefficient	0.938 mm ⁻¹
F(000)	520
Crystal size	0.180 x 0.160 x 0.150 mm
Theta range for data collection	3.655 to 68.391 deg.
Limiting indices	-8<=h<=8, -8<=k<=8, -29<=l<=29
Reflections collected / unique	12764 / 2095 [R(int) = 0.1044]
Completeness to theta = 67.679	99.1 %
Refinement method	Full-matrix least-squares on F ²
Data / restraints / parameters	2095 / 0 / 163
Goodness-of-fit on F ²	1.038
Final R indices [I>2sigma(I)]	R1 = 0.0329, wR2 = 0.0805
R indices (all data)	R1 = 0.0687, wR2 = 0.0898
Absolute structure parameter	0.03(9)
Extinction coefficient	n/a
Largest diff. peak and hole	0.250 and -0.251 e.Å ⁻³

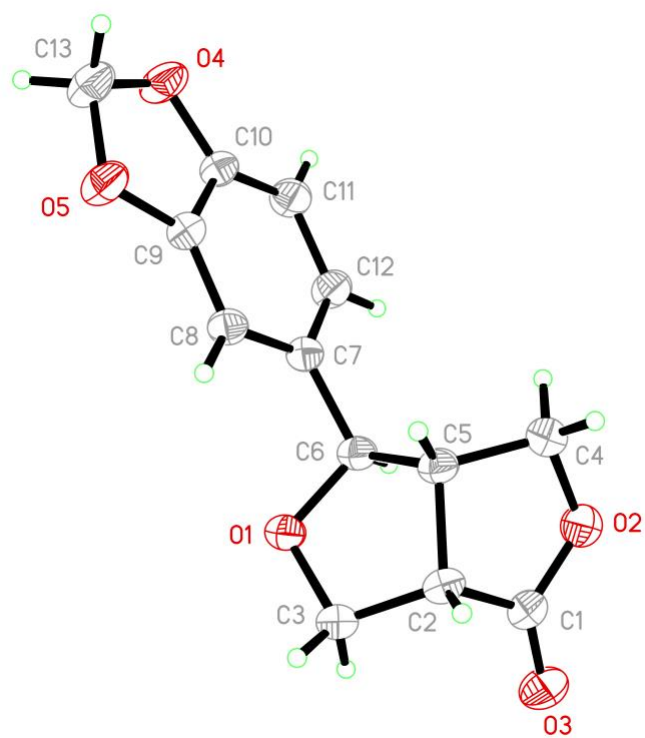
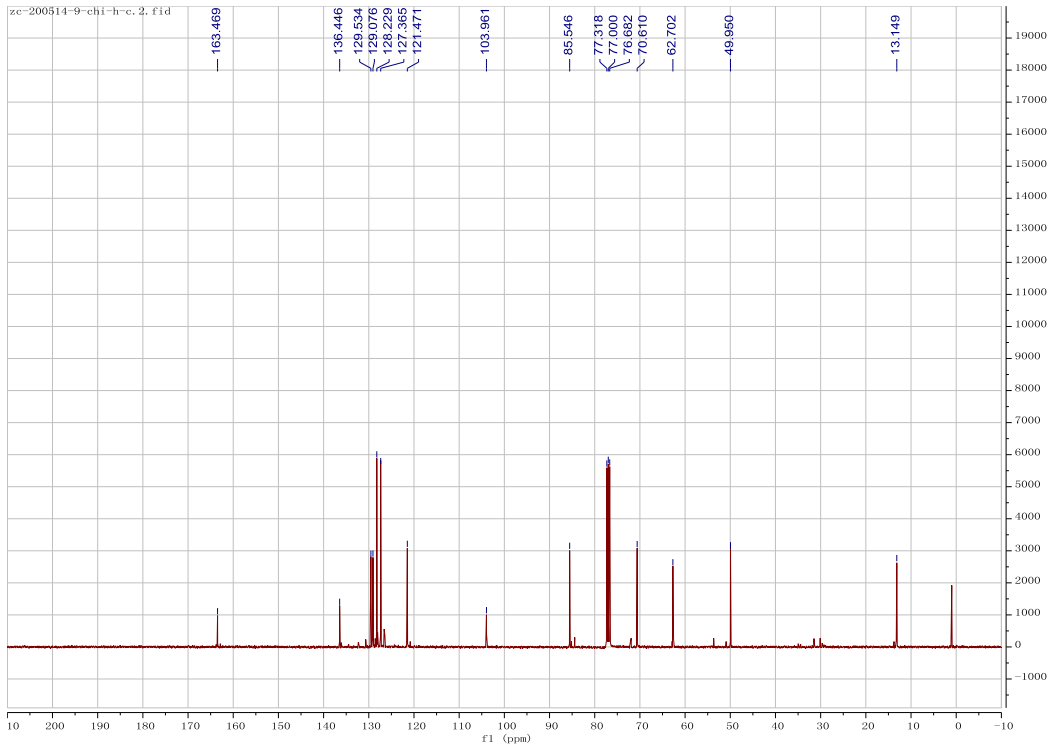
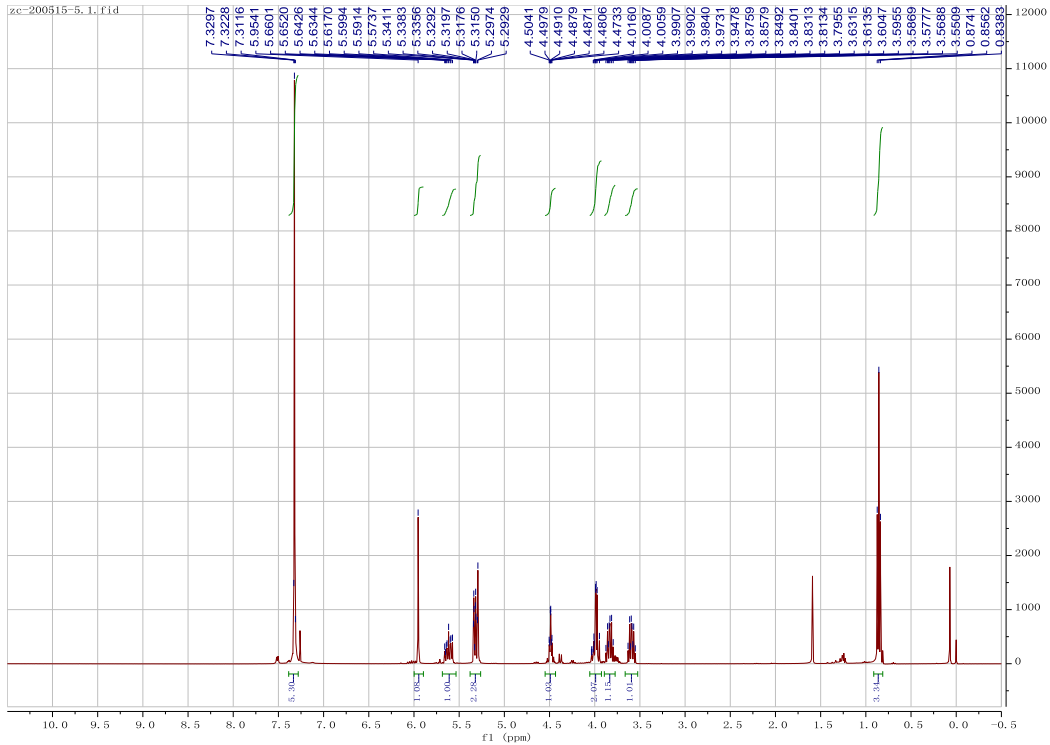
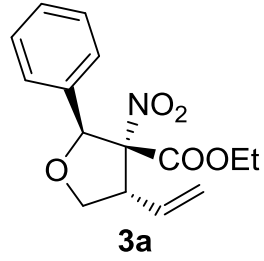
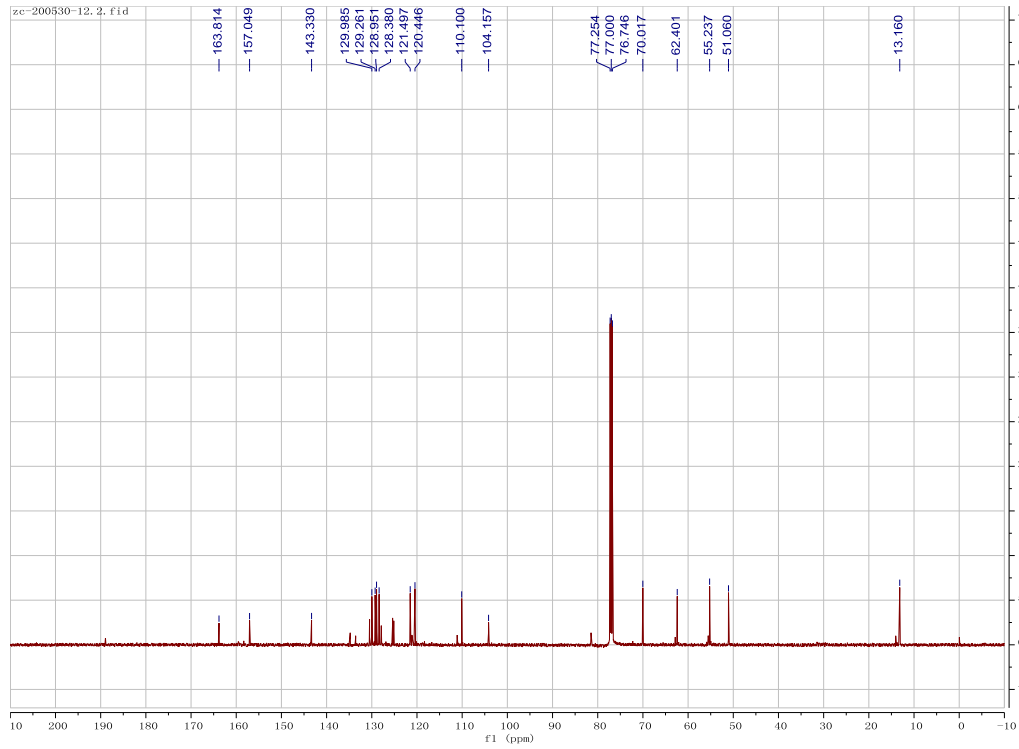
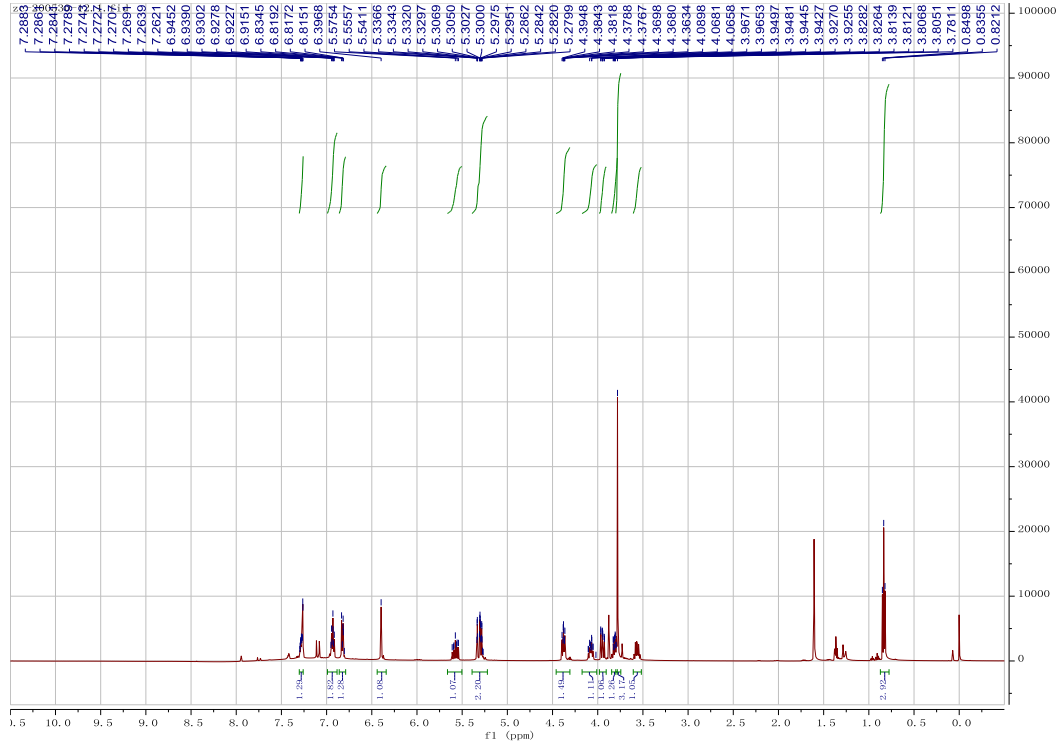
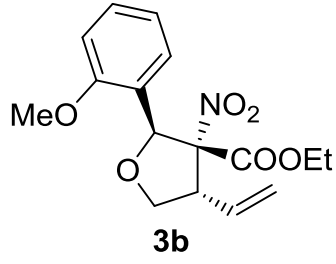


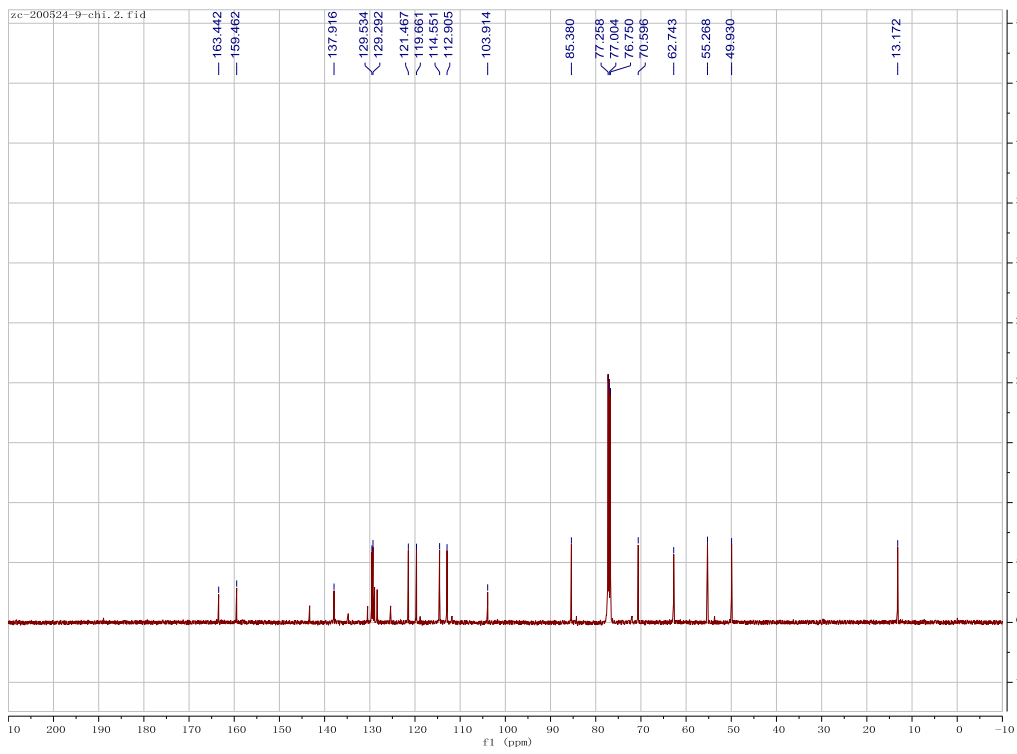
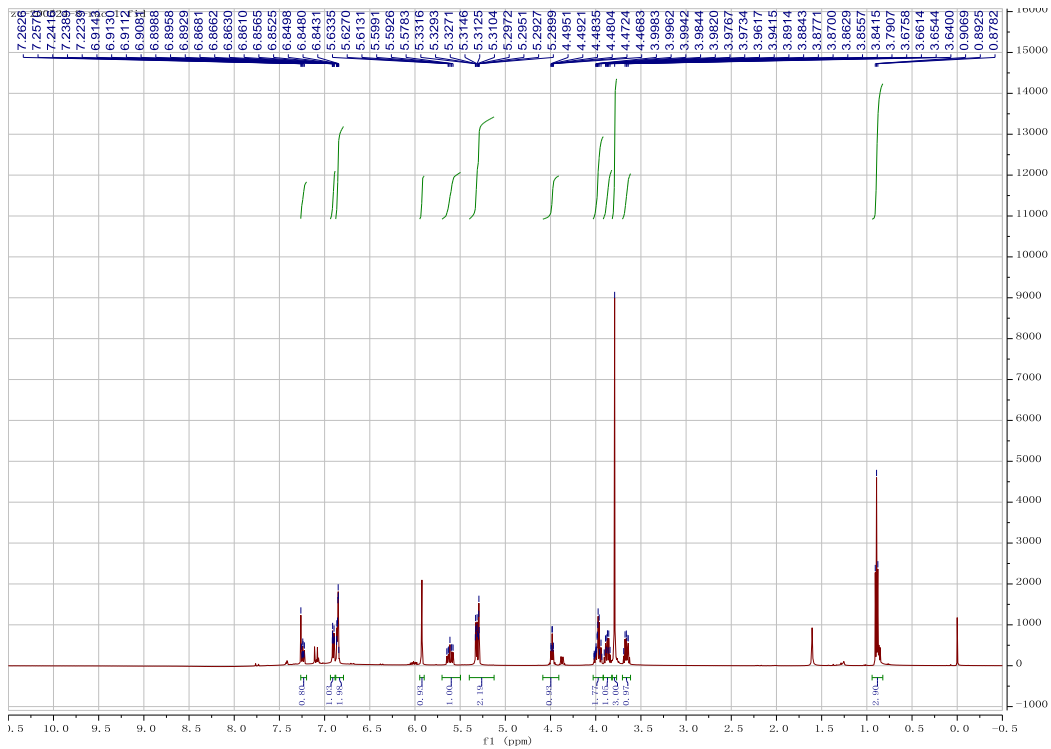
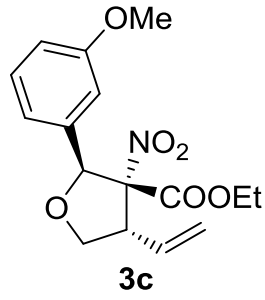
Figure S2: Molecular structure of (-)-Acuminatolide

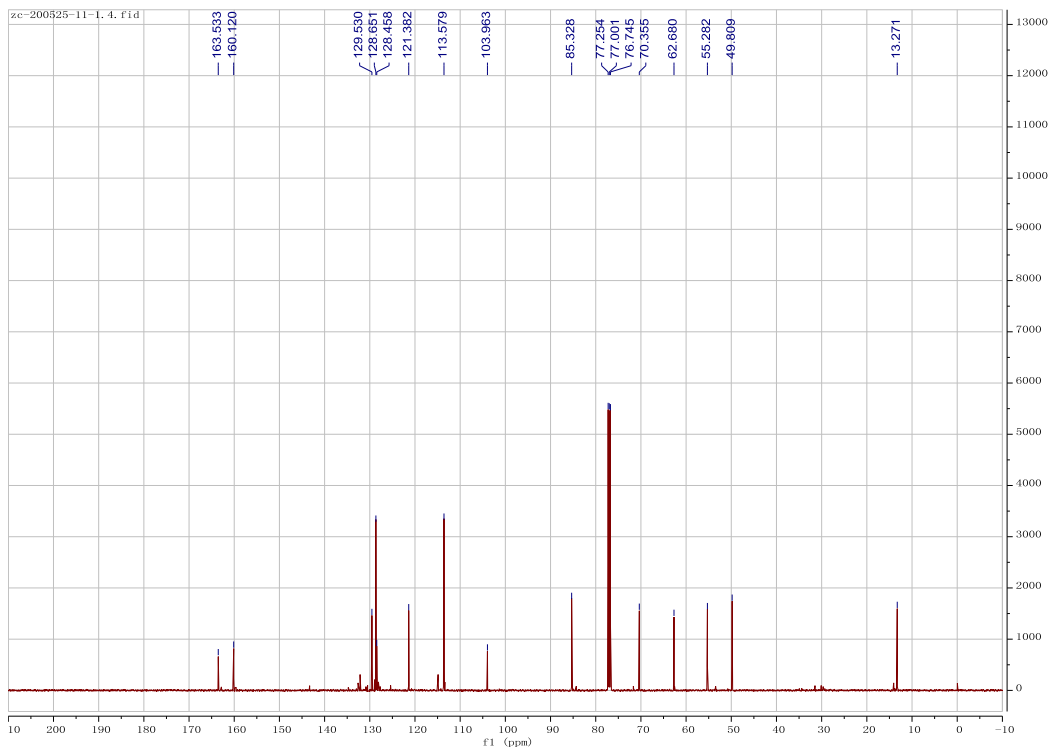
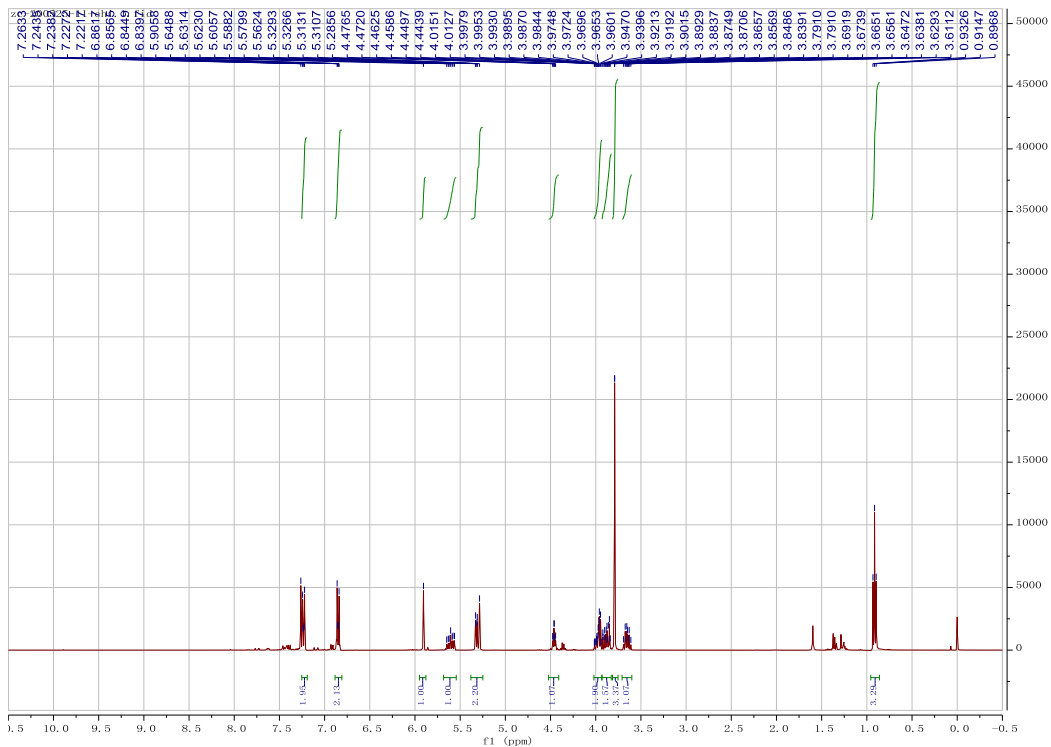
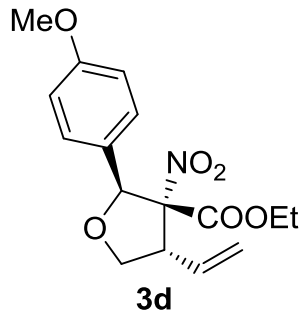
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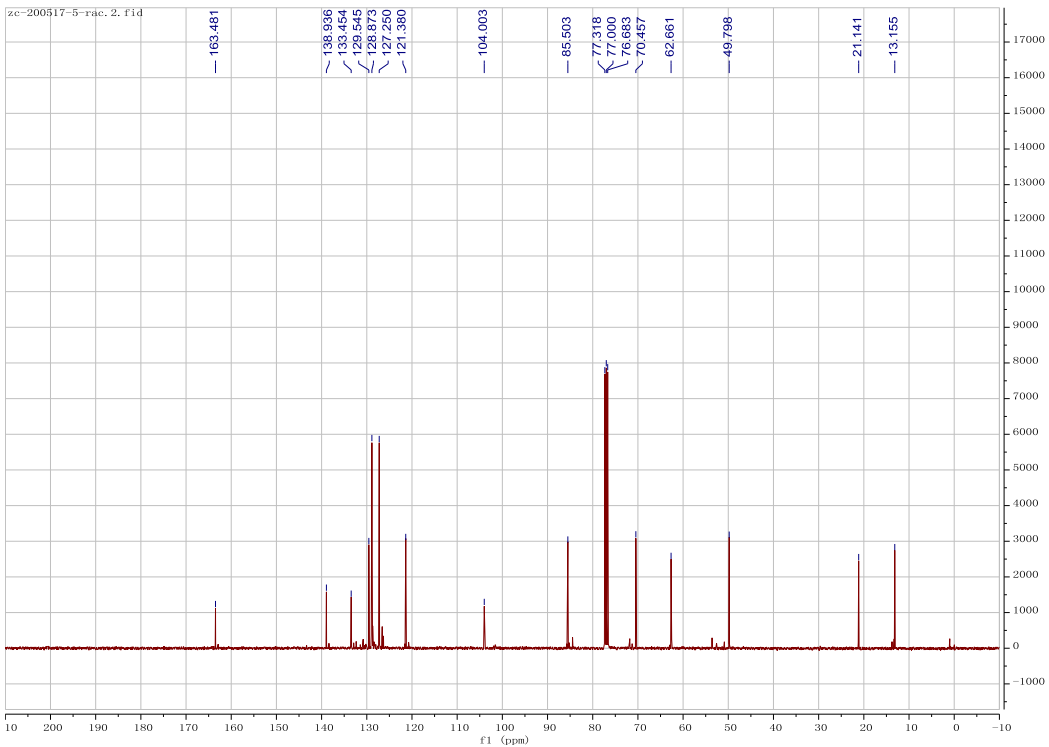
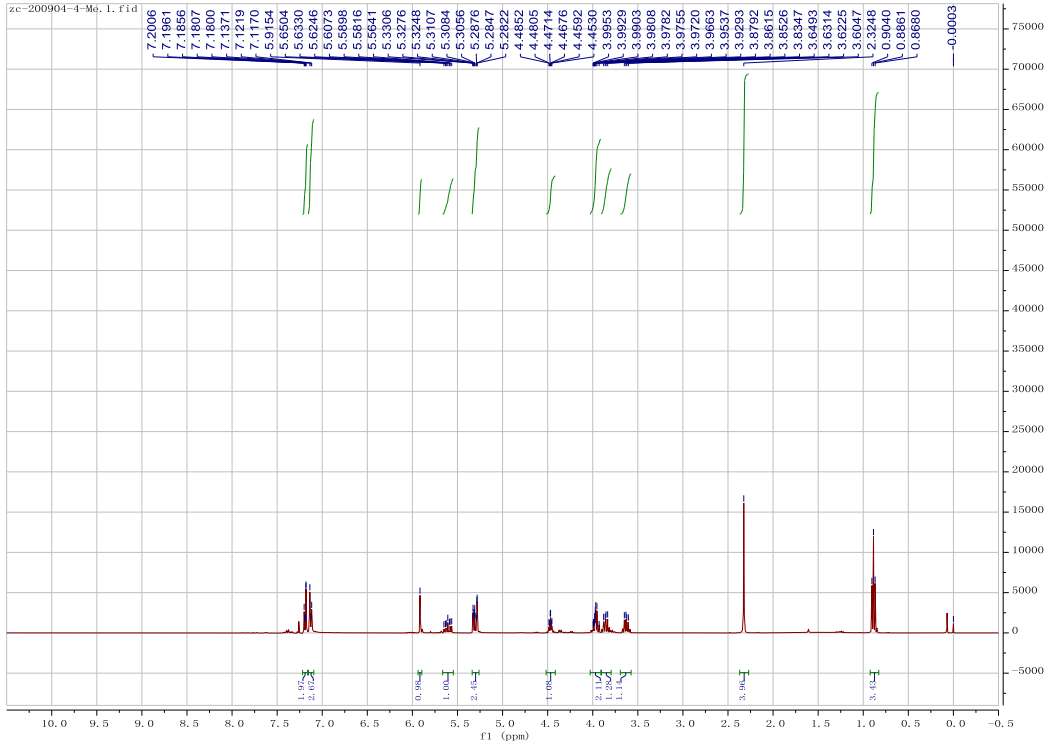
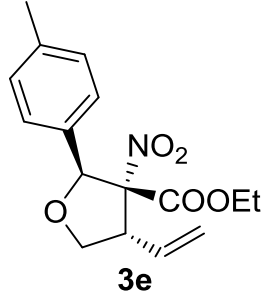
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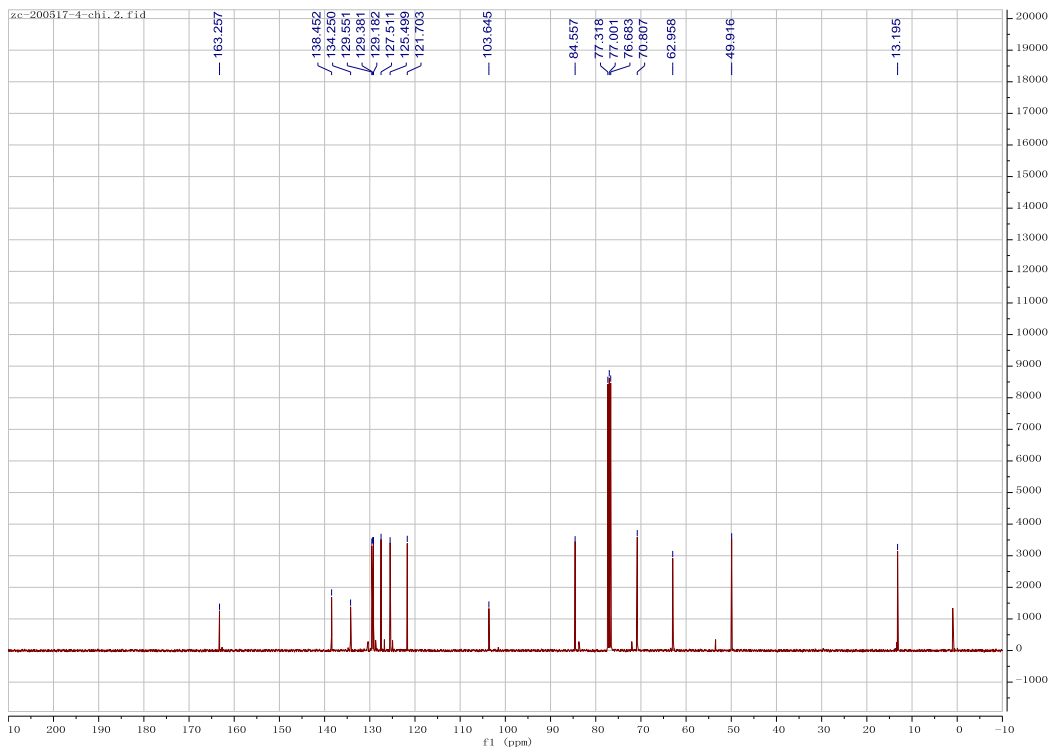
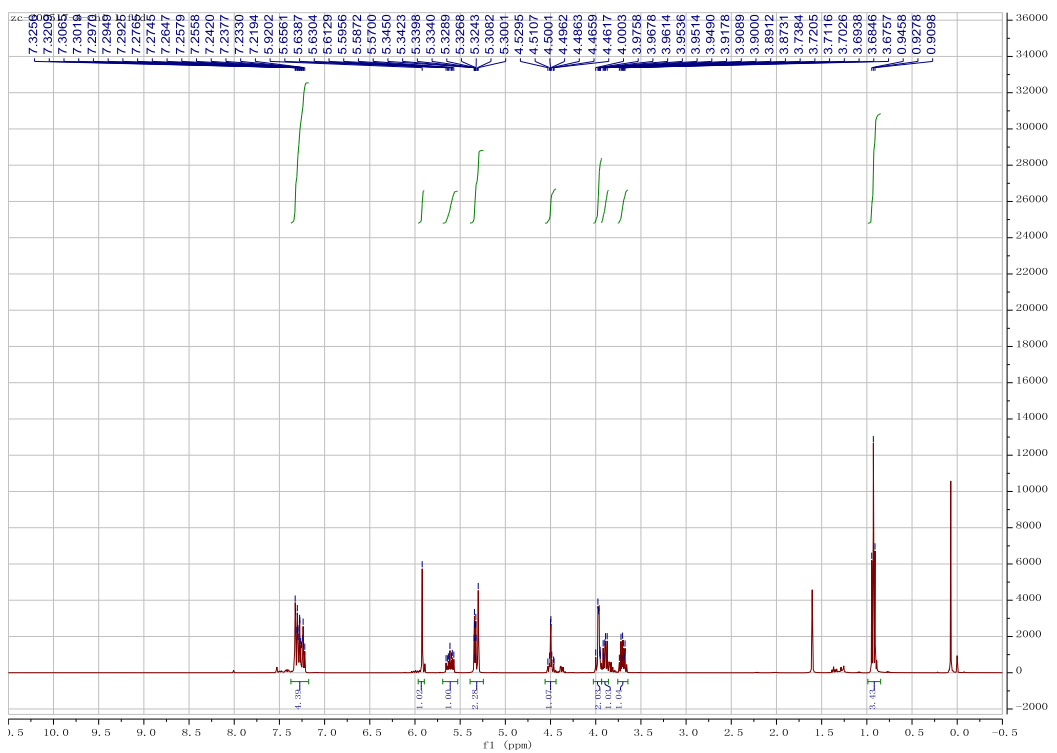
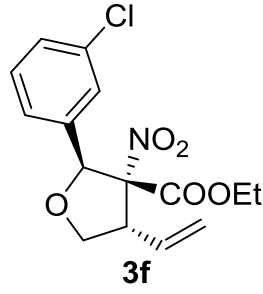


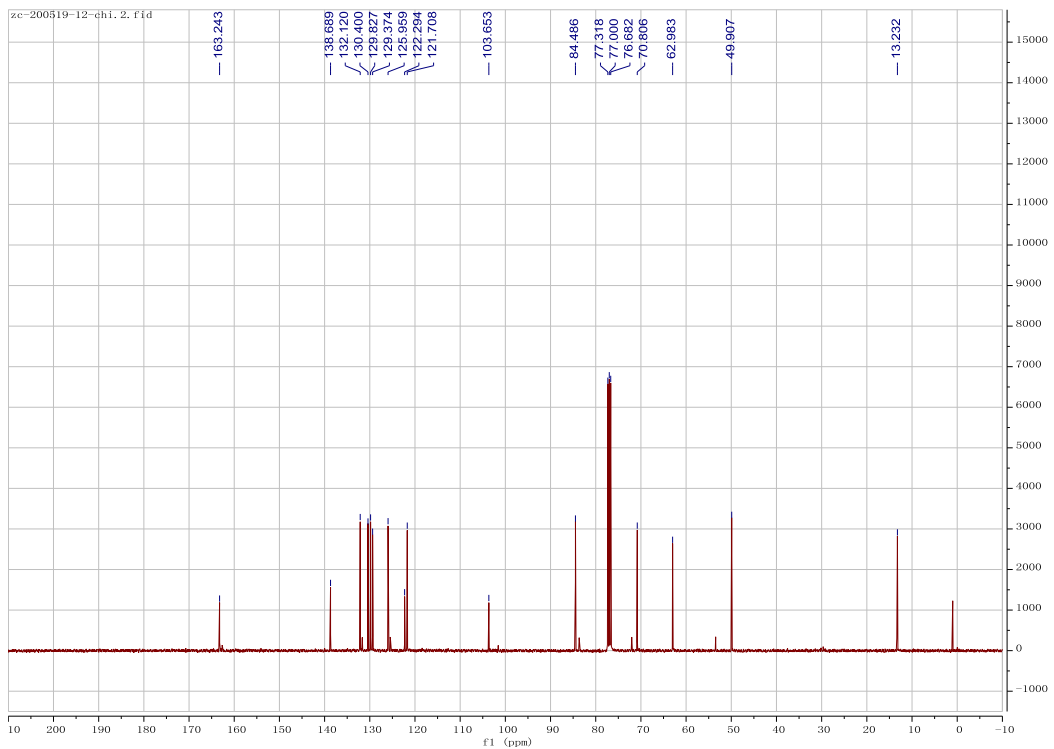
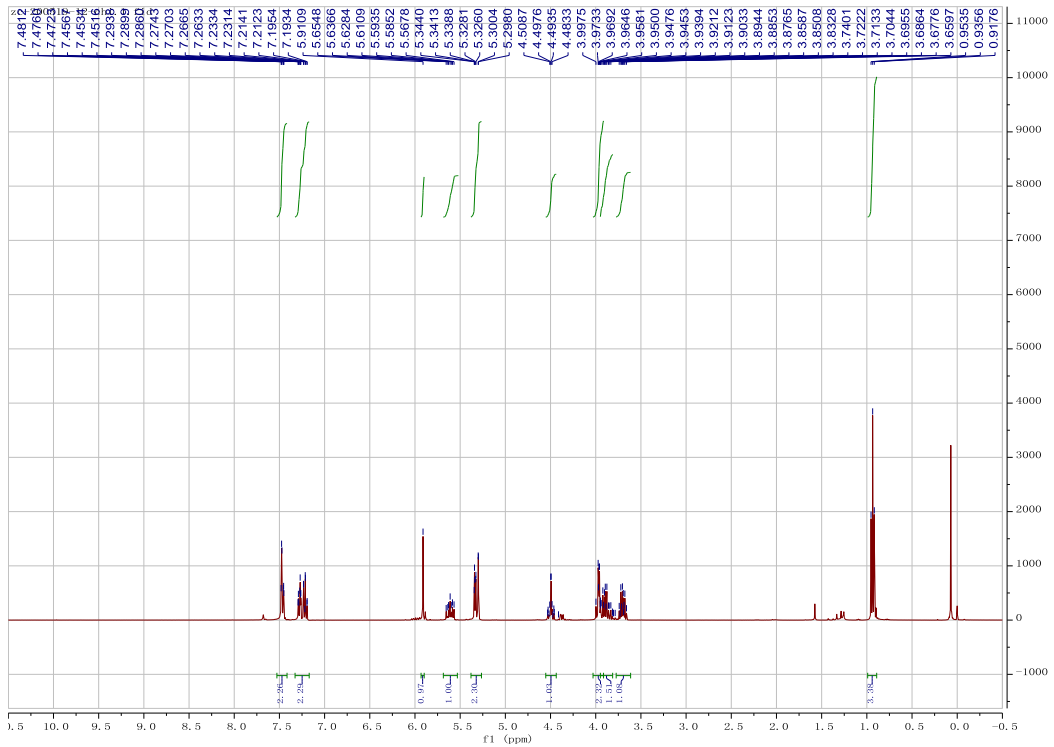
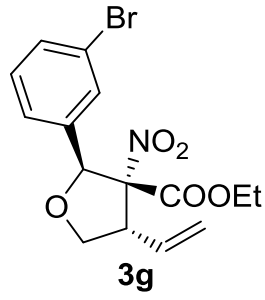


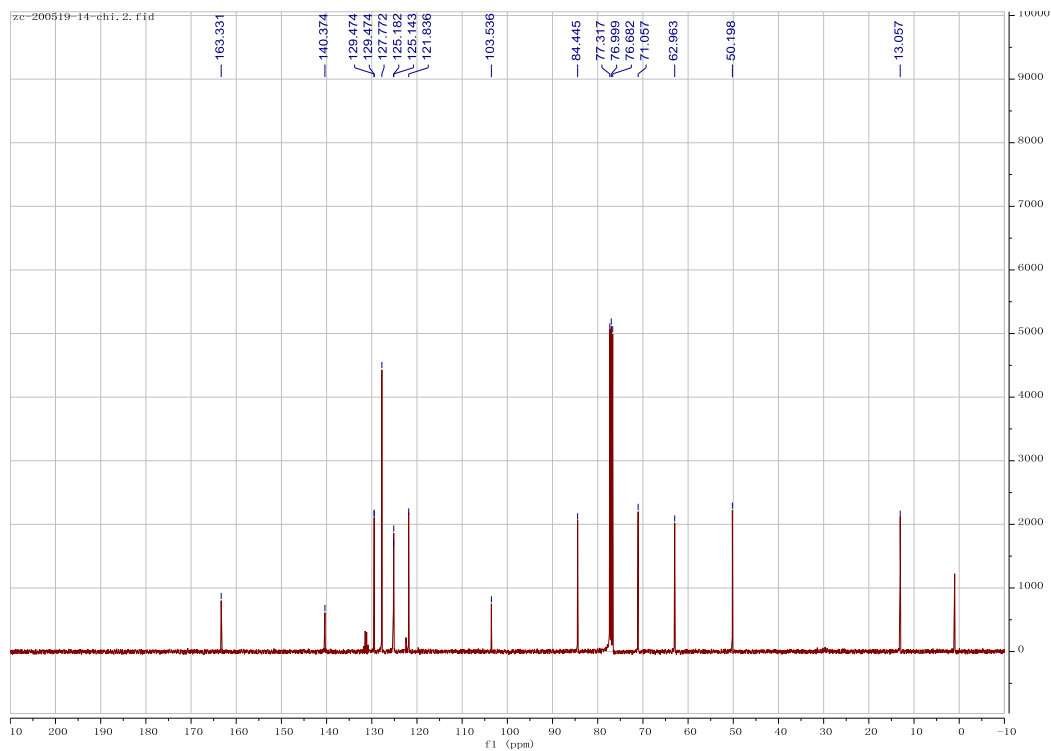
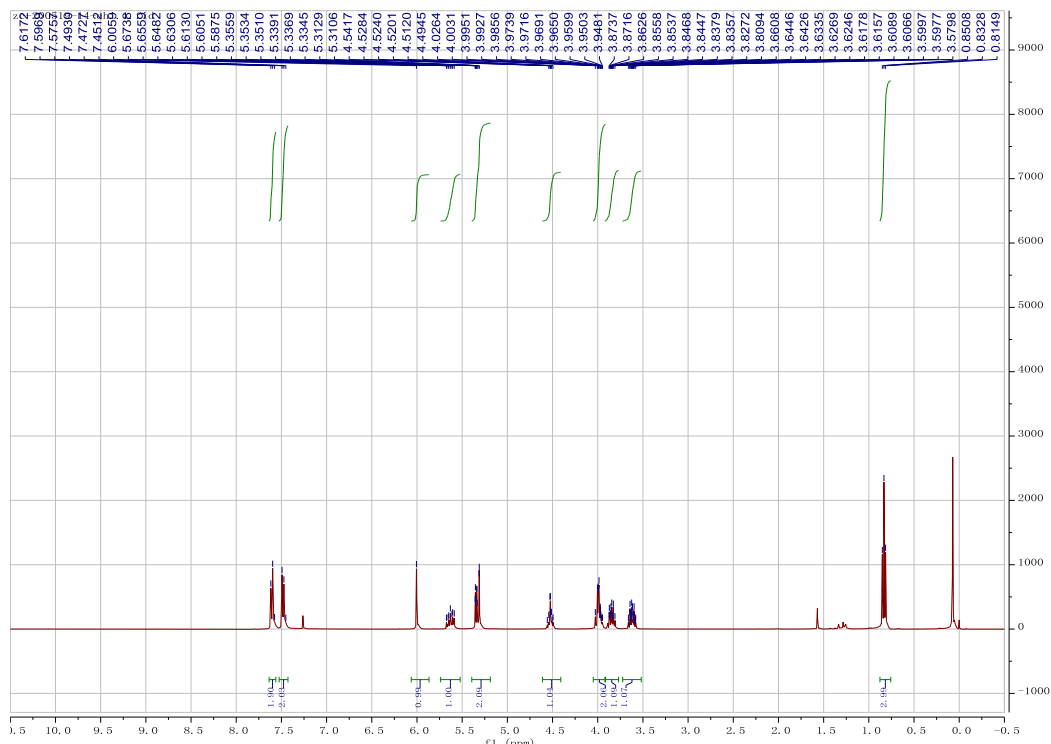
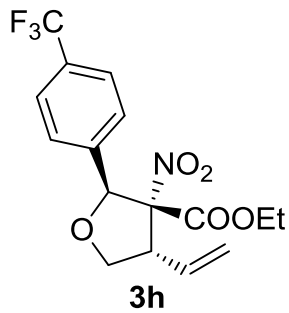


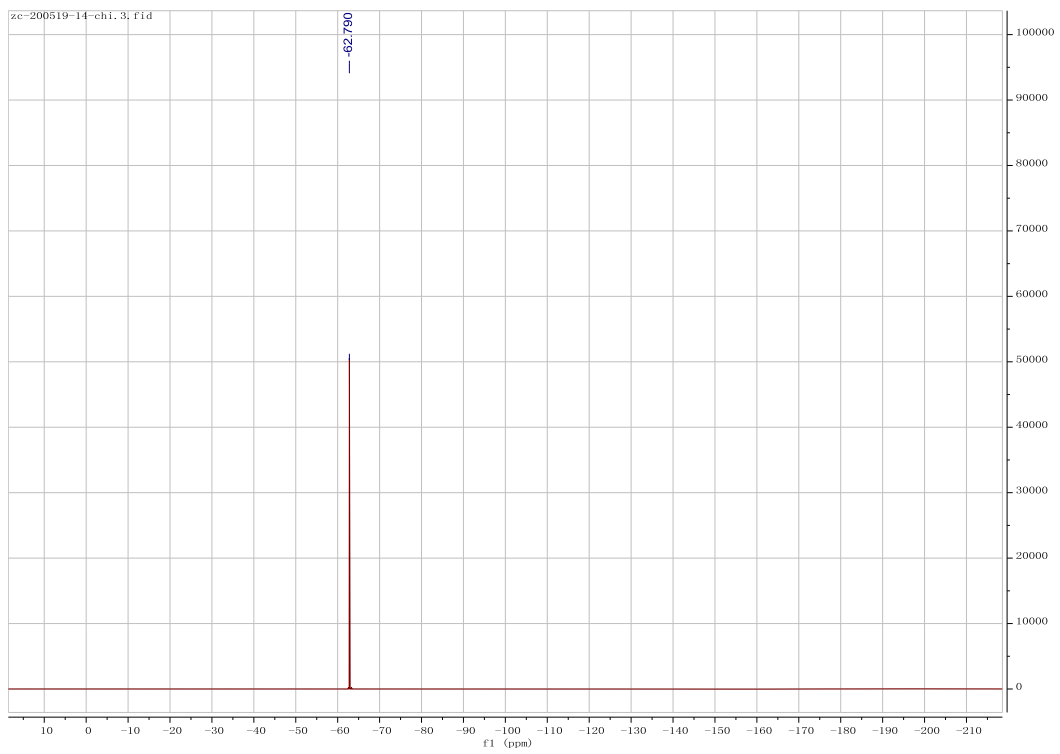


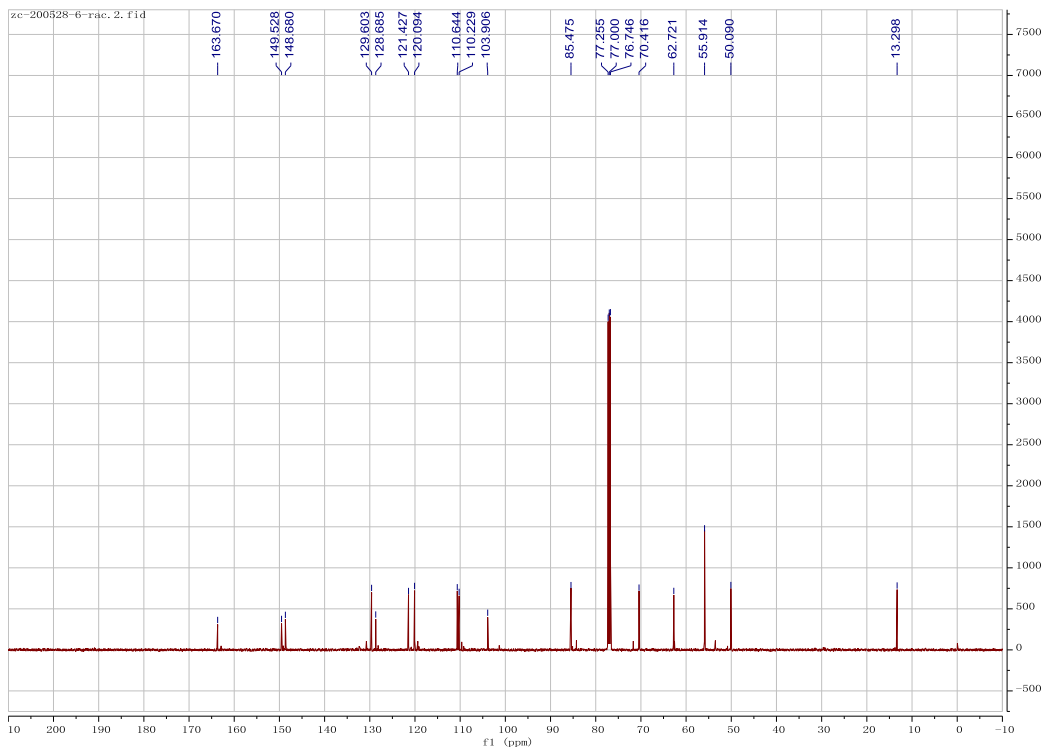
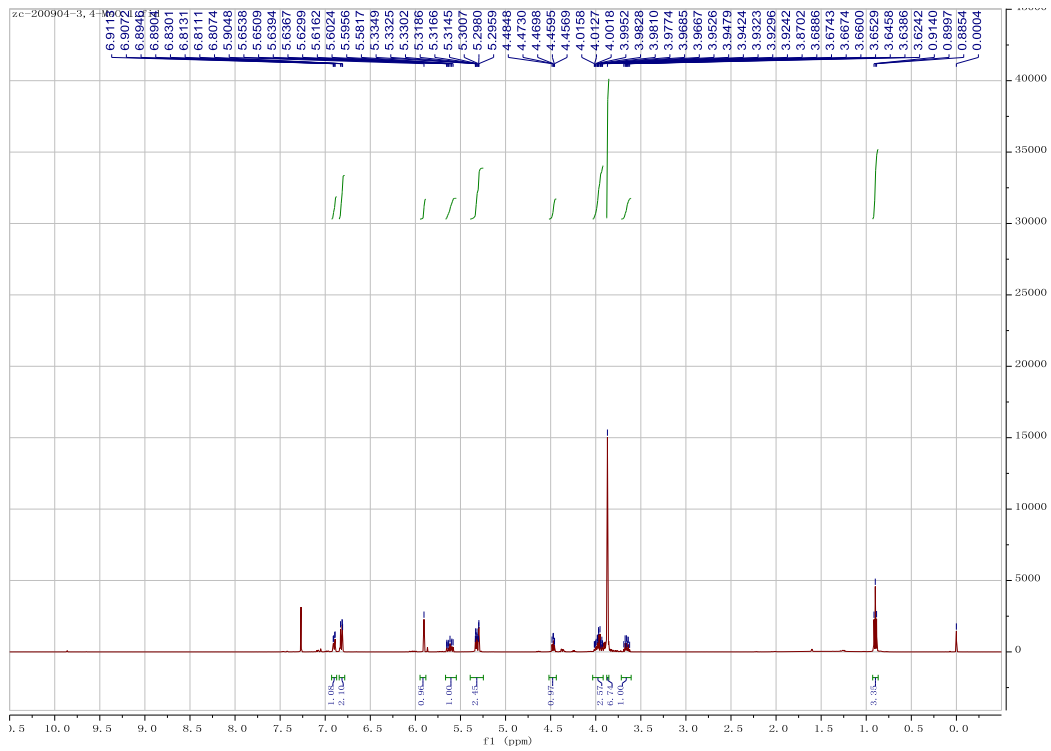
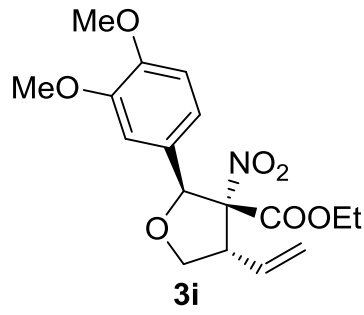


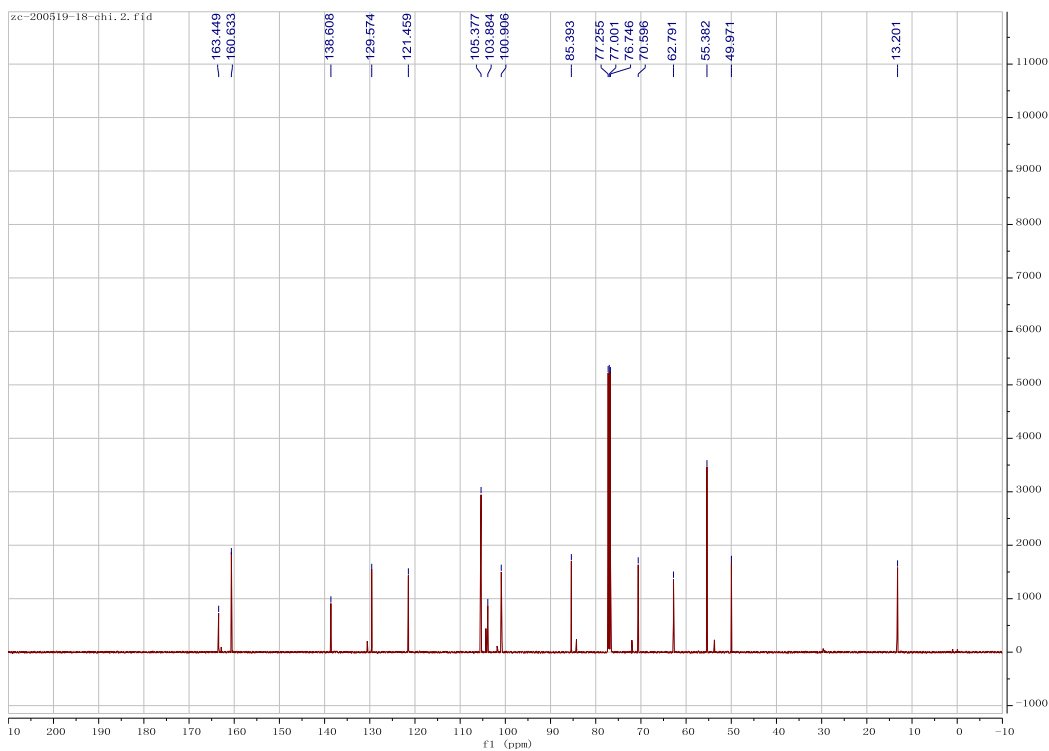
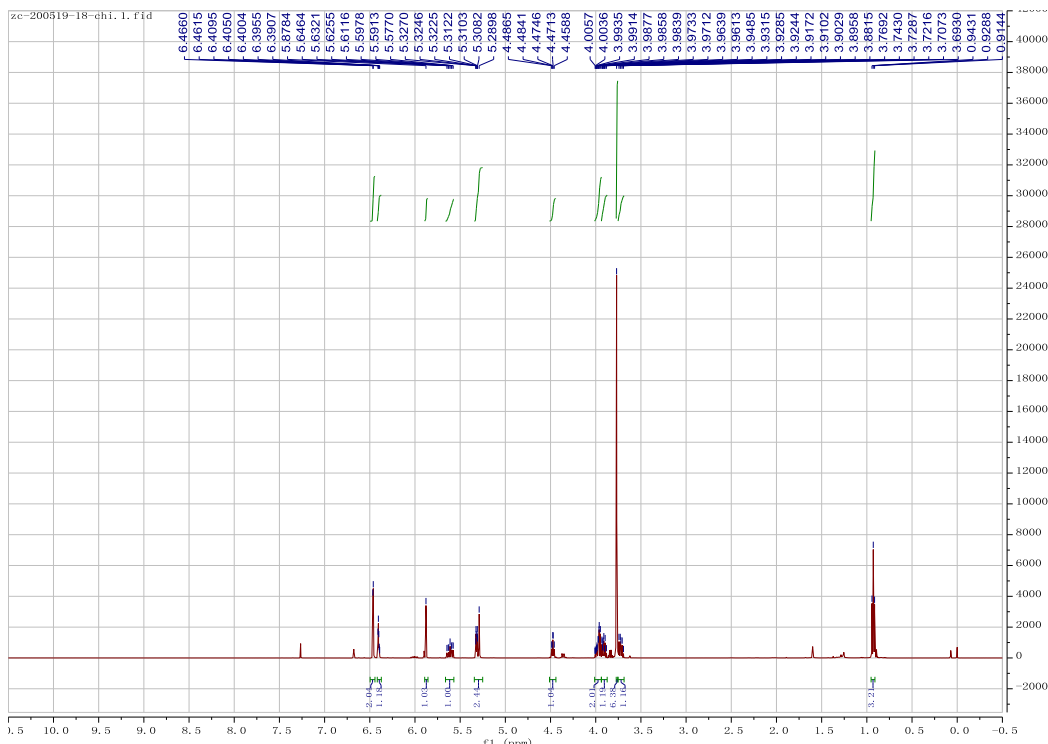
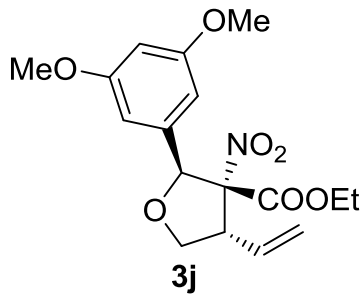


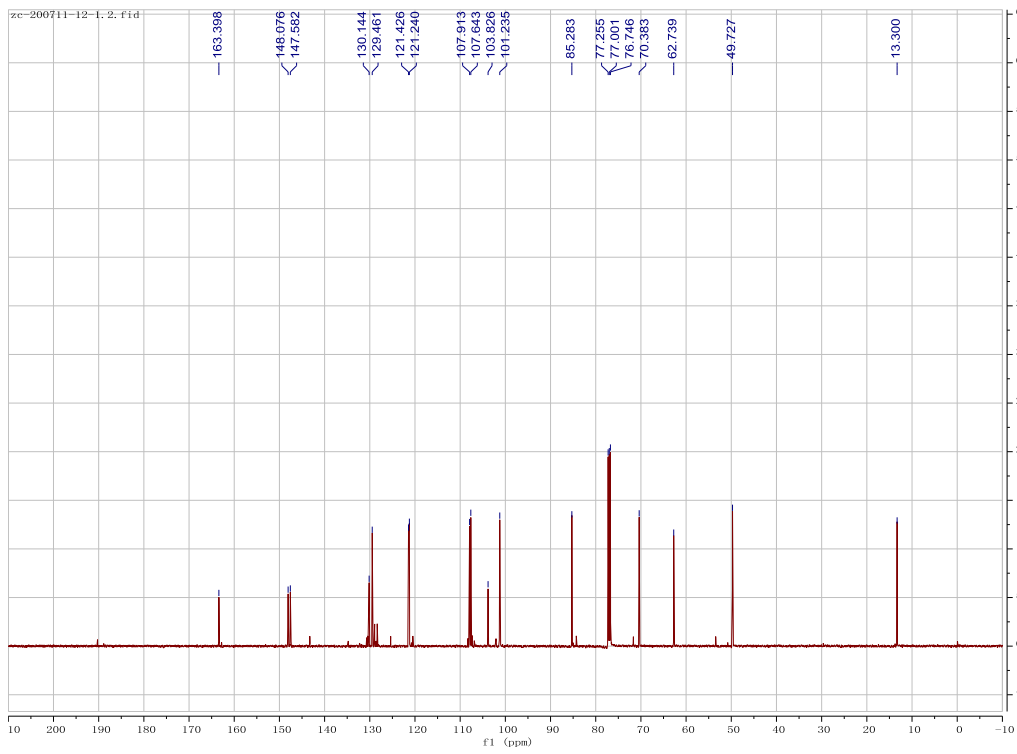
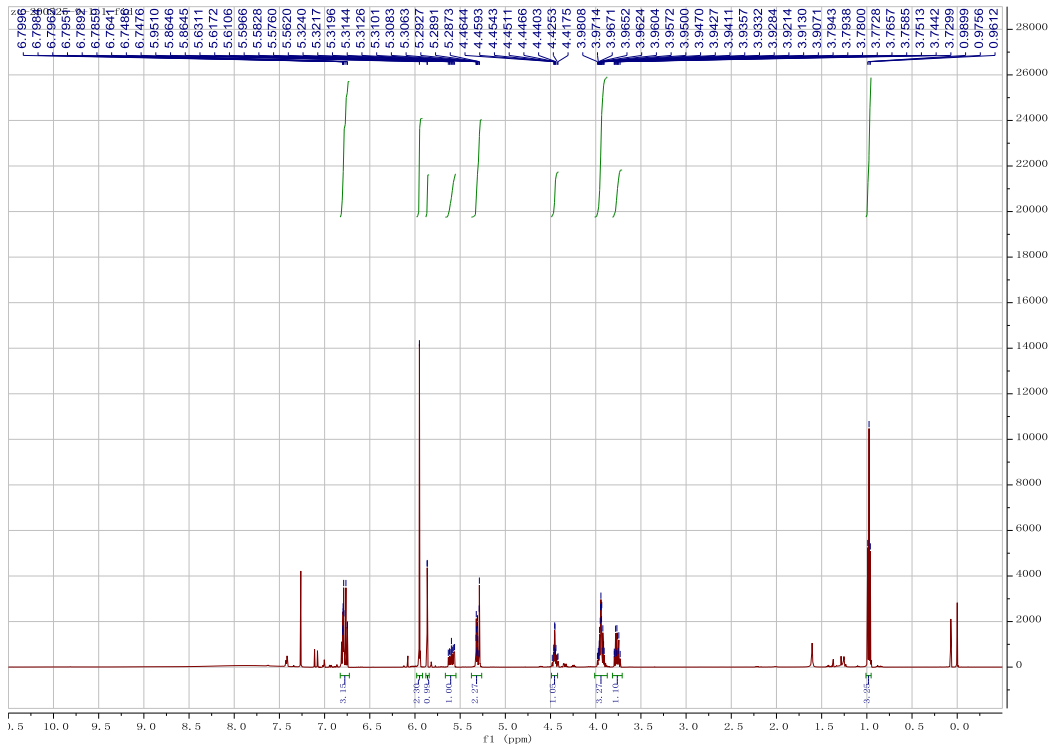
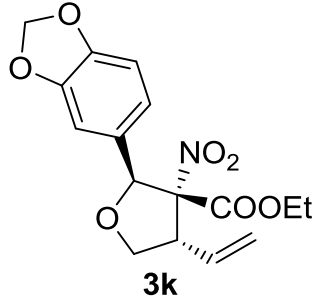


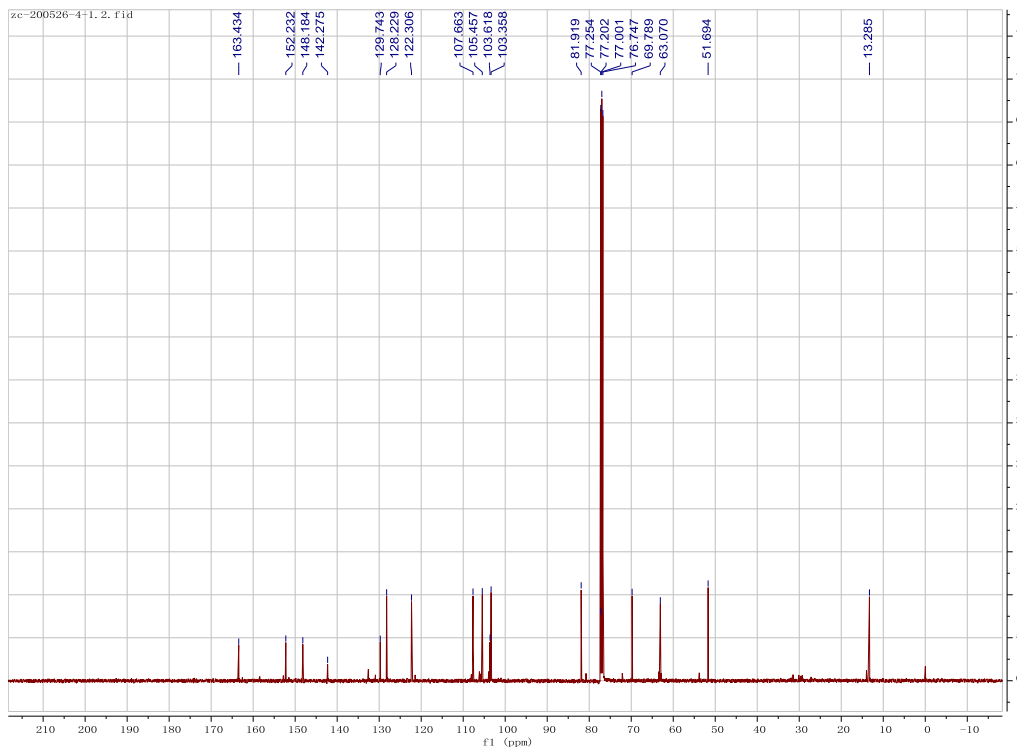
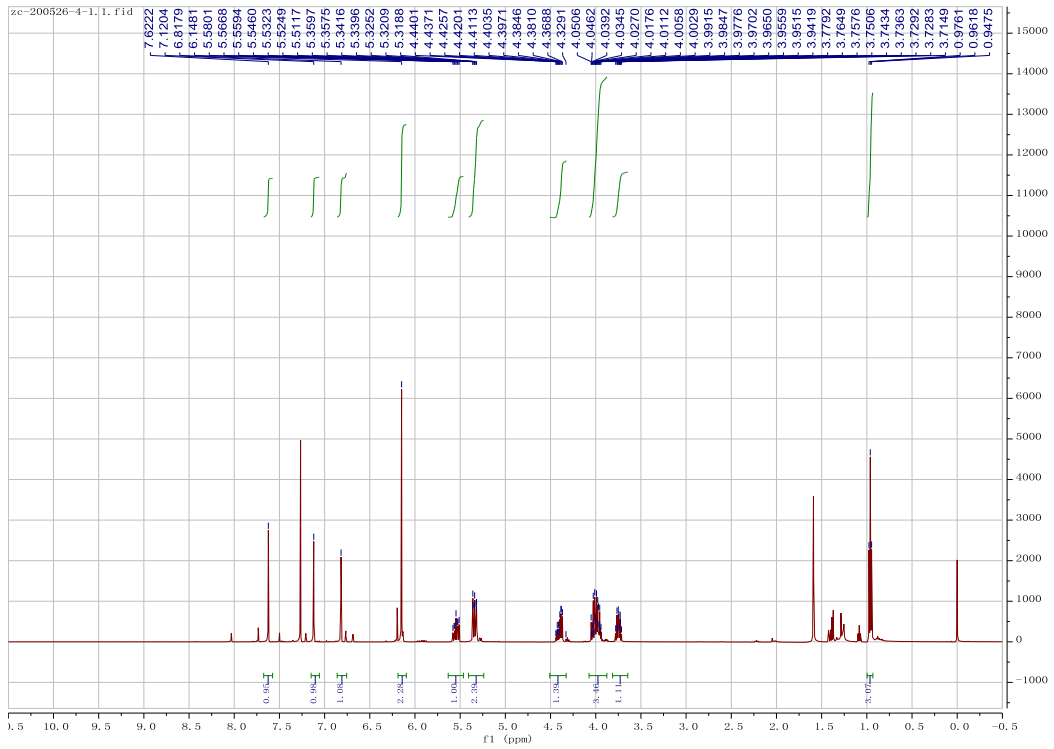
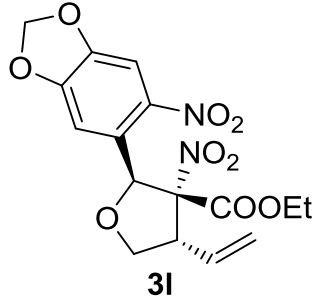


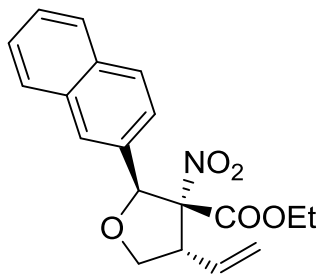




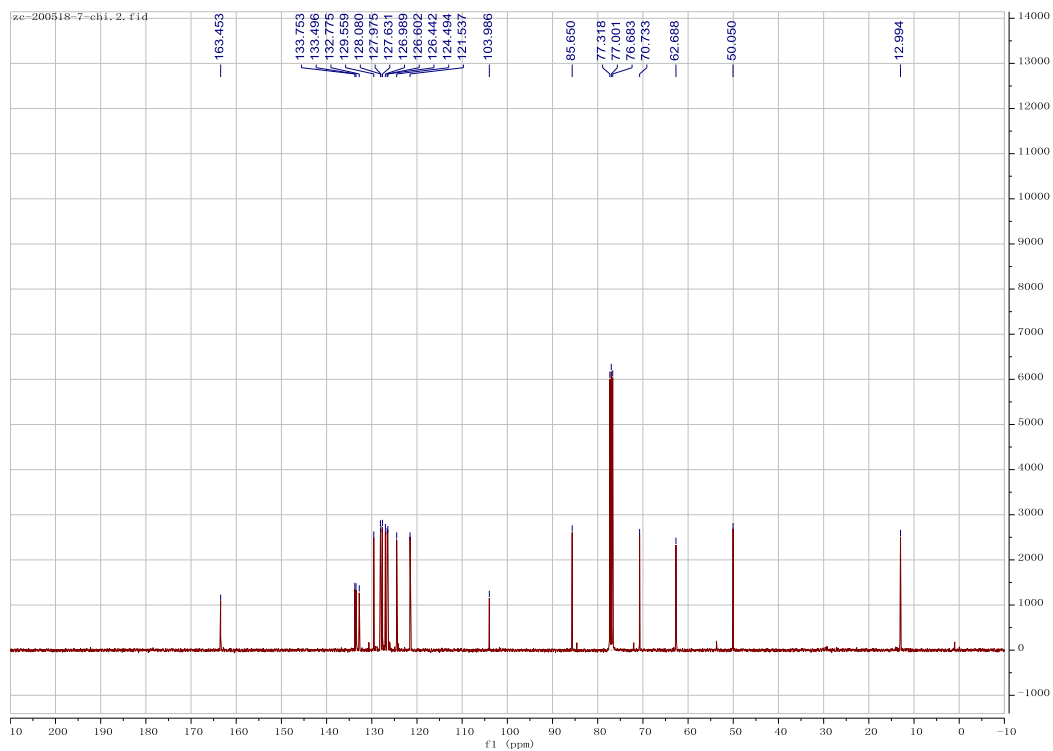
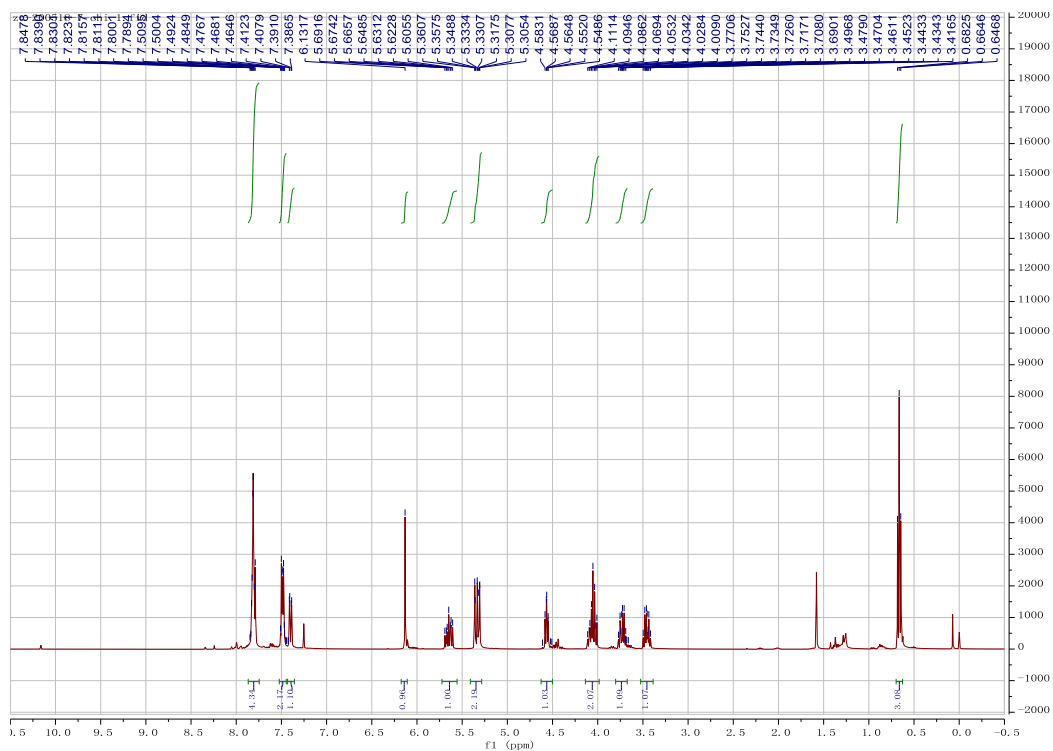


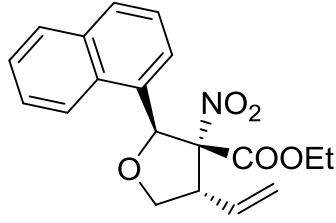




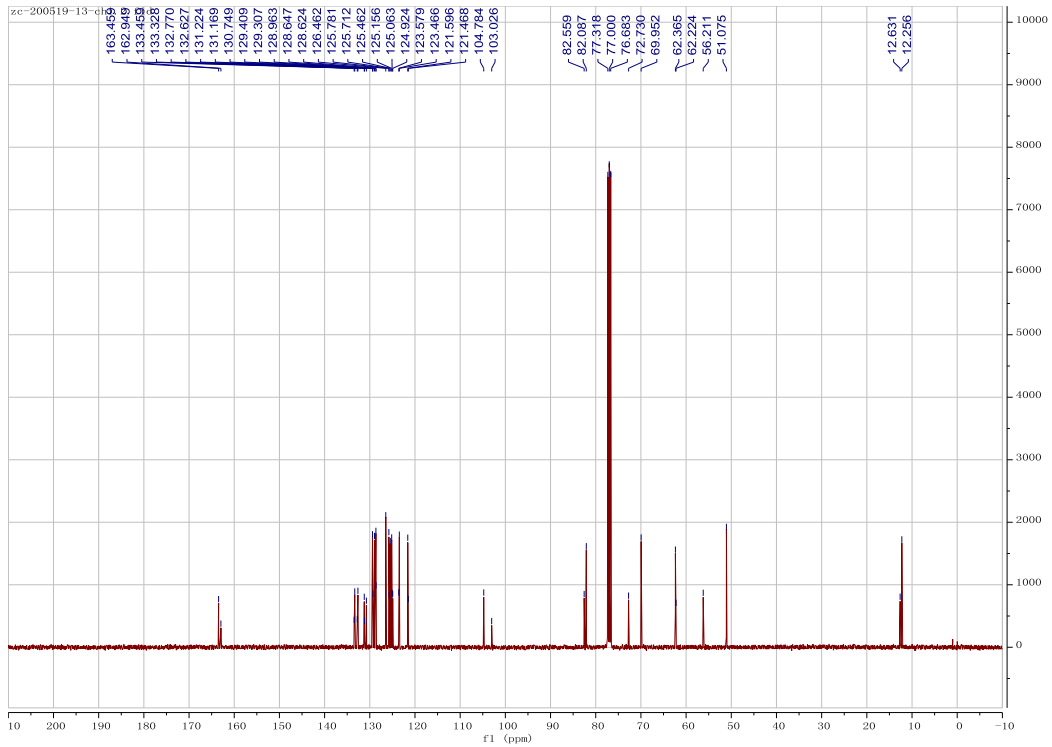
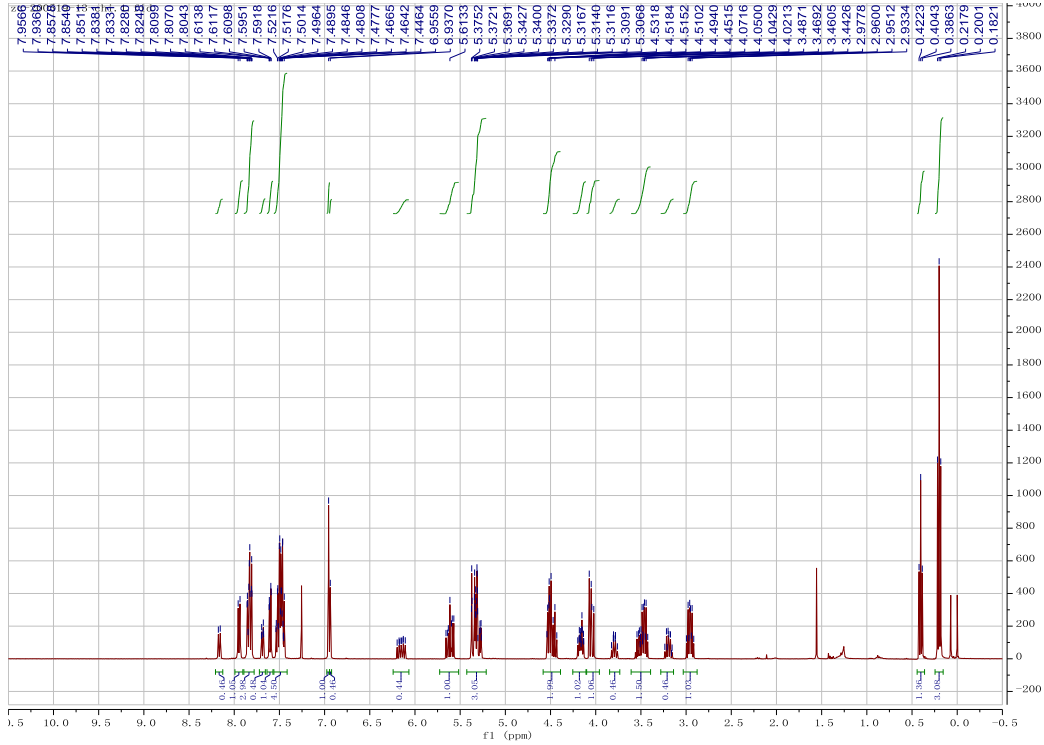


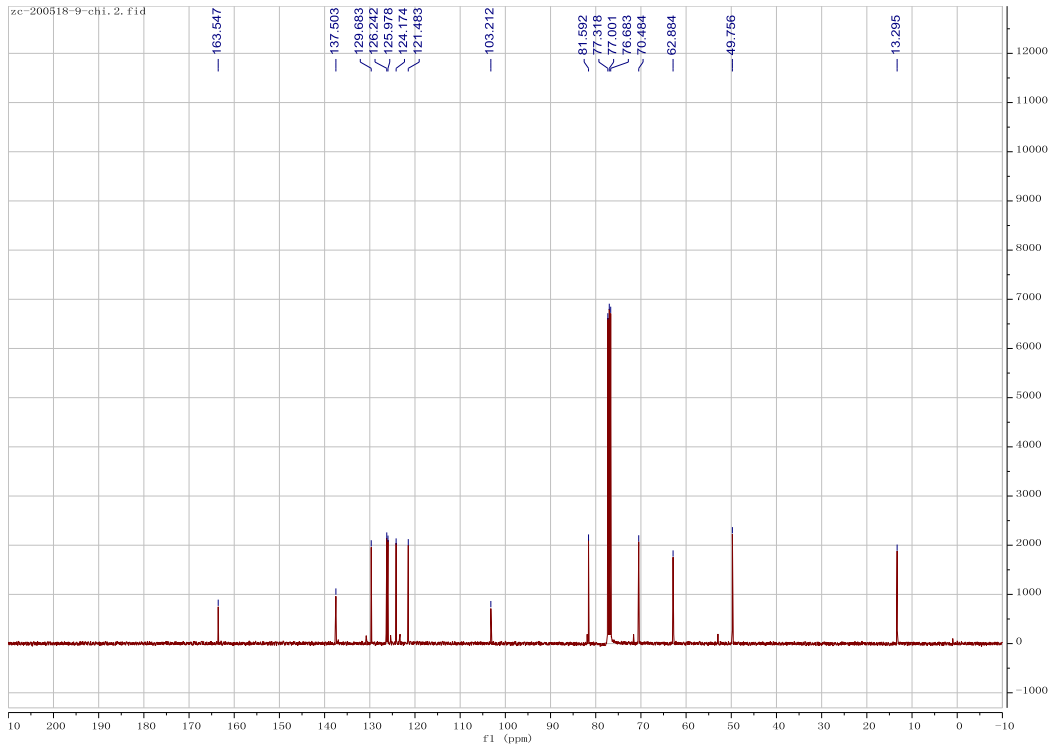
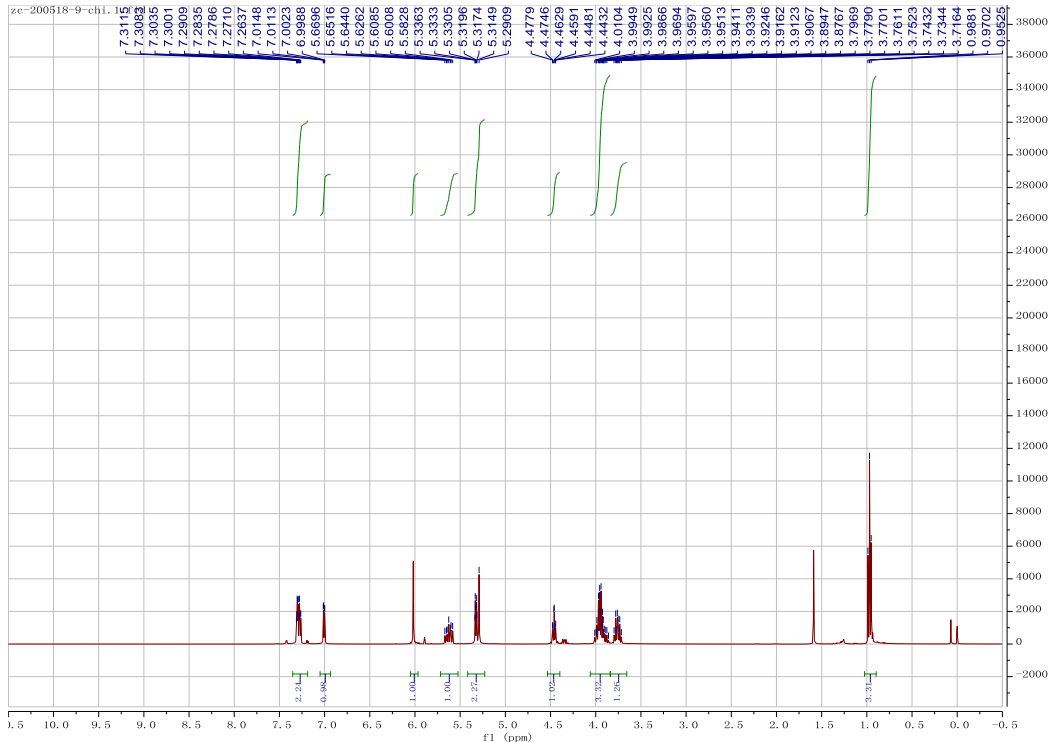
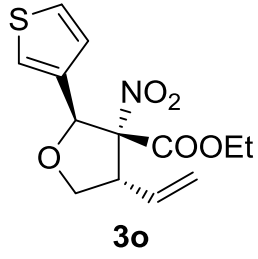
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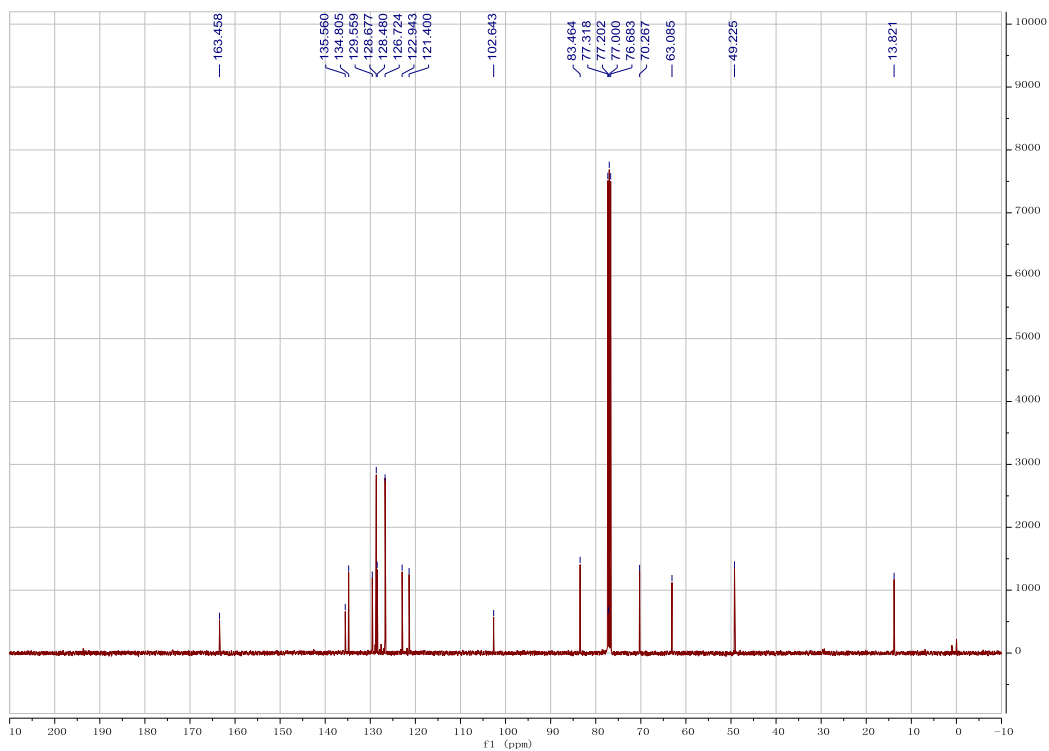
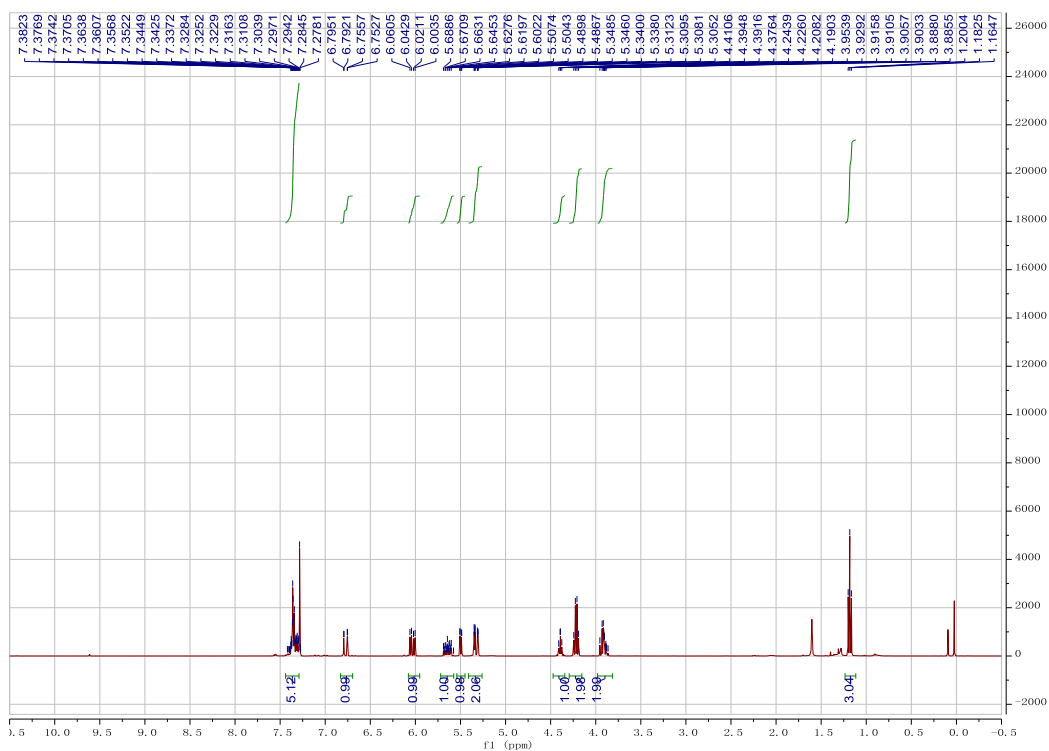
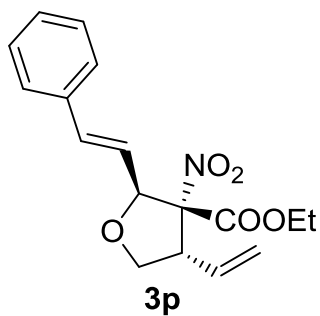


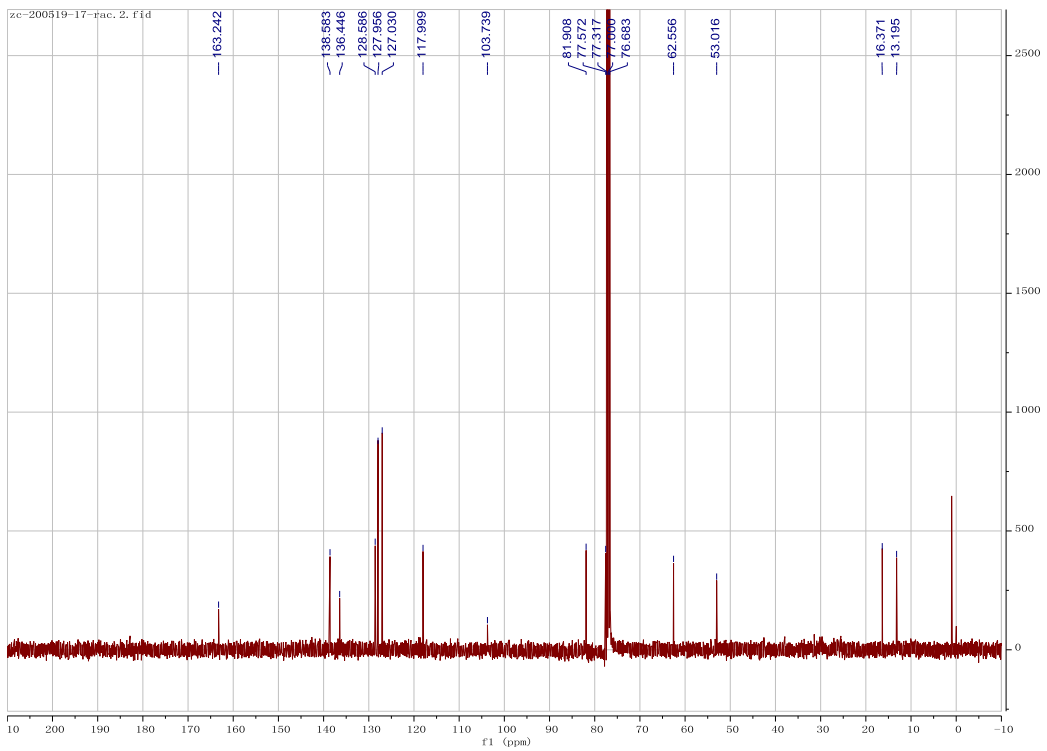
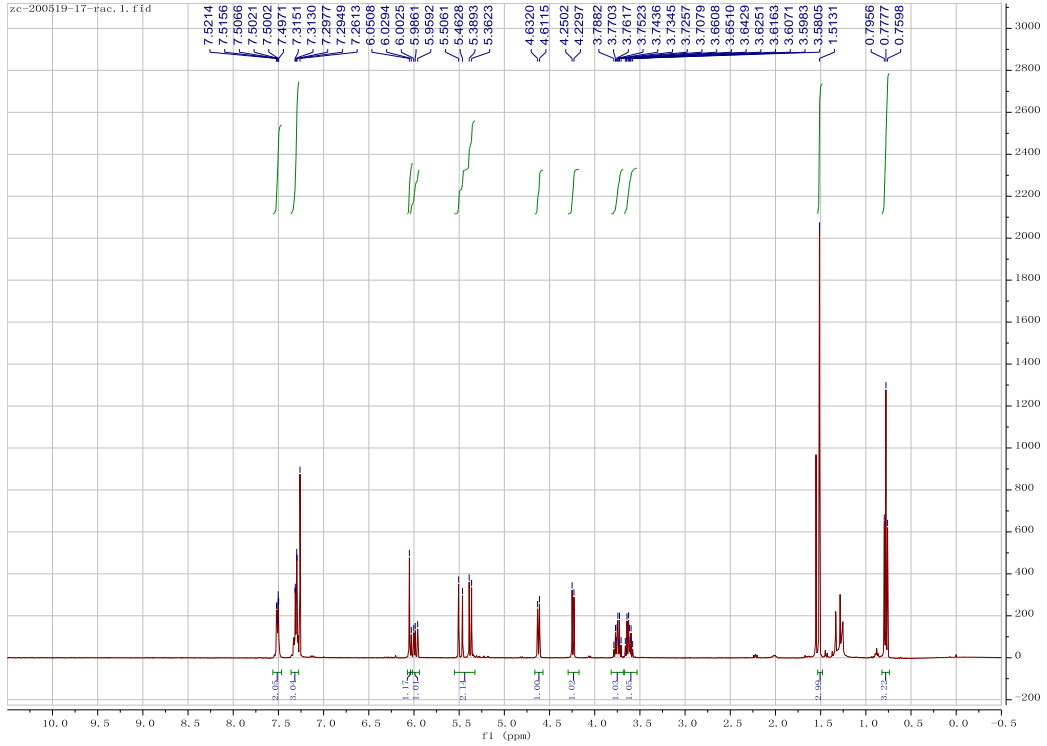
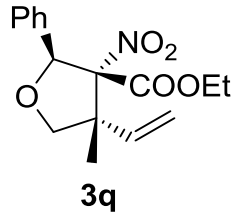


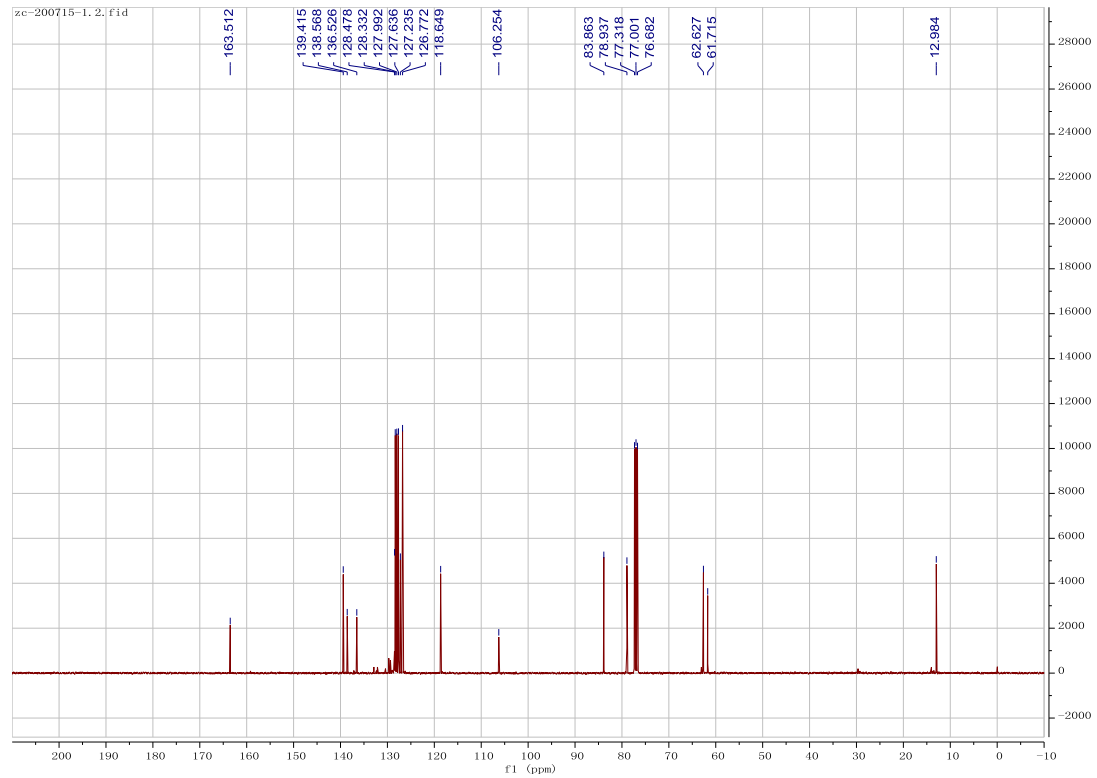
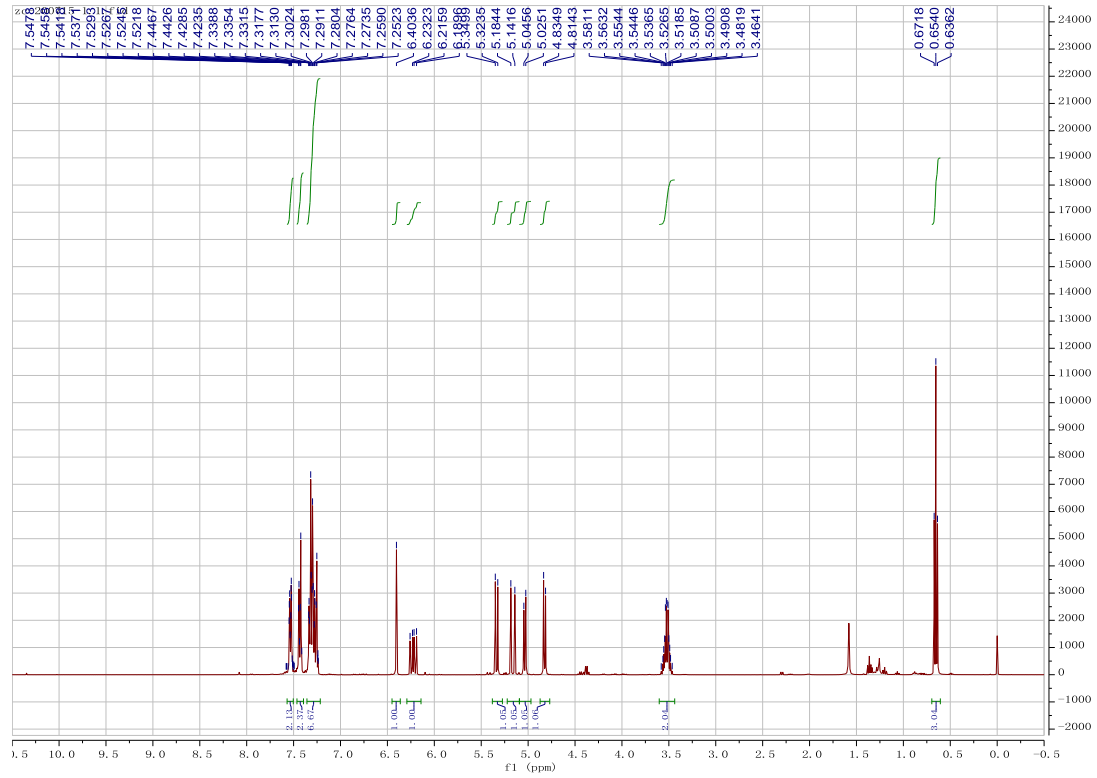
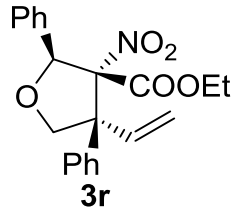
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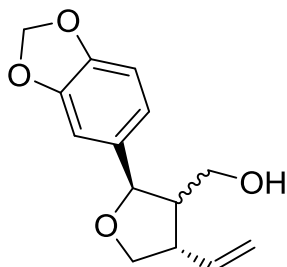




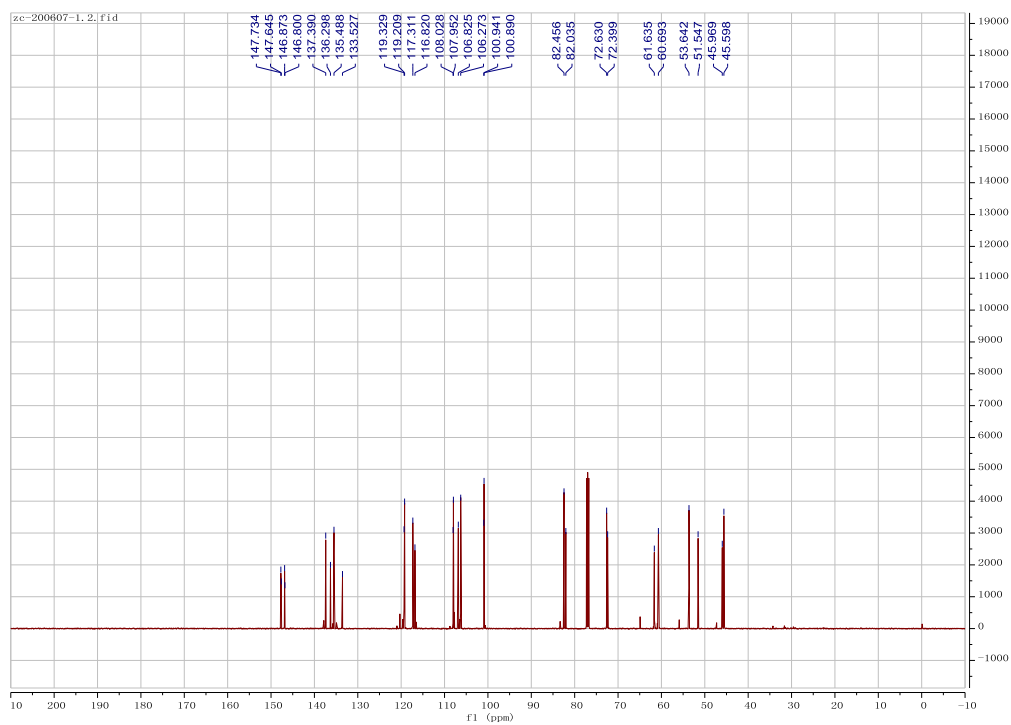
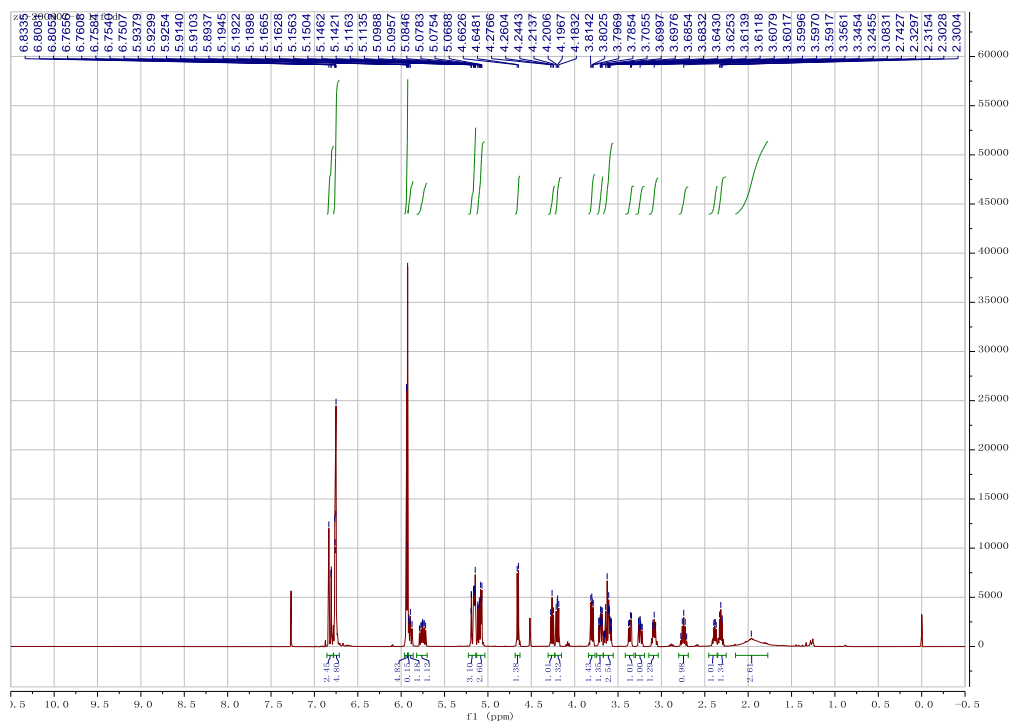


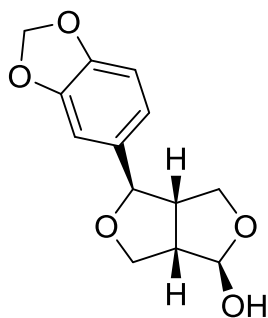




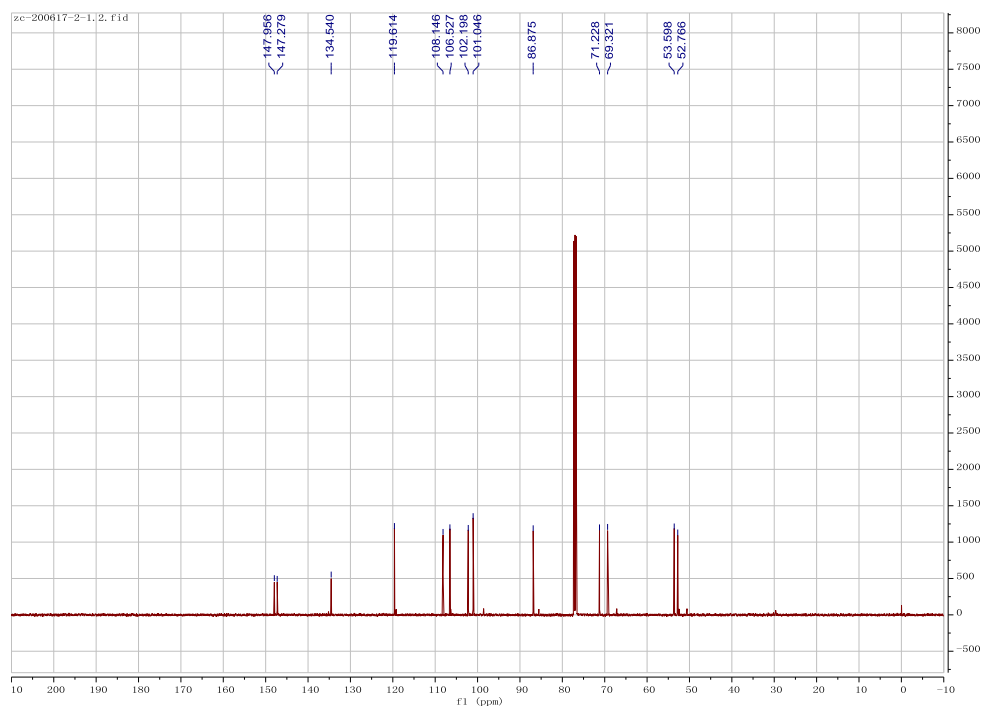
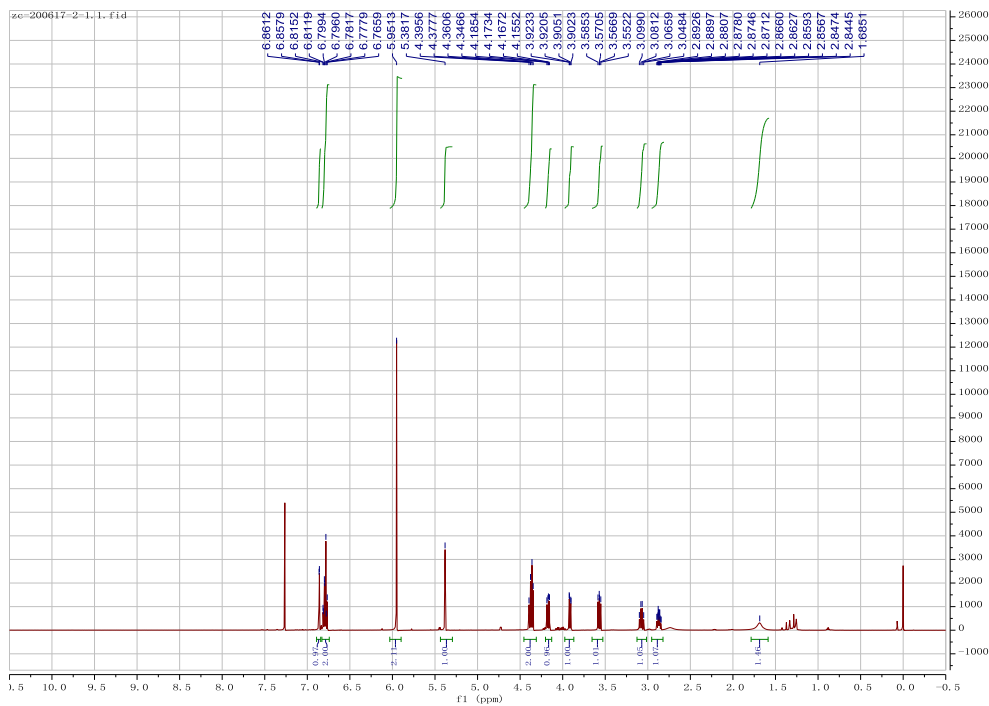


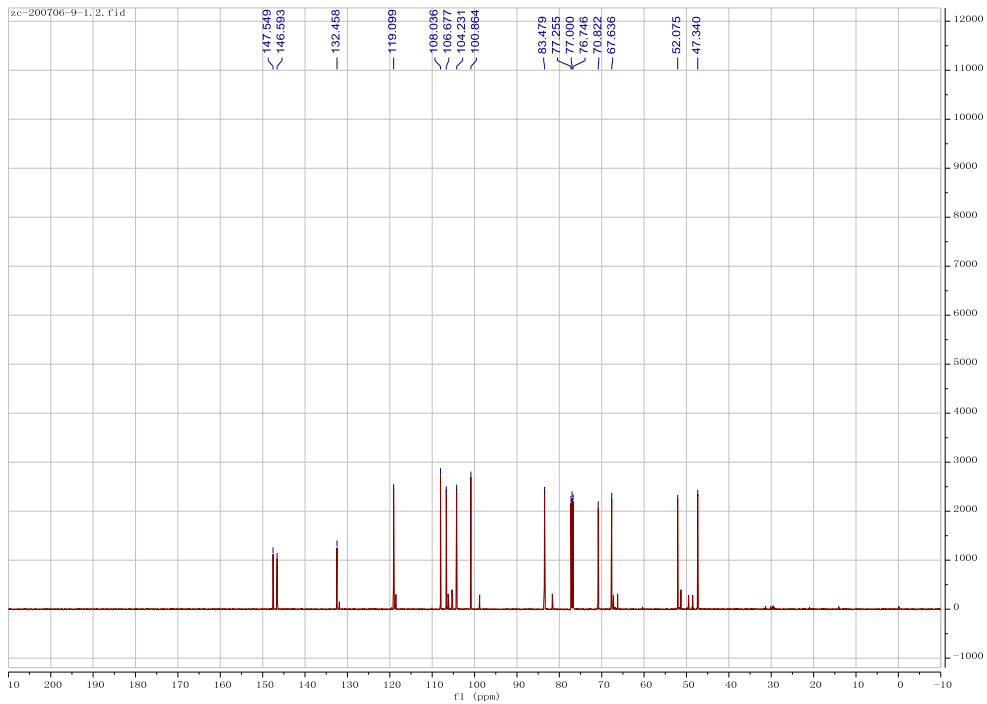
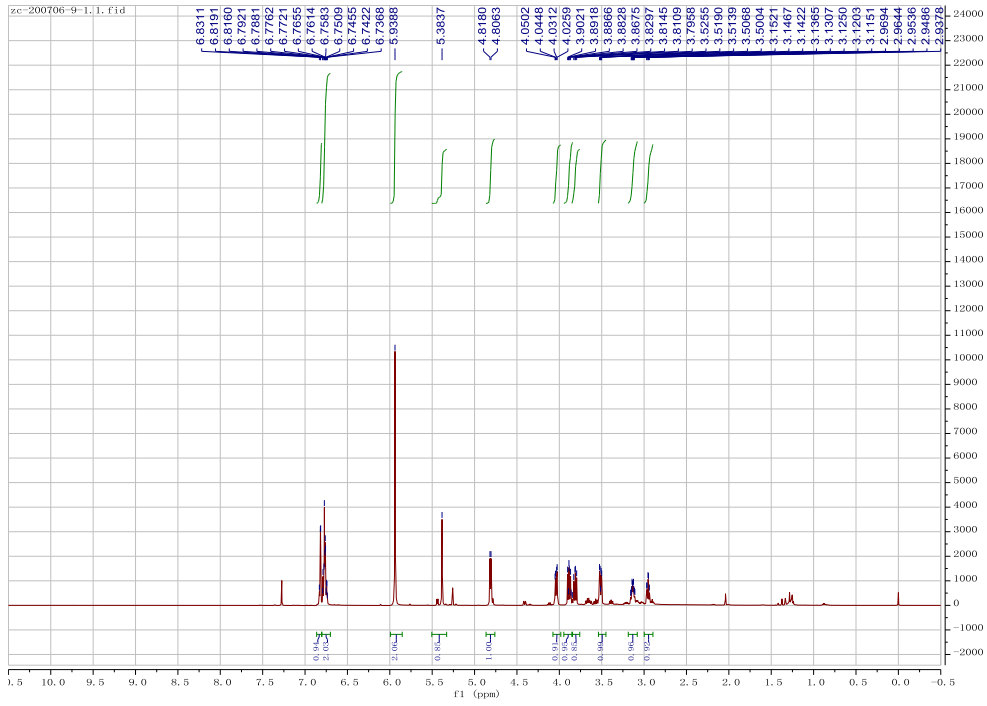
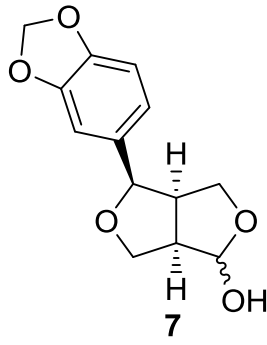
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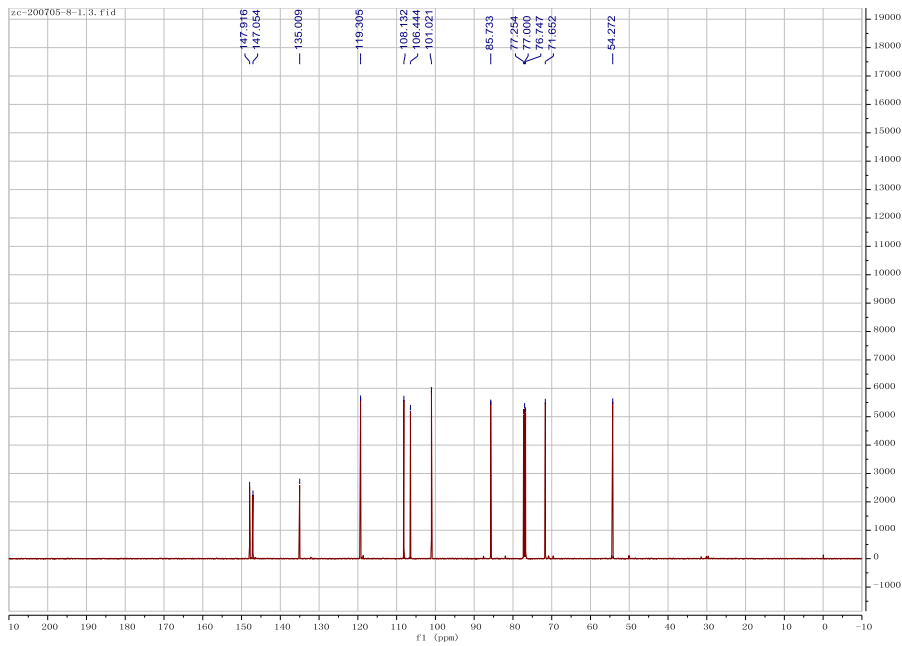
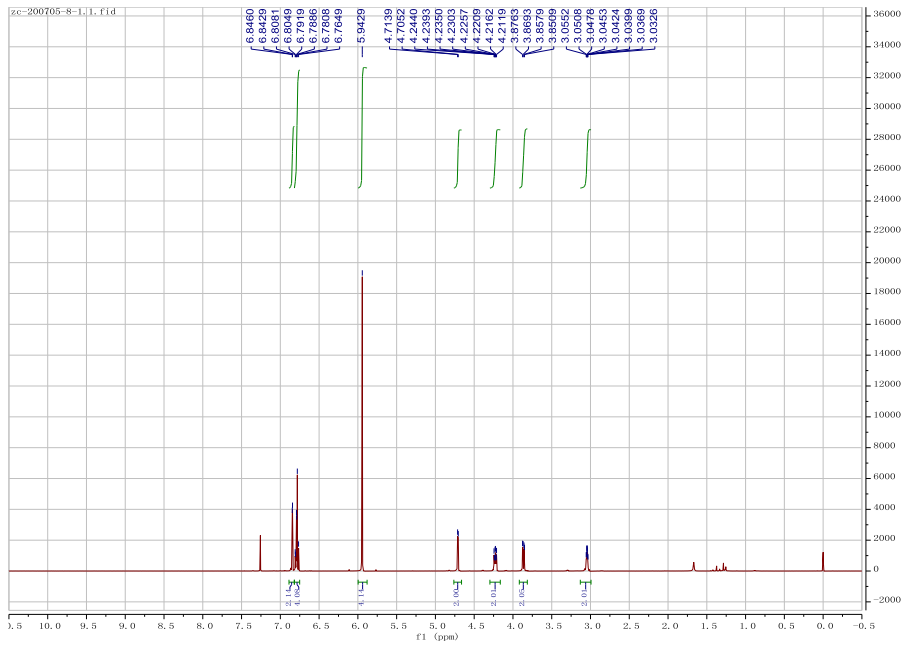
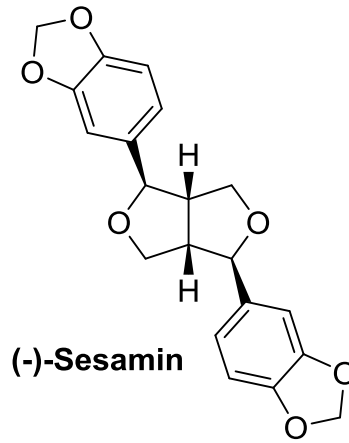


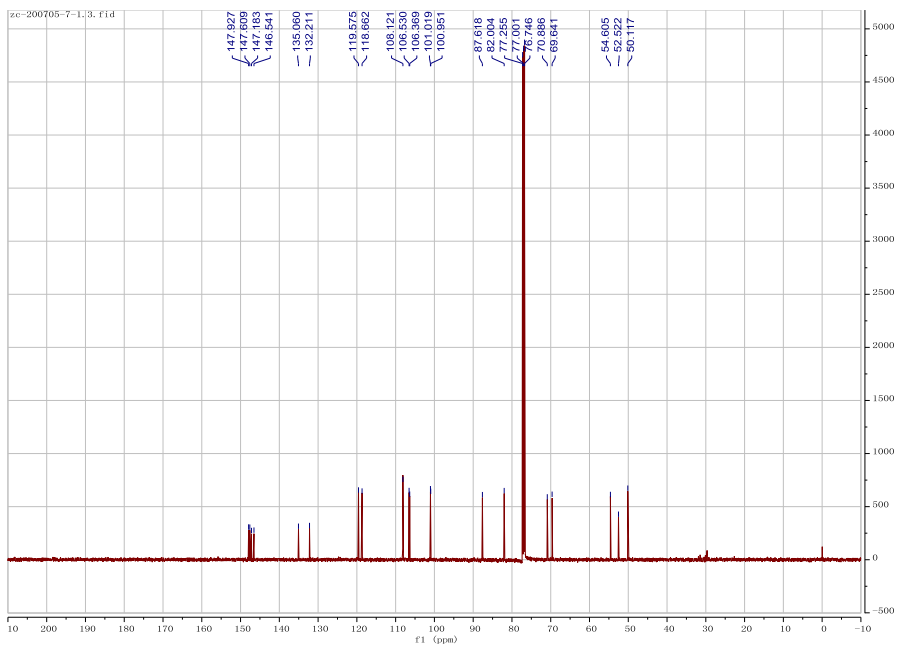
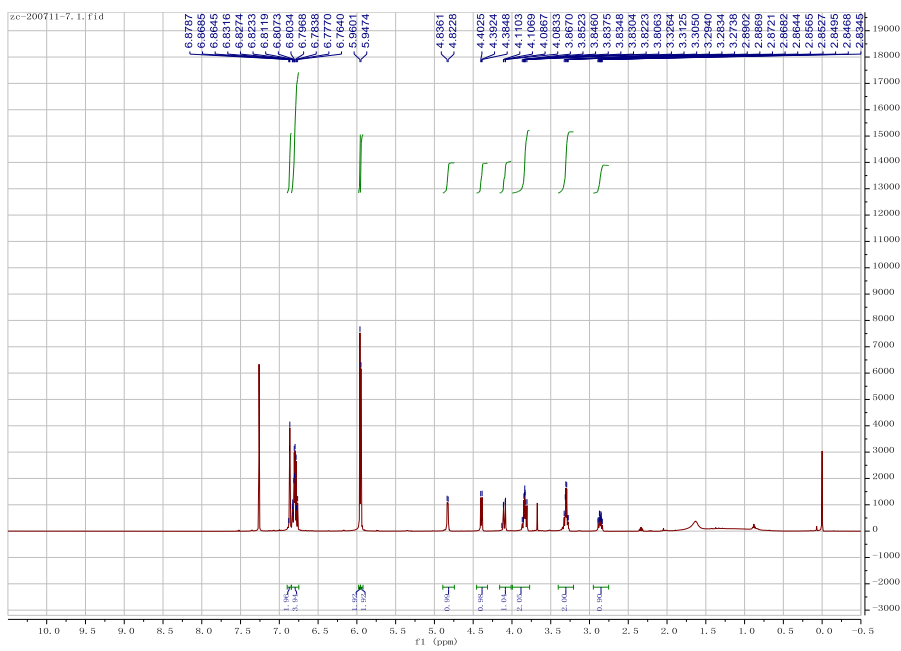
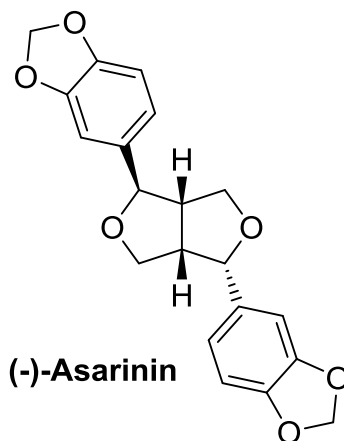


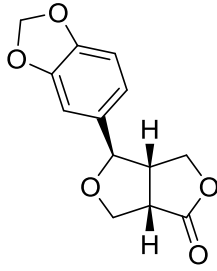
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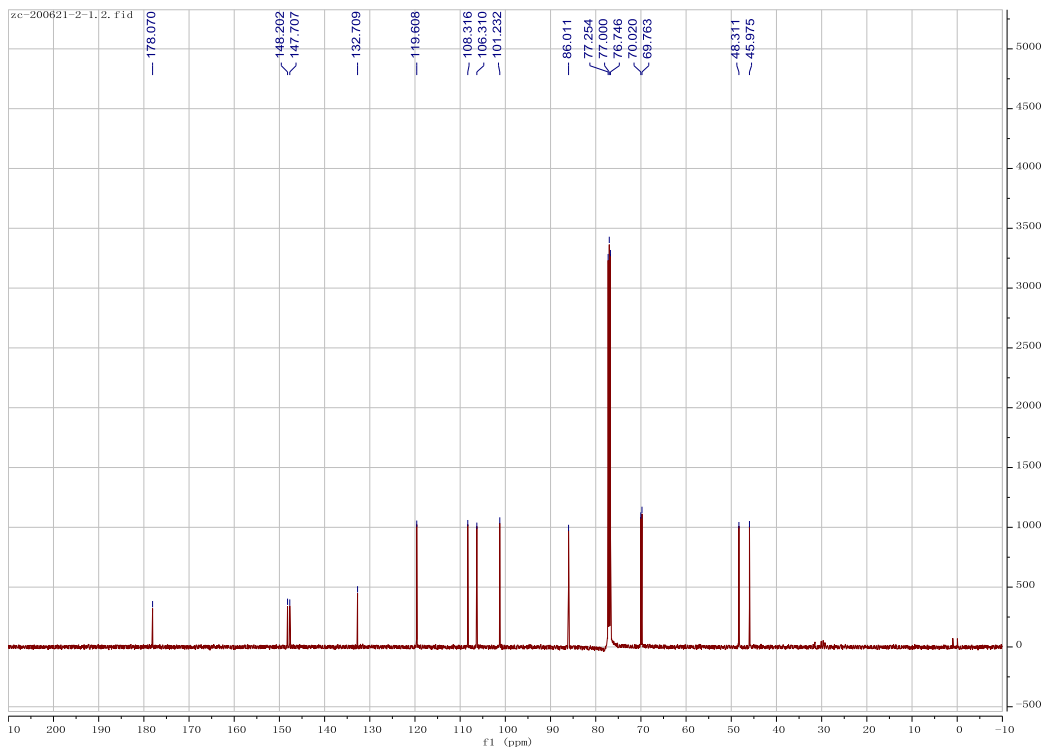
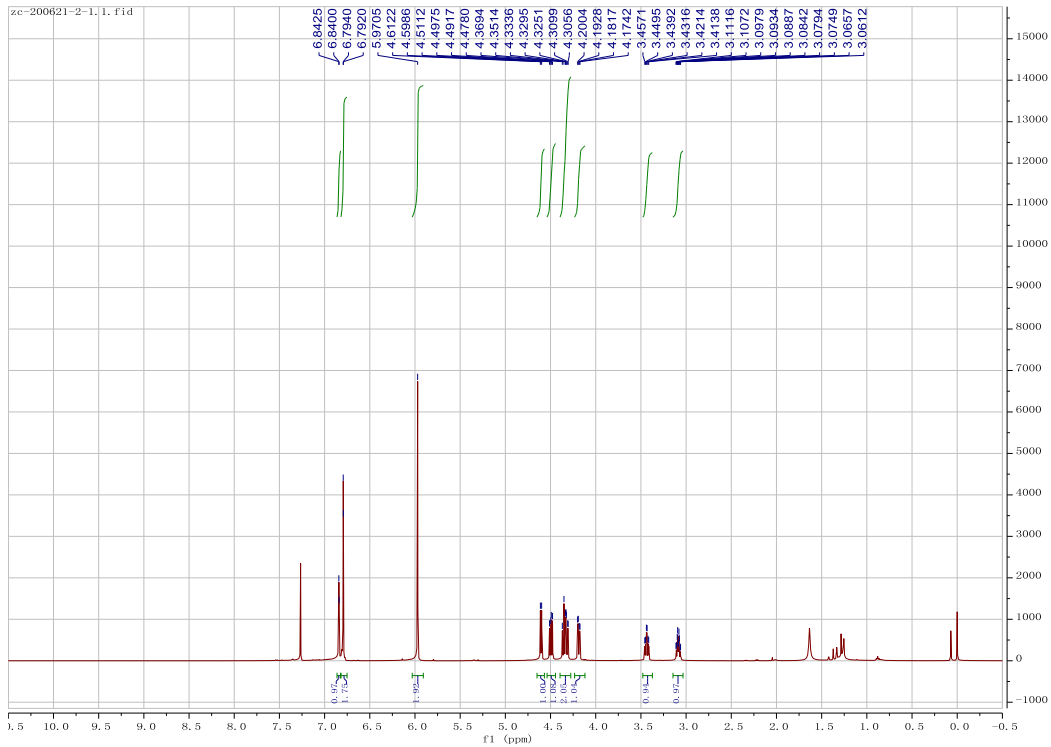


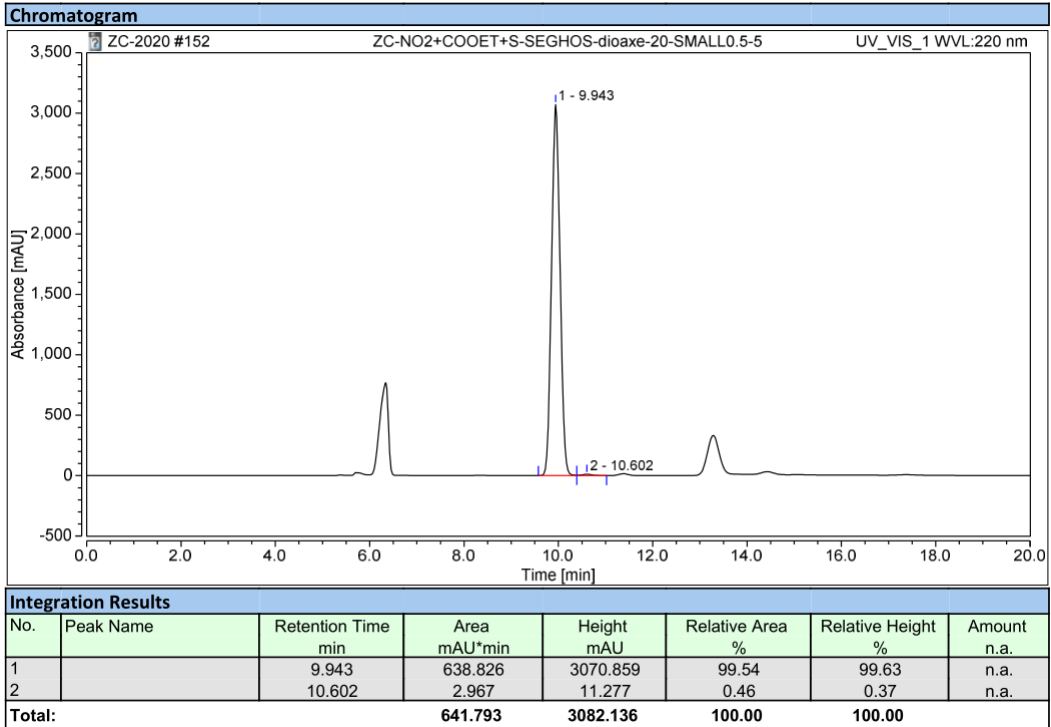
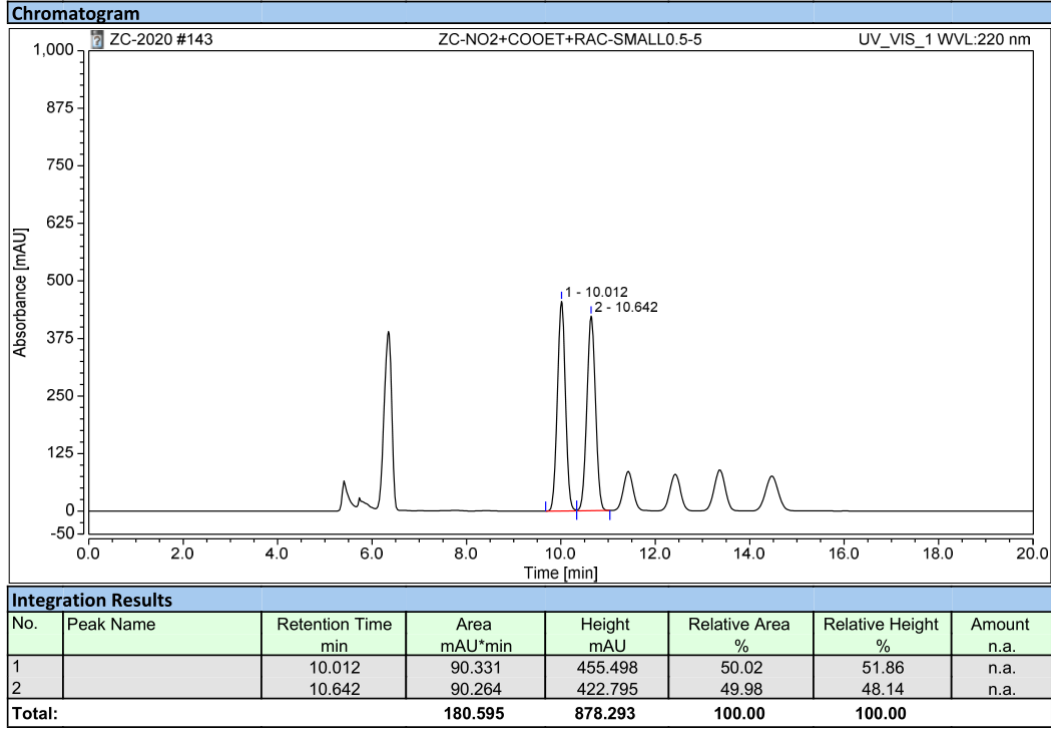
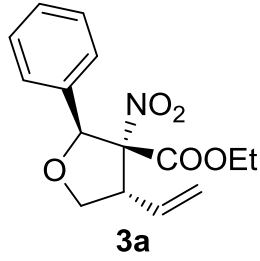


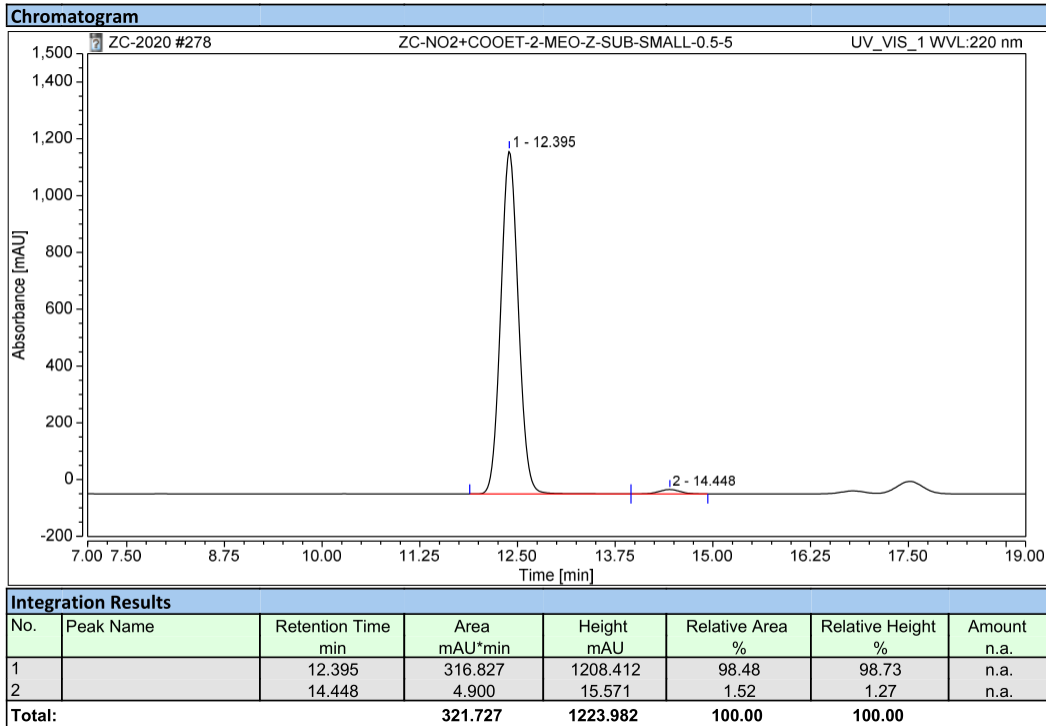
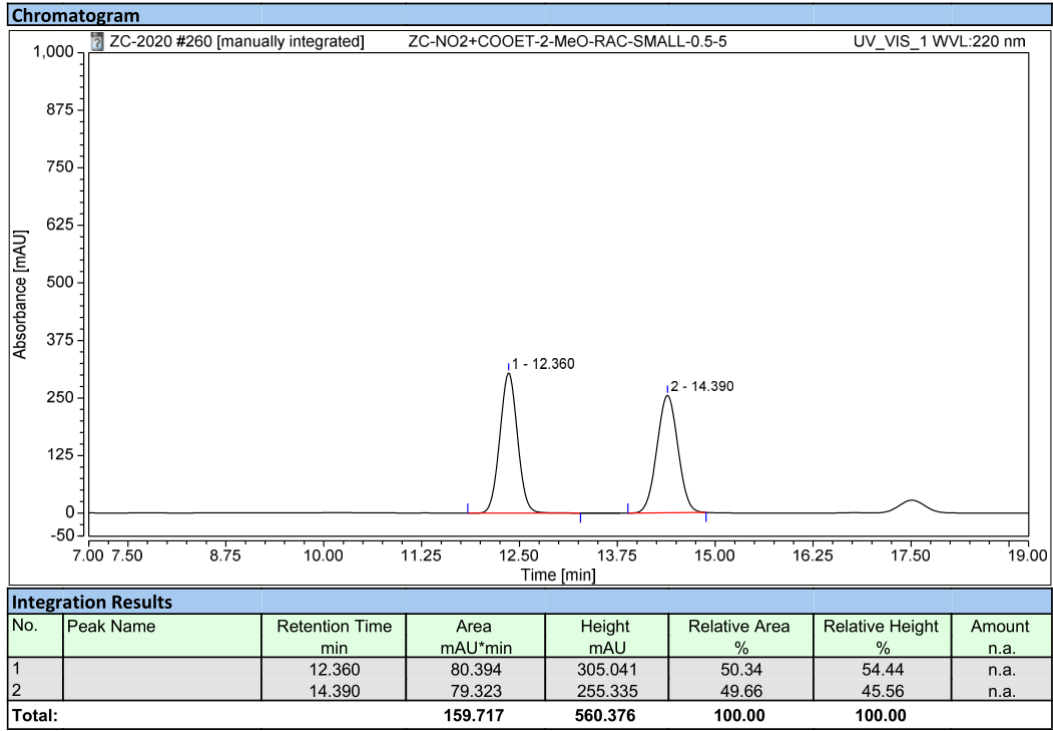
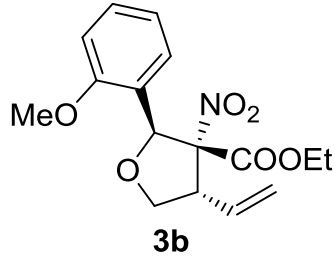


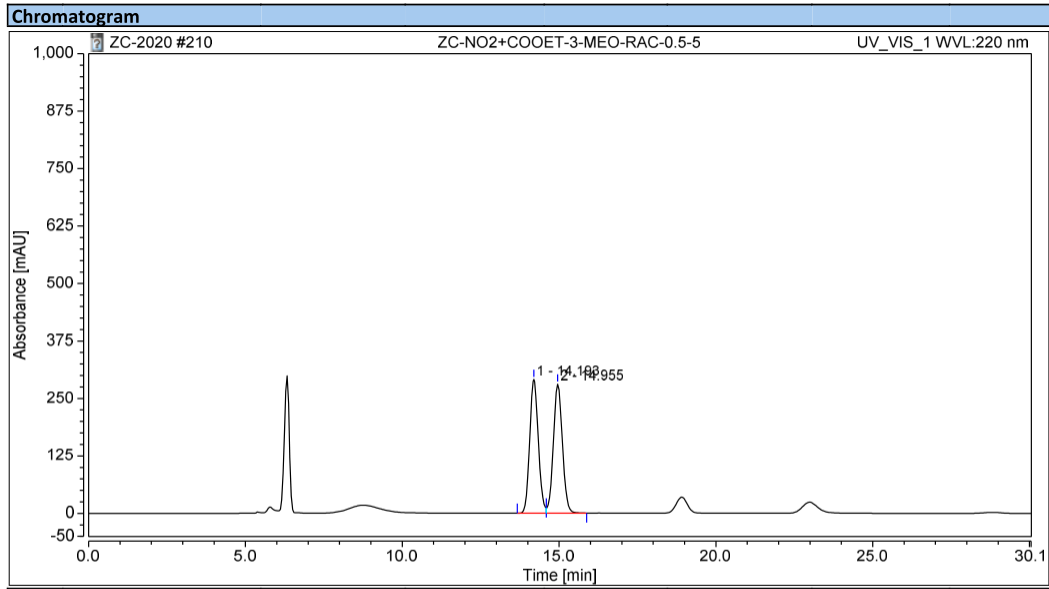
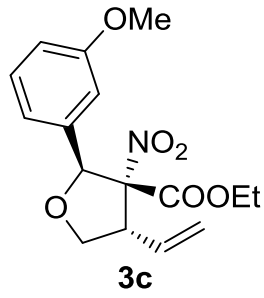


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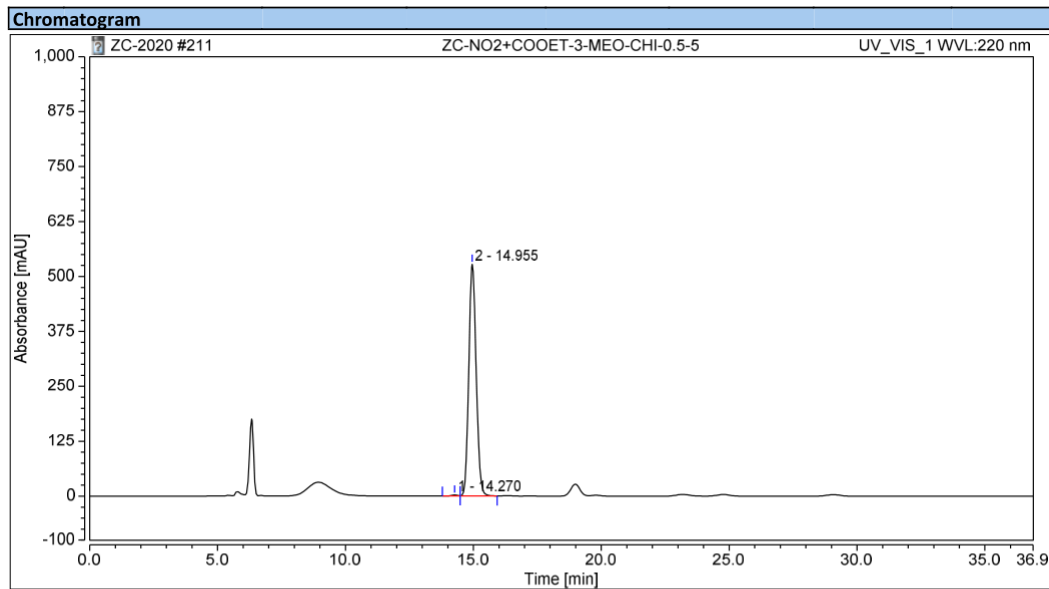






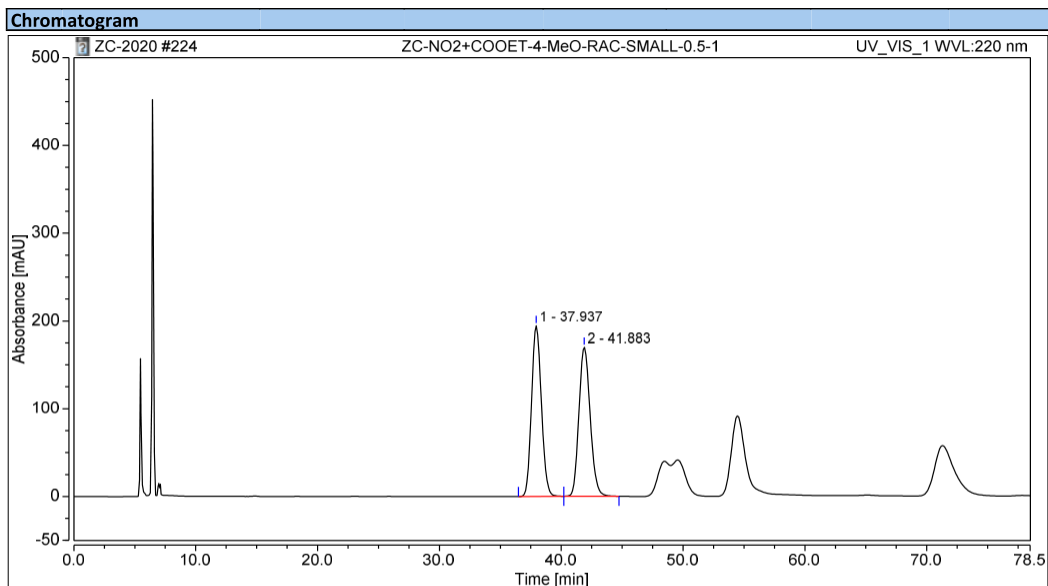
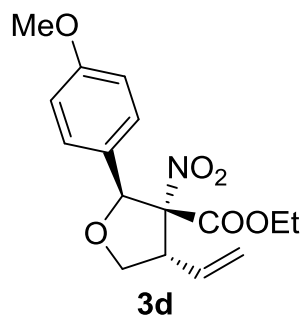
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		14.193	92.412	290.976	49.61	50.88	n.a.
2		14.955	93.849	280.889	50.39	49.12	n.a.
Total:			186.261	571.865	100.00	100.00	



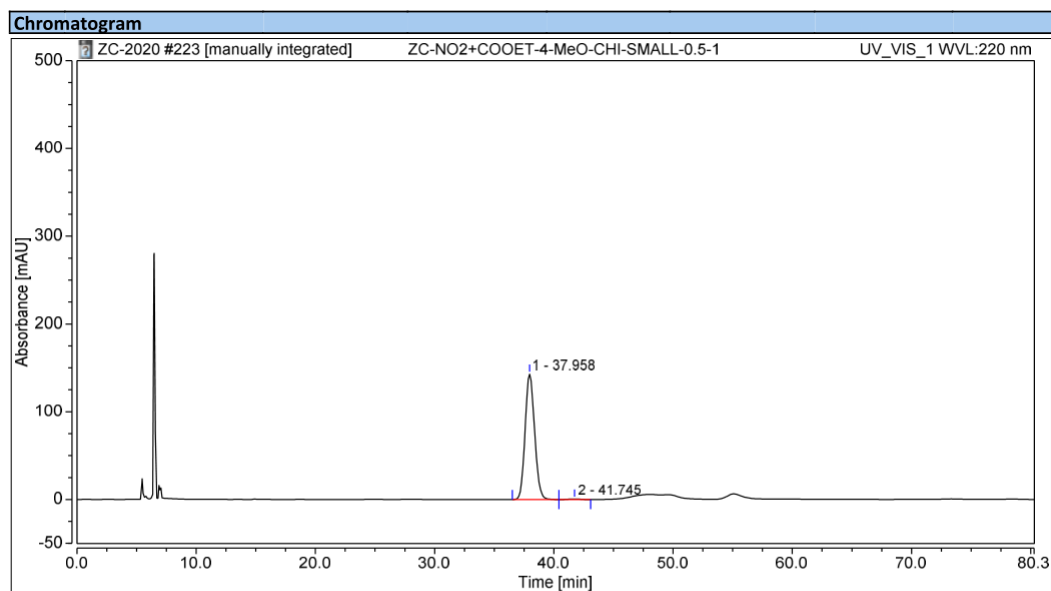
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		14.270	0.760	2.507	0.43	0.47	n.a.
2		14.955	175.519	527.315	99.57	99.53	n.a.
Total:			176.279	529.822	100.00	100.00	



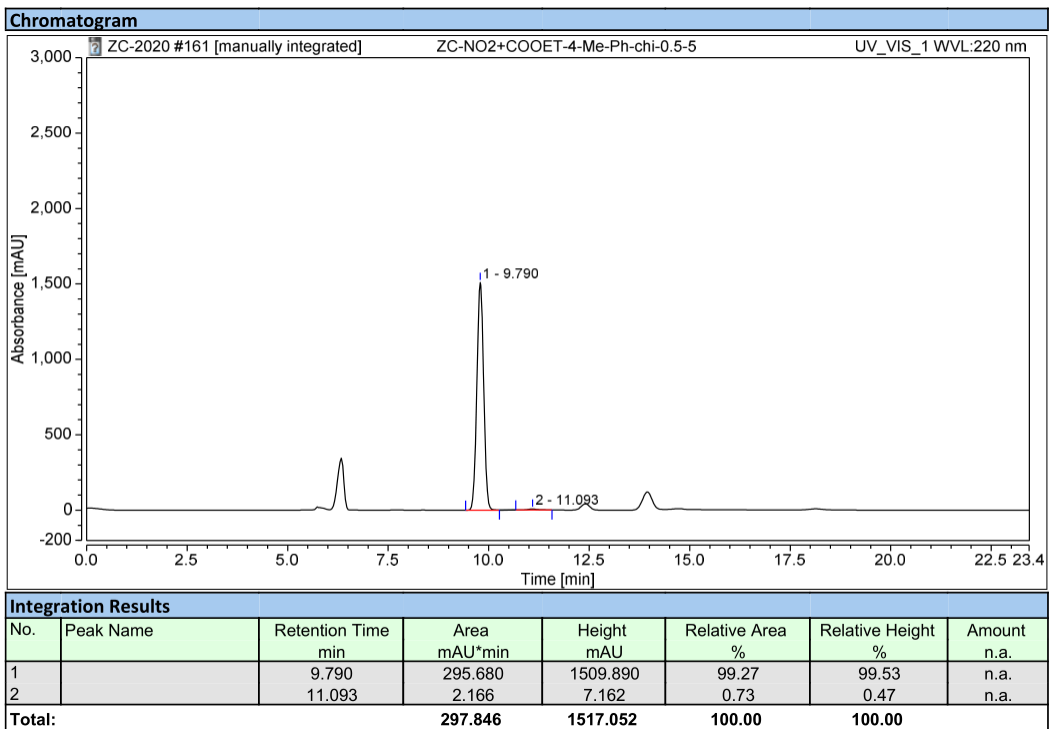
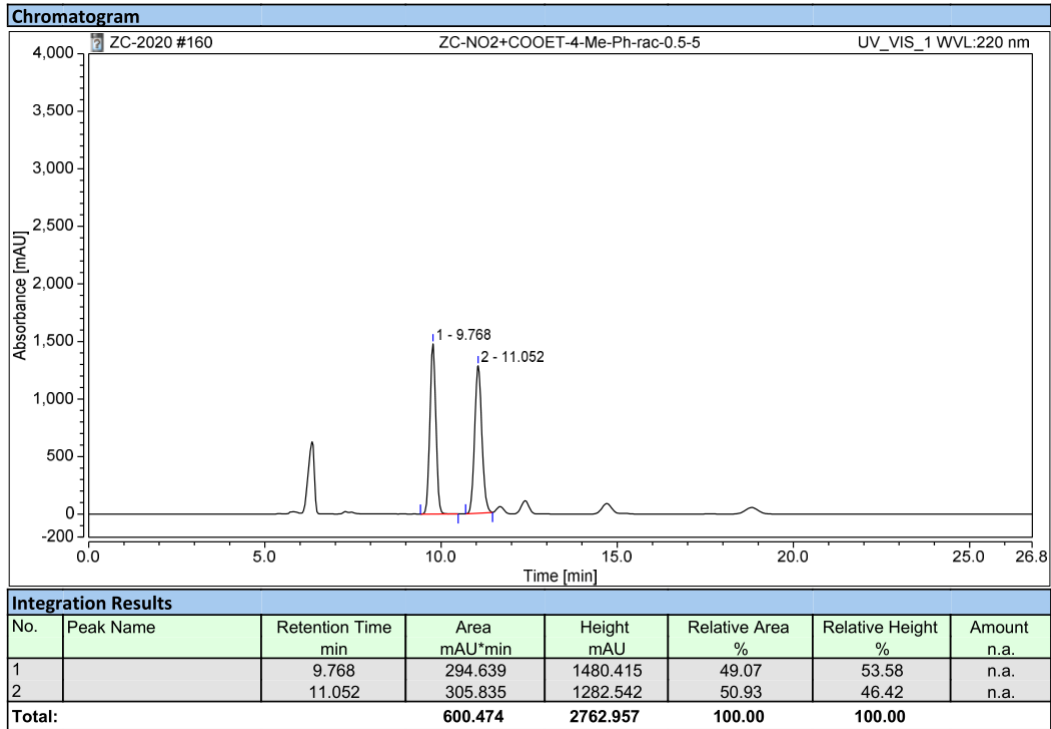
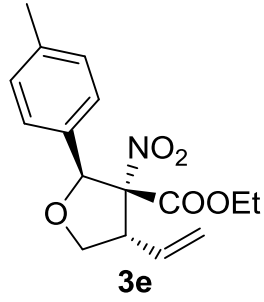
Integration Results

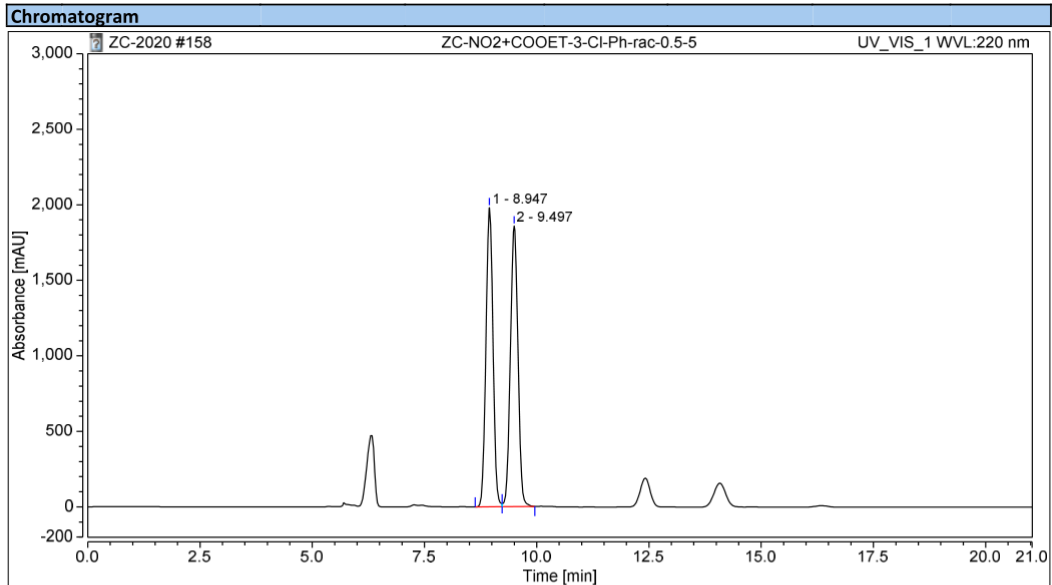
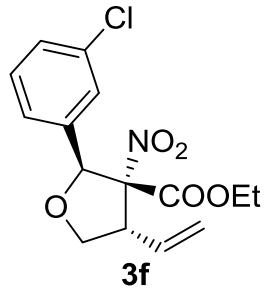
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		37.937	182.521	194.804	50.05	53.37	n.a.
2		41.883	182.155	170.224	49.95	46.63	n.a.
Total:			364.676	365.028	100.00	100.00	



Integration Results

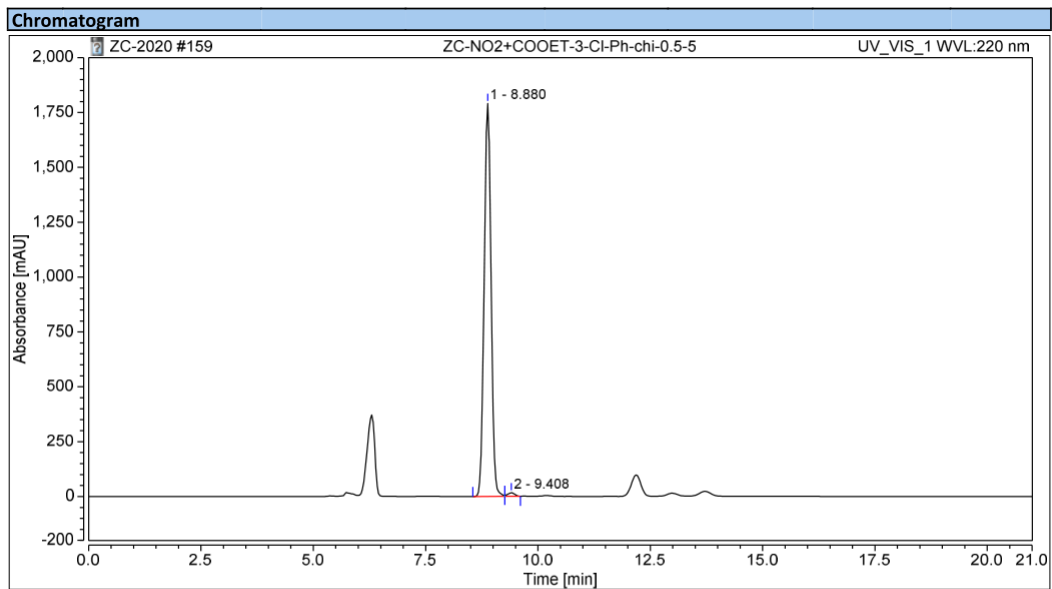
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		37.958	132.280	142.960	99.35	99.52	n.a.
2		41.745	0.866	0.683	0.65	0.48	n.a.
Total:			133.146	143.642	100.00	100.00	





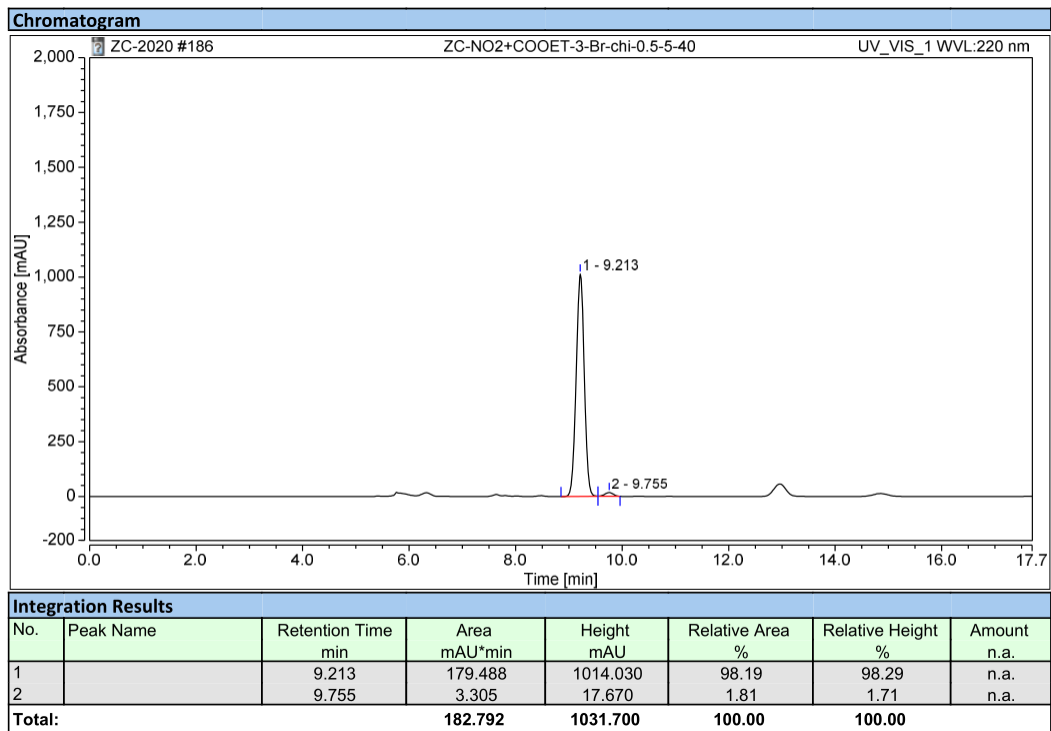
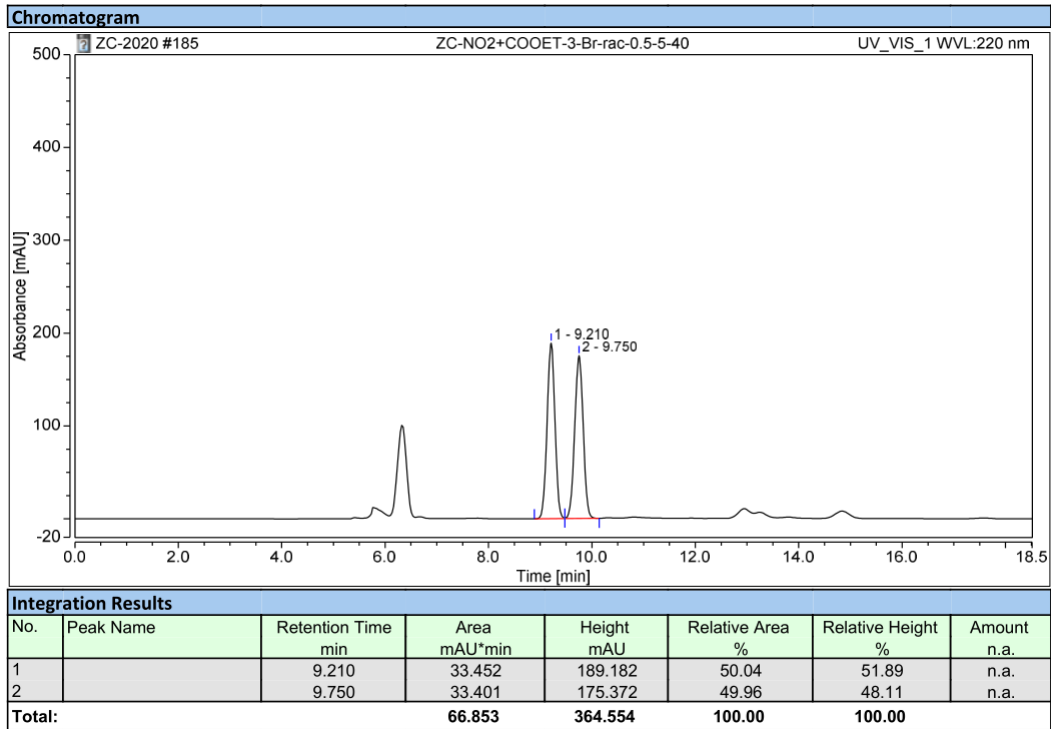
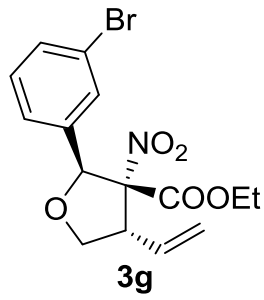
Integration Results

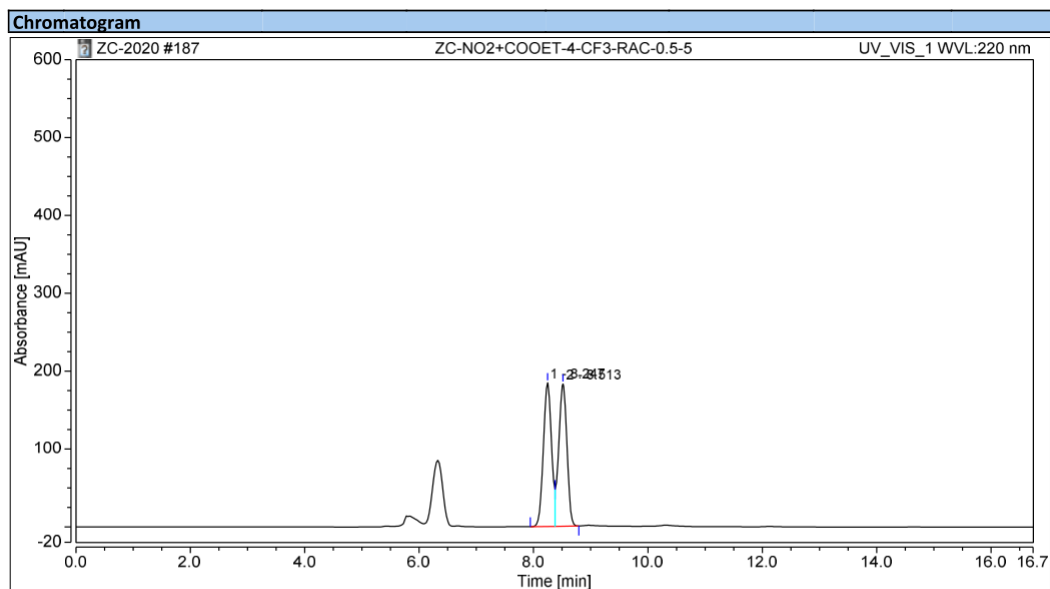
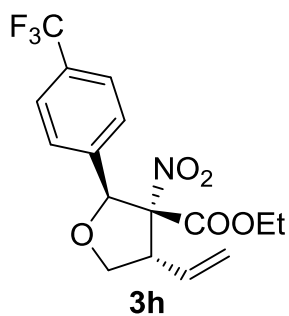
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		8.947	361.061	1980.926	49.80	51.58	n.a.
2		9.497	363.994	1859.239	50.20	48.42	n.a.
Total:			725.056	3840.165	100.00	100.00	



Integration Results

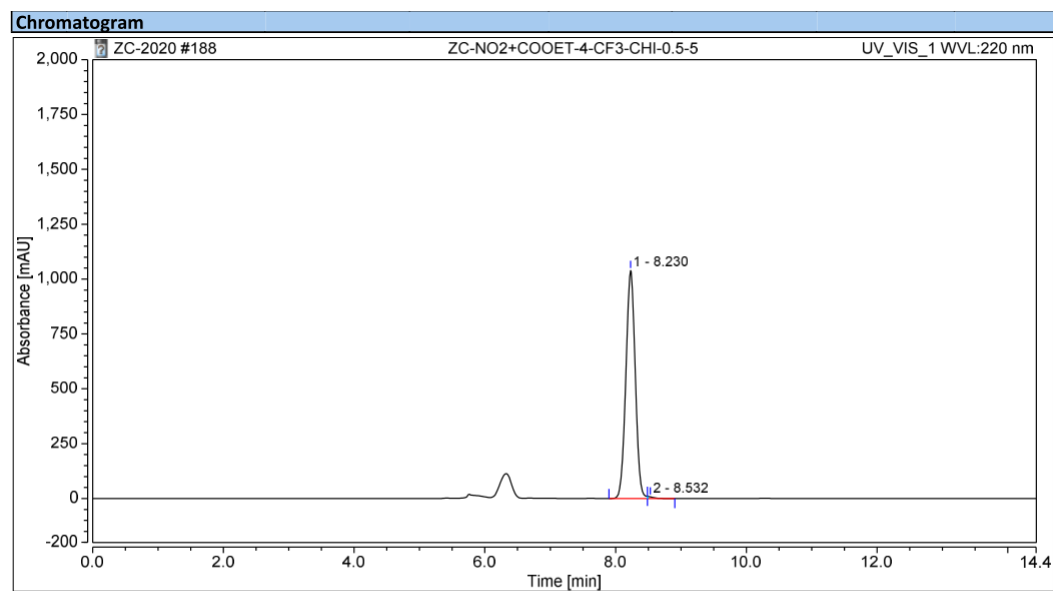
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		8.880	318.100	1791.437	99.12	99.12	n.a.
2		9.408	2.834	15.919	0.88	0.88	n.a.
Total:			320.933	1807.356	100.00	100.00	





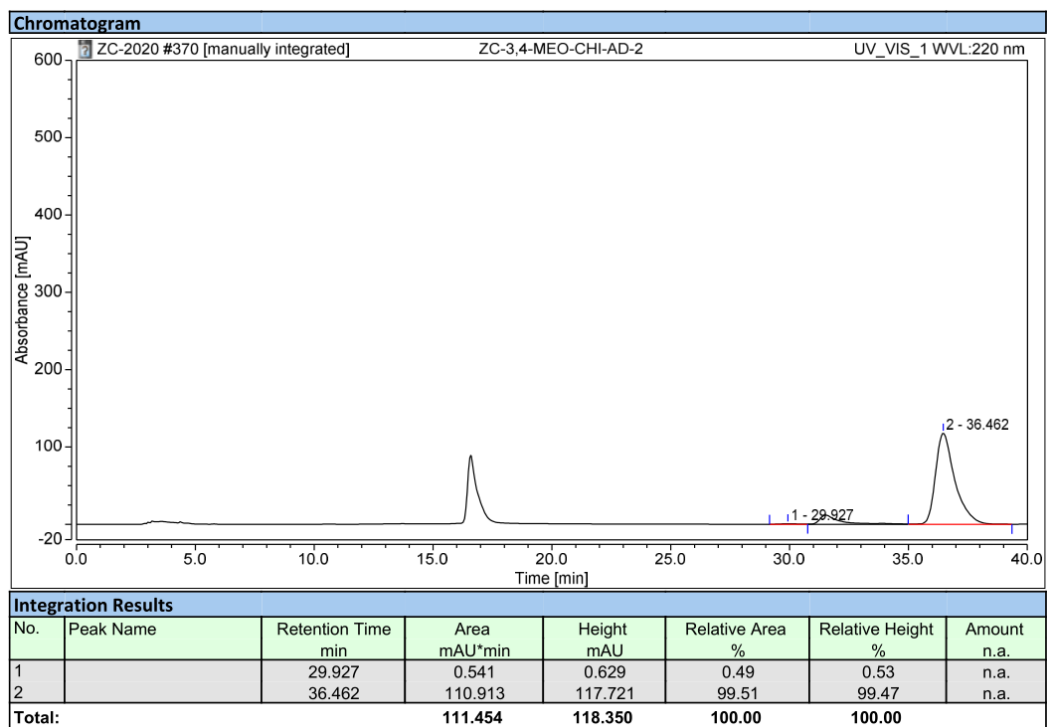
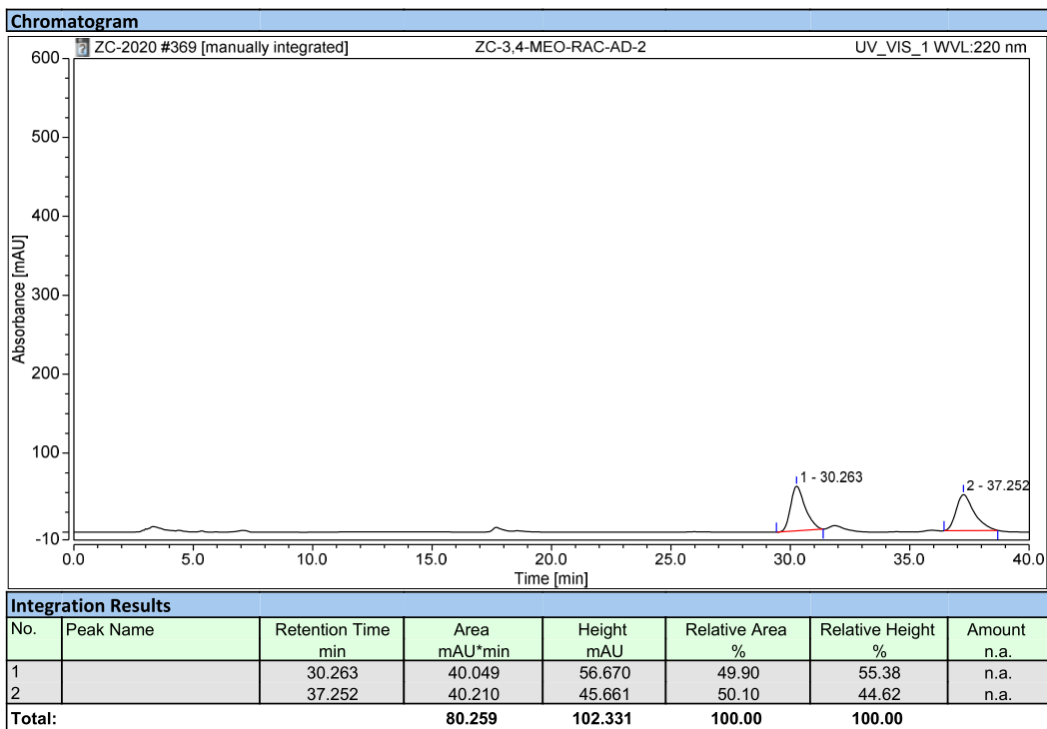
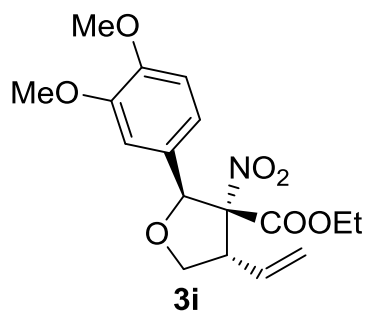
Integration Results

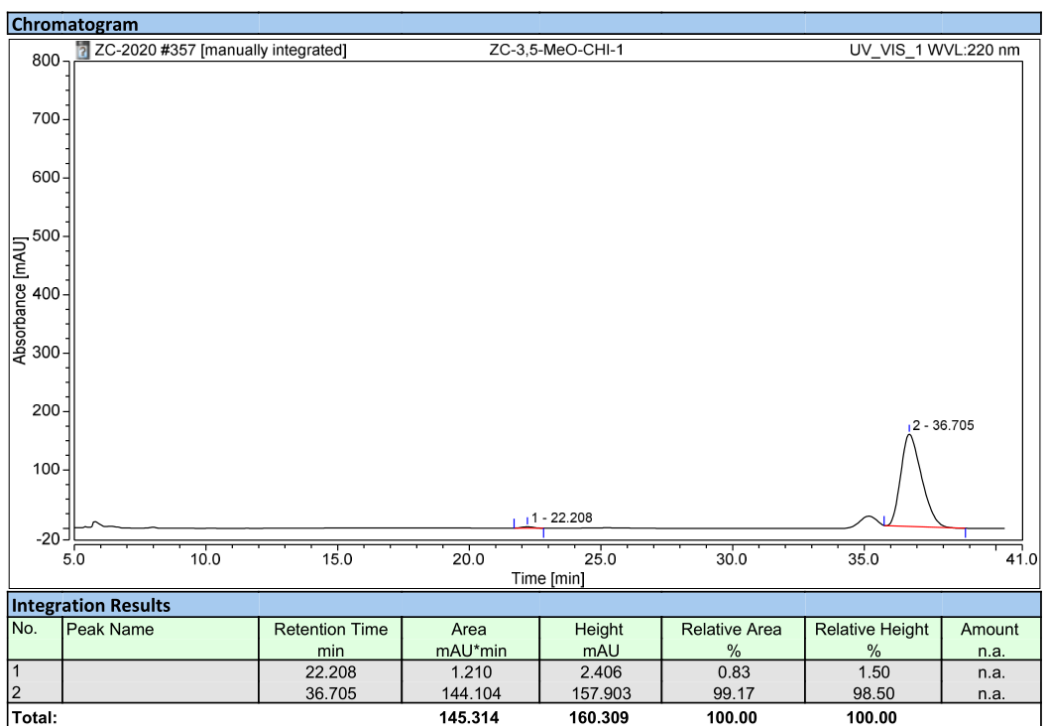
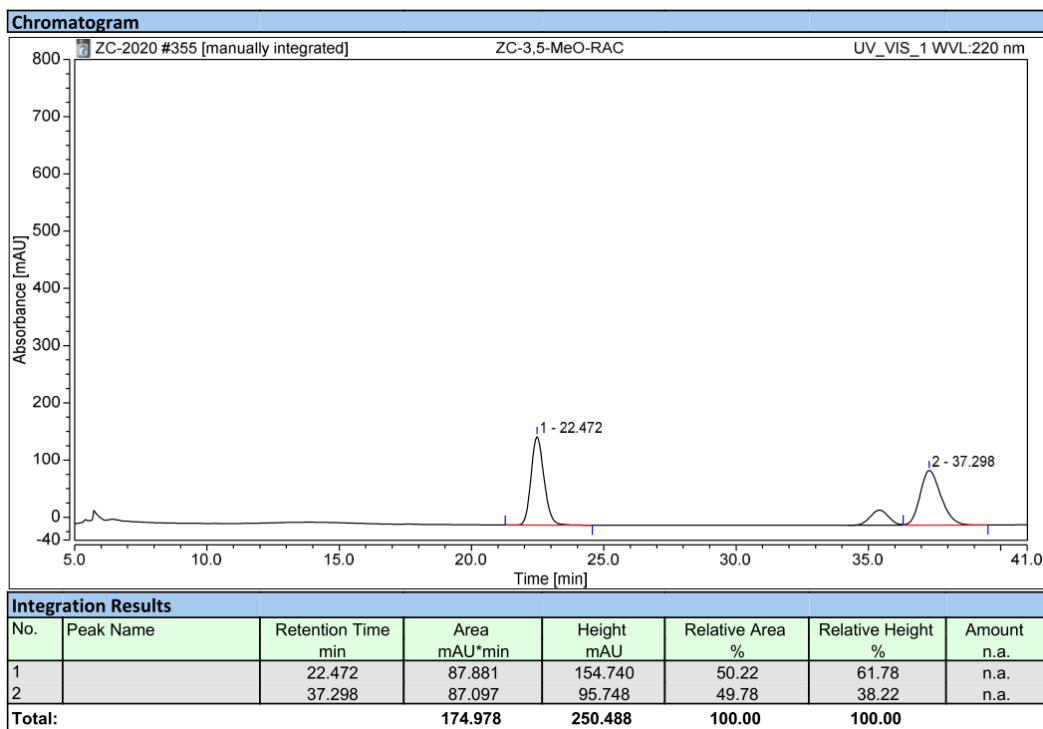
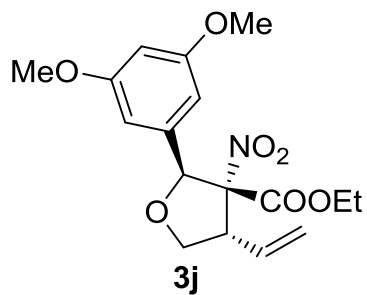
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount
1		8.247	30.479	184.856	50.05	50.25	n.a.
2		8.513	30.421	183.015	49.95	49.75	n.a.
Total:			60.900	367.871	100.00	100.00	

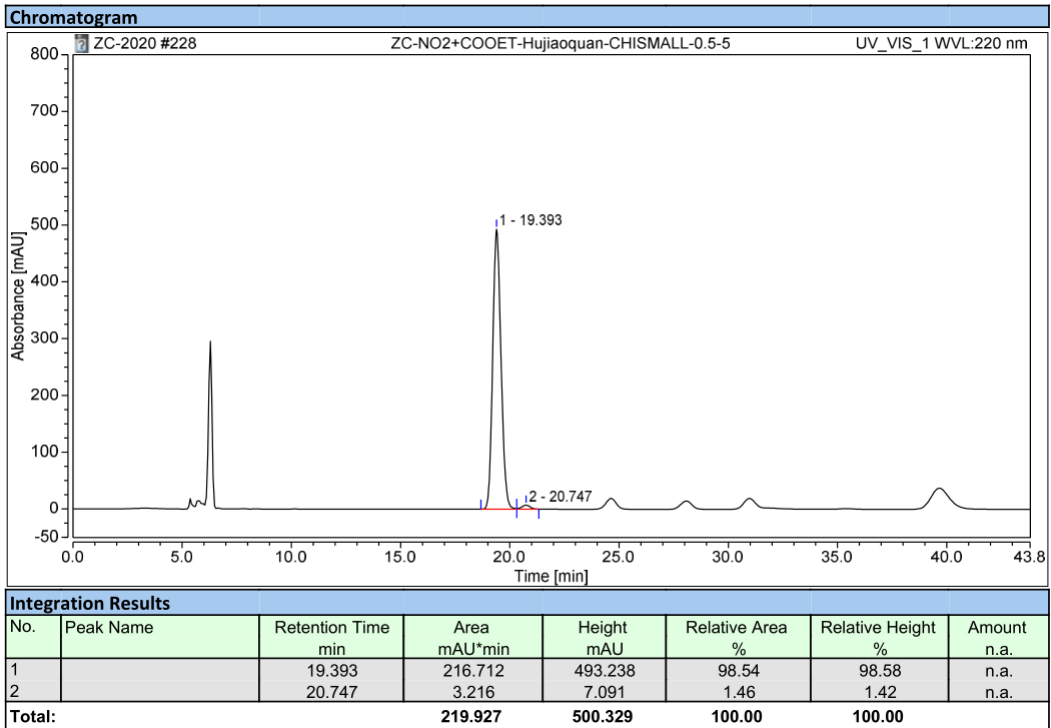
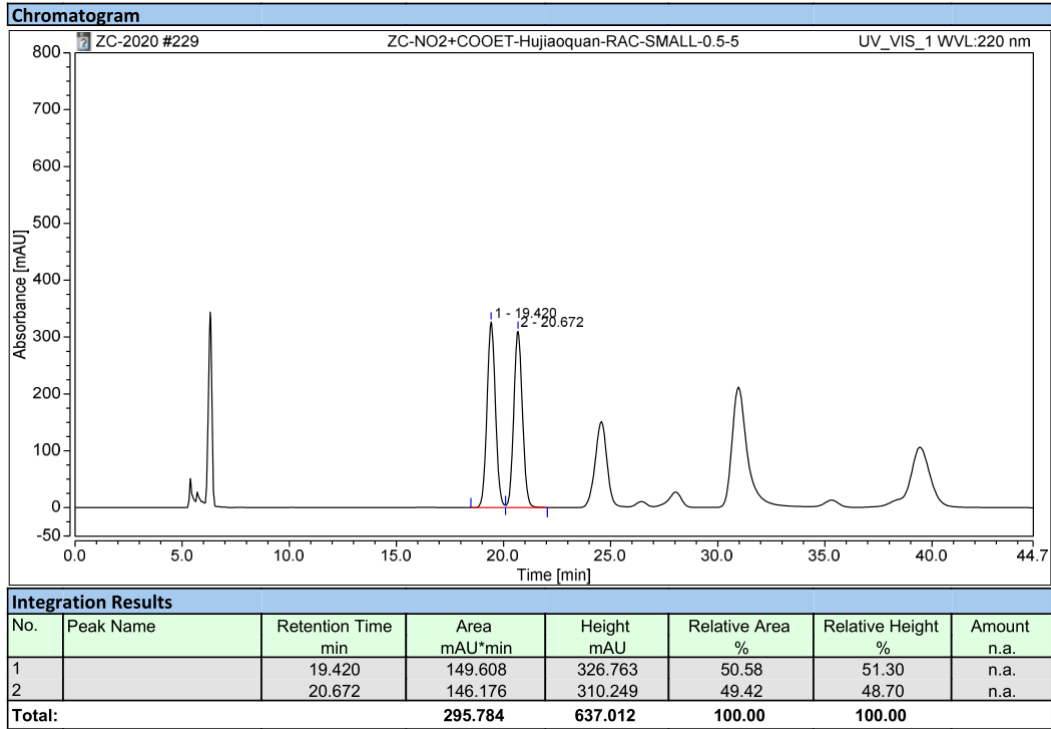
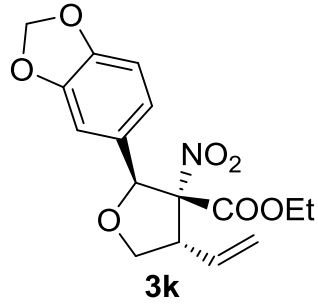


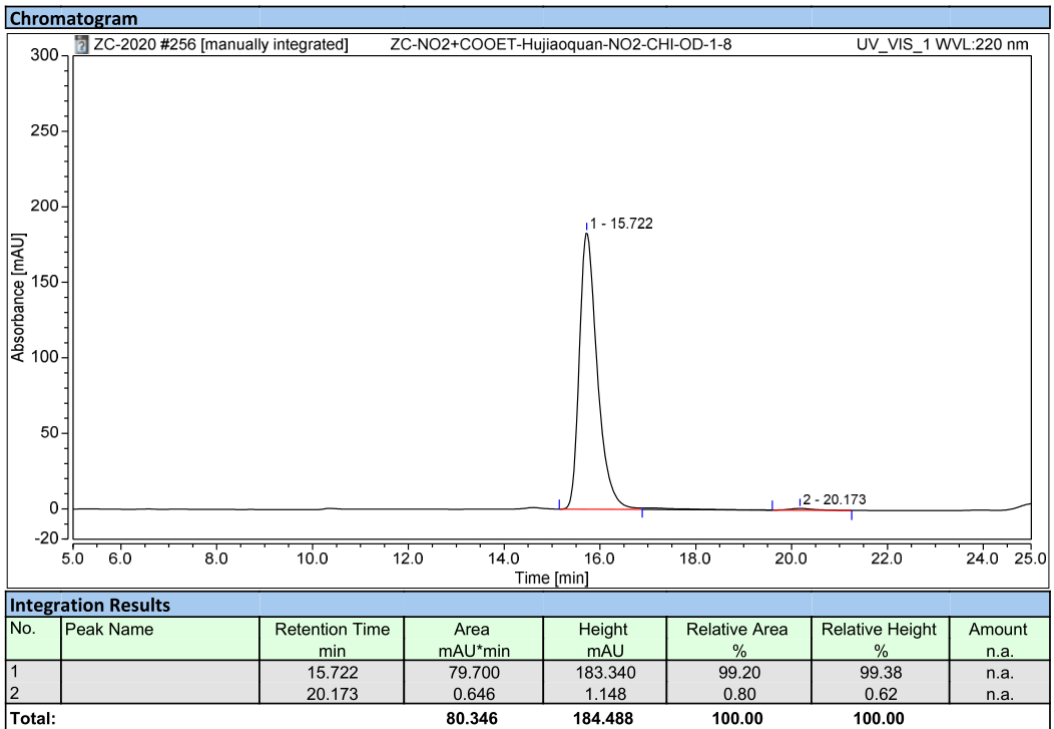
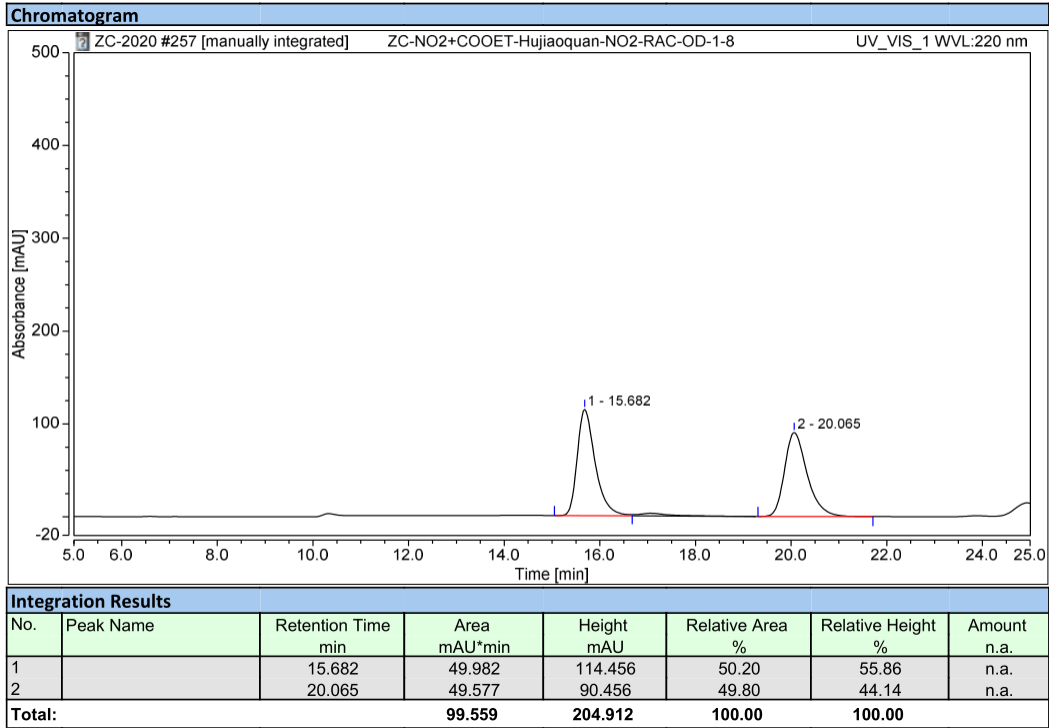
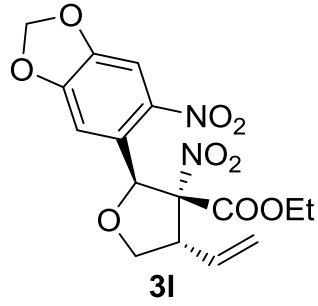
Integration Results

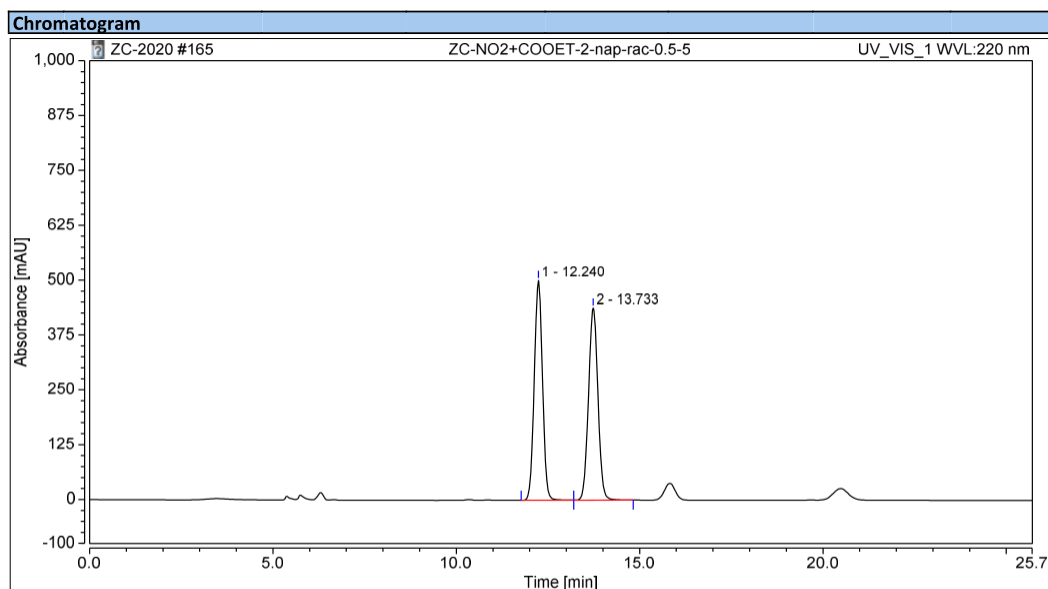
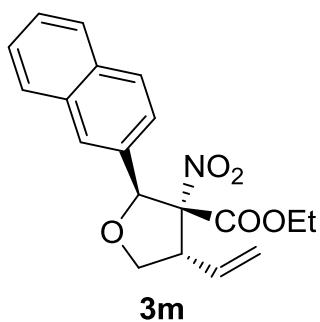
No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount
1		8.230	173.078	1038.844	99.50	99.29	n.a.
2		8.532	0.877	7.475	0.50	0.71	n.a.
Total:			173.955	1046.320	100.00	100.00	





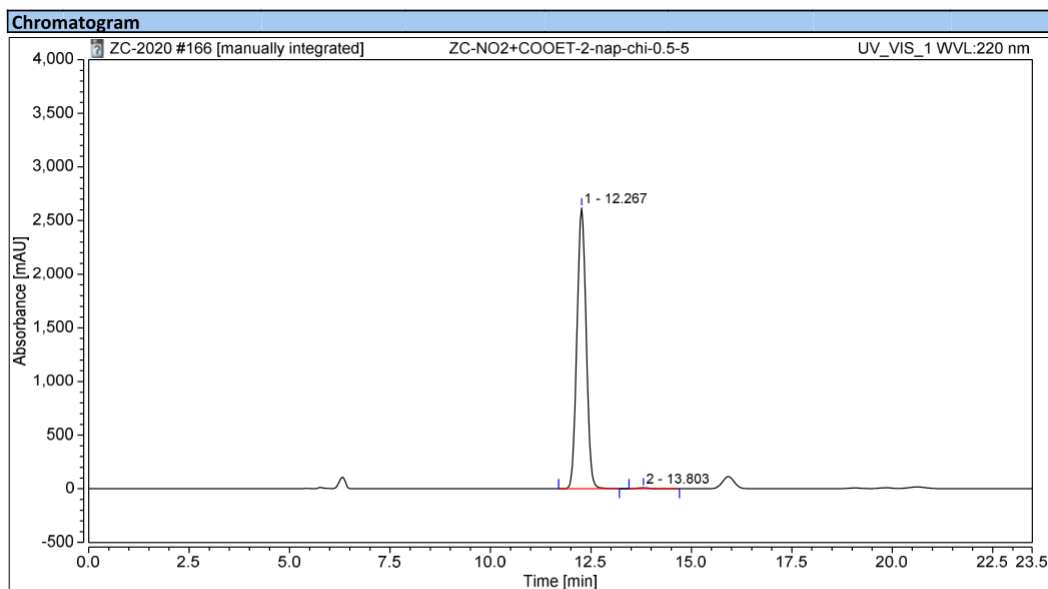






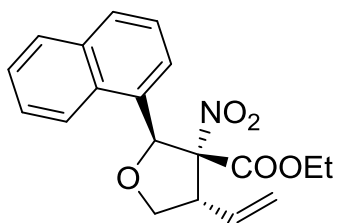
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		12.240	130.704	500.929	50.01	53.35	n.a.
2		13.733	130.664	438.060	49.99	46.65	n.a.
Total:			261.368	938.990	100.00	100.00	

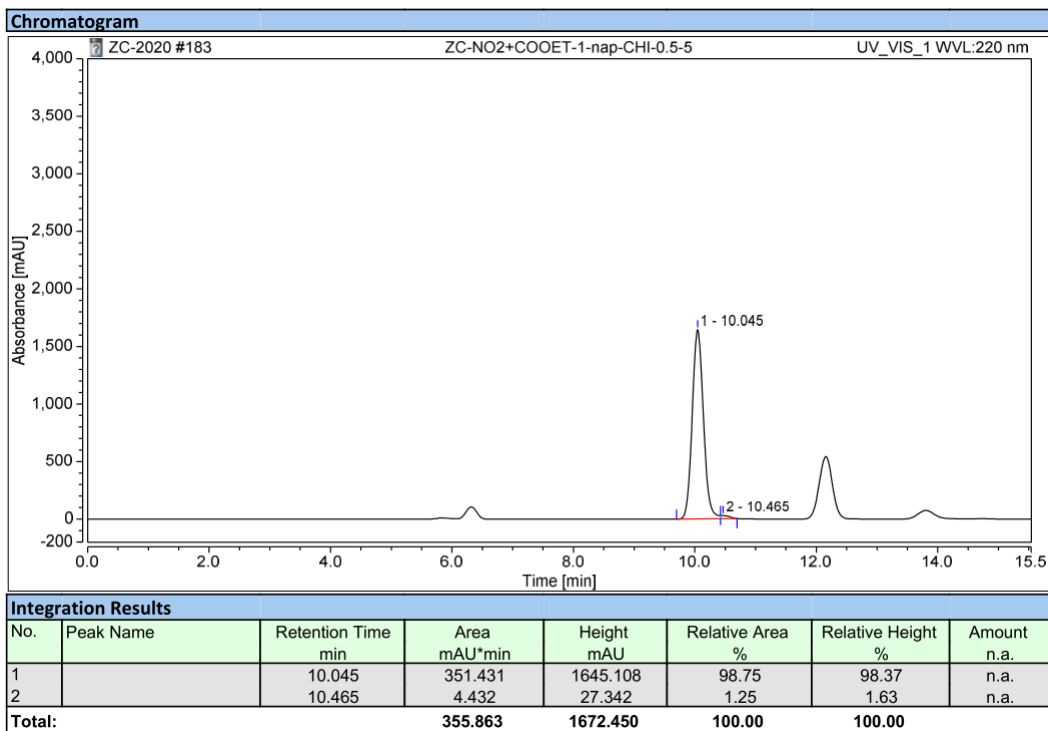
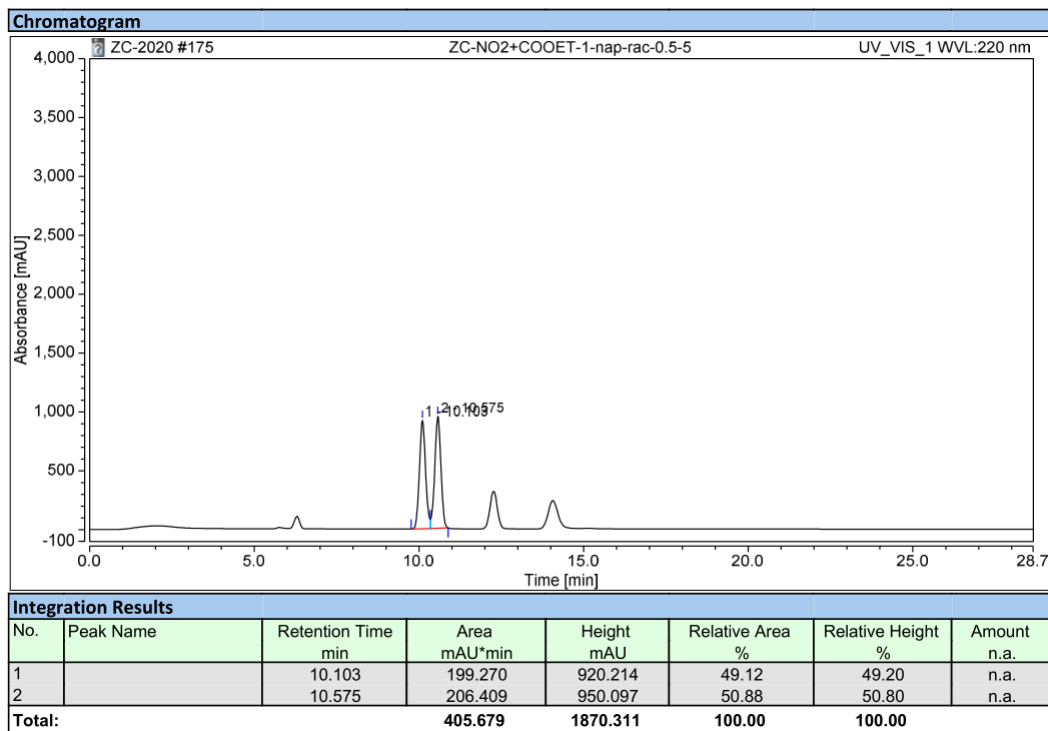


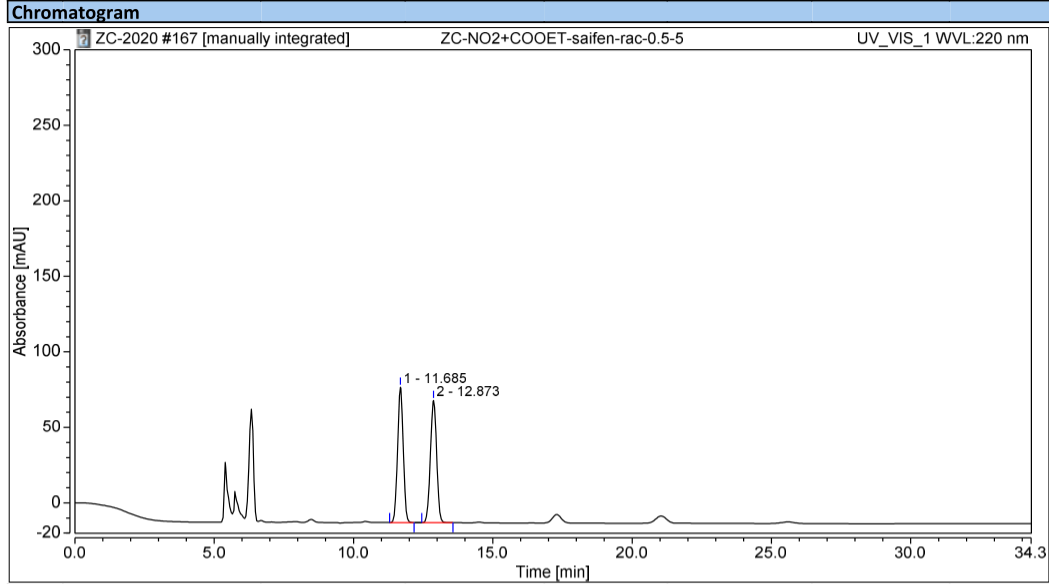
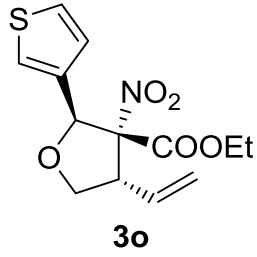
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		12.267	695.577	2620.383	99.57	99.65	n.a.
2		13.803	3.027	9.320	0.43	0.35	n.a.
Total:			698.604	2629.702	100.00	100.00	



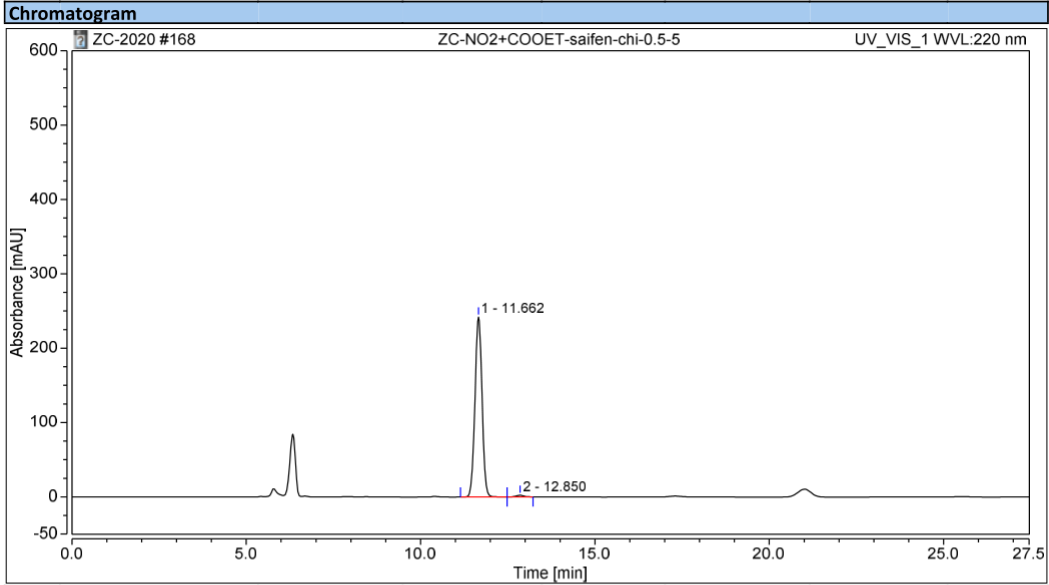
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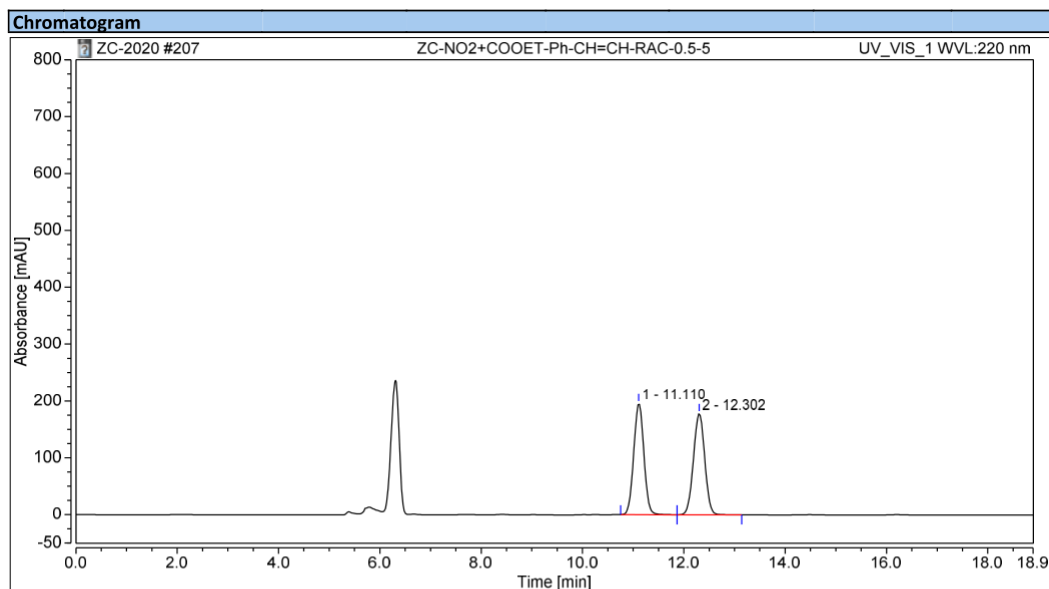
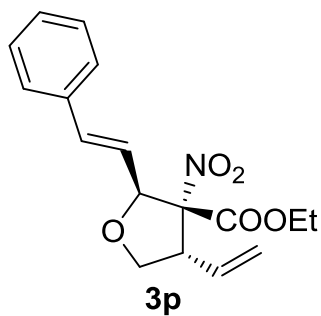
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		11.685	21.198	89.711	50.02	52.57	n.a.
2		12.873	21.179	80.949	49.98	47.43	n.a.
Total:			42.377	170.661	100.00	100.00	



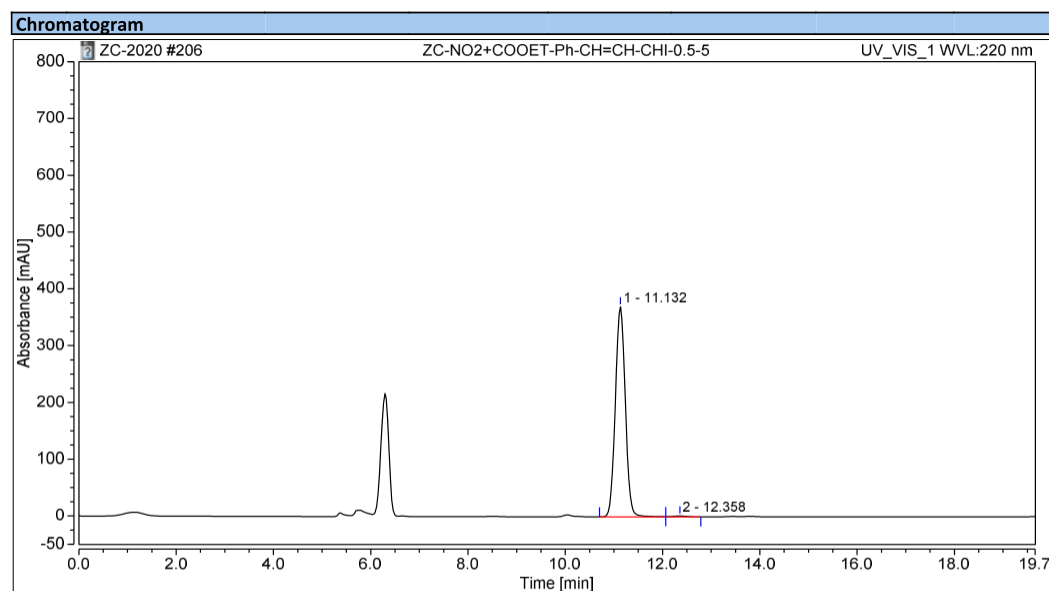
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		11.662	56.960	242.002	99.03	99.12	n.a.
2		12.850	0.561	2.149	0.97	0.88	n.a.
Total:			57.521	244.151	100.00	100.00	



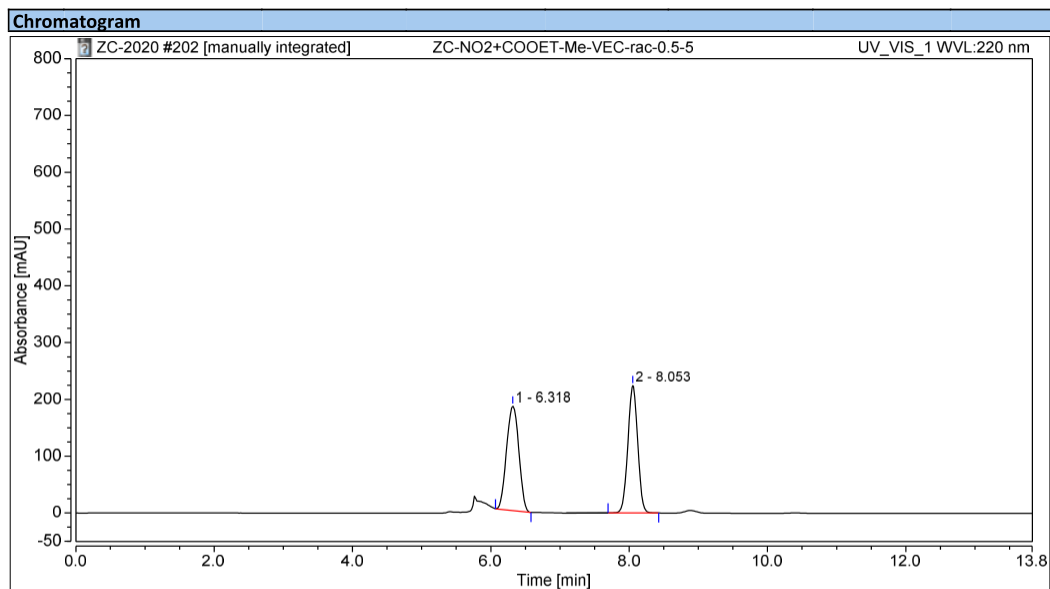
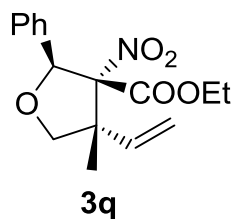
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount
1		11.110	45.665	195.972	49.78	52.40	n.a.
2		12.302	46.072	178.022	50.22	47.60	n.a.
Total:			91.737	373.995	100.00	100.00	



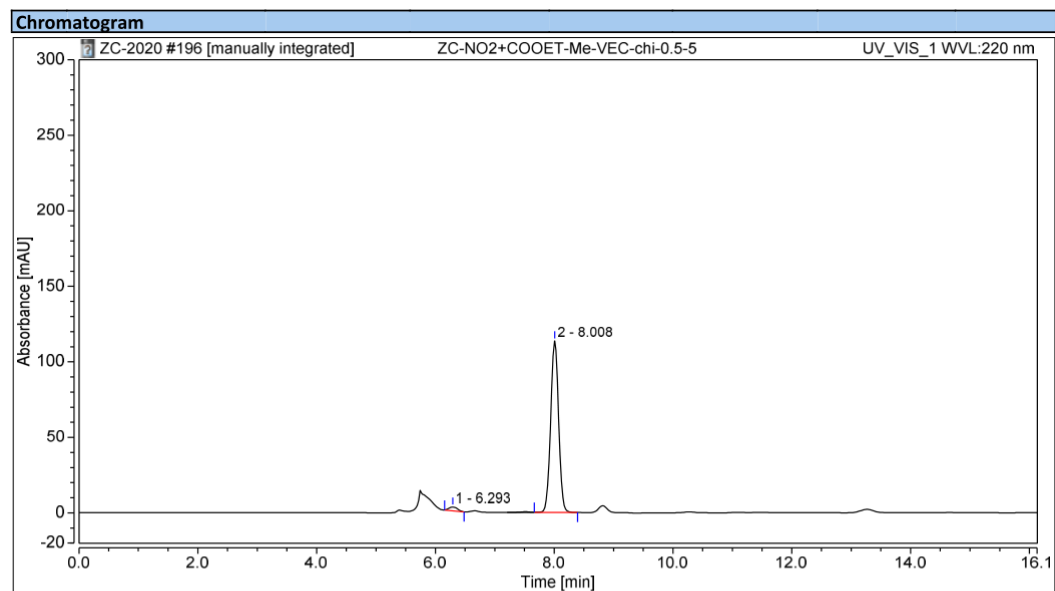
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount
1		11.132	87.759	369.953	99.50	99.59	n.a.
2		12.358	0.437	1.535	0.50	0.41	n.a.
Total:			88.196	371.488	100.00	100.00	



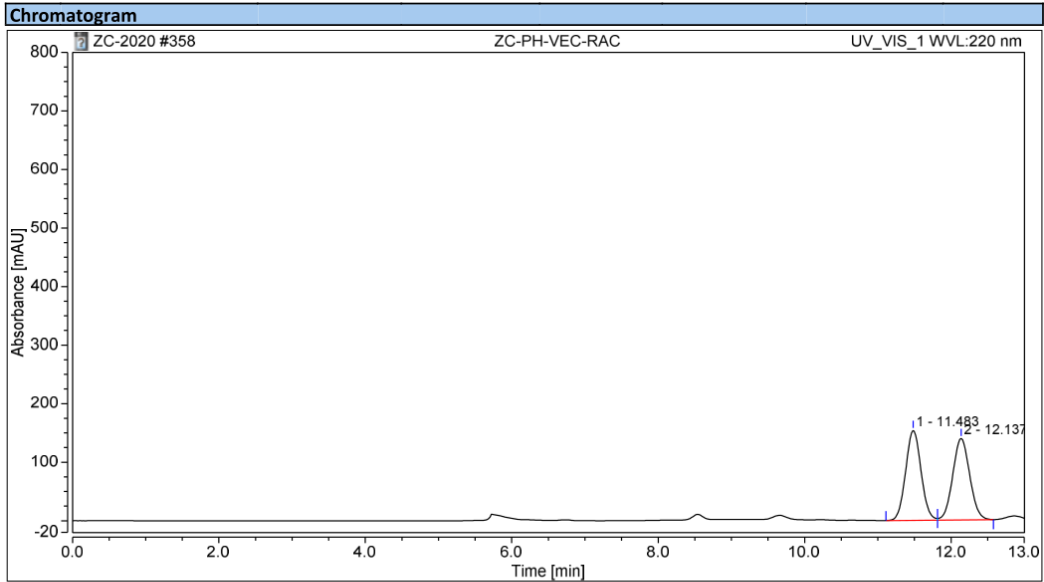
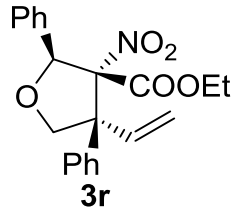
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		6.318	37.798	184.011	50.53	45.04	n.a.
2		8.053	37.013	224.567	49.47	54.96	n.a.
Total:			74.811	408.579	100.00	100.00	



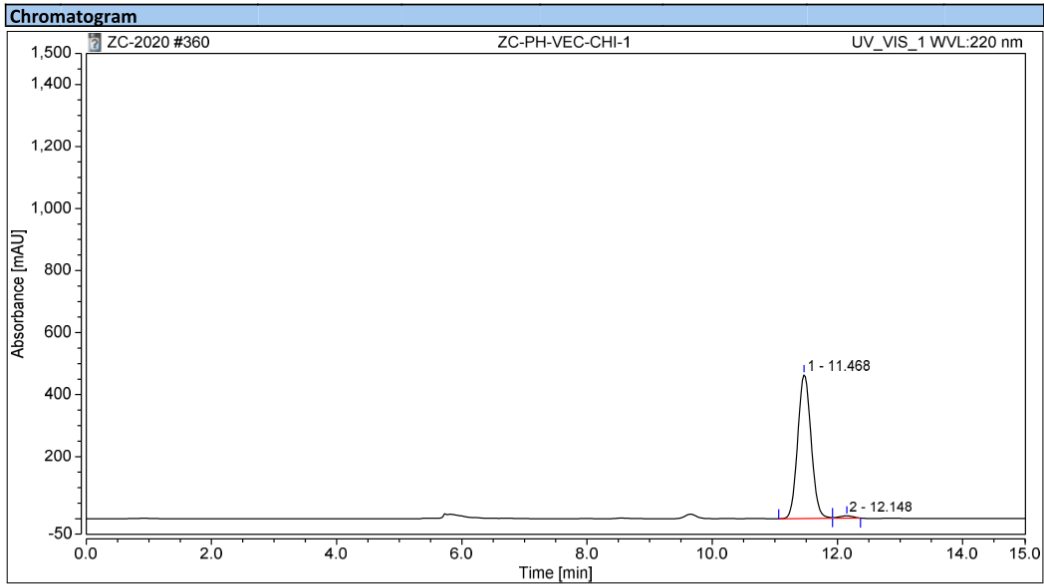
Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		6.293	0.423	2.503	2.35	2.16	n.a.
2		8.008	17.577	113.606	97.65	97.84	n.a.
Total:			18.000	116.109	100.00	100.00	



Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		11.483	37.442	153.639	50.05	52.45	n.a.
2		12.137	37.366	139.313	49.95	47.55	n.a.
Total:			74.808	292.952	100.00	100.00	



Integration Results

No.	Peak Name	Retention Time min	Area mAU*min	Height mAU	Relative Area %	Relative Height %	Amount n.a.
1		11.468	114.667	463.667	98.29	98.37	n.a.
2		12.148	1.993	7.690	1.71	1.63	n.a.
Total:			116.661	471.357	100.00	100.00	