

Metal-Free Oxidative Cross-Dehydrogenative Coupling of Quinones with Benzylic C(sp³)-H Bonds

Yu Dong,^{a,b} Jian Yang,^{a,b} Shuai He,^c Zhi-Chuan Shi,^c Yu Wang,^d Xiao-Mei Zhang^a
and Ji Yu Wang^{*a}

^a Chengdu Institute of Organic Chemistry, Chinese Academy of Sciences, Chengdu 610041, P. R. of China

jiyuwang@cioc.ac.cn

^b University of Chinese Academy of Sciences, Beijing 100049, P. R. of China.

^c University of the Southwest Minzu, Chengdu 610041, P. R. China.

^d Guizhou Education University, Guiyang 550018, China

1.	General	information
.....		
		S2
2.	Experimental	
Section		
		S2
3	Procedure	for
reaction		gram-scale
.....		
		S2
4	Typical procedure	for the synthesis of starting
materials		S3
5.	Characterization	data of
products		S5

6.

References

S17

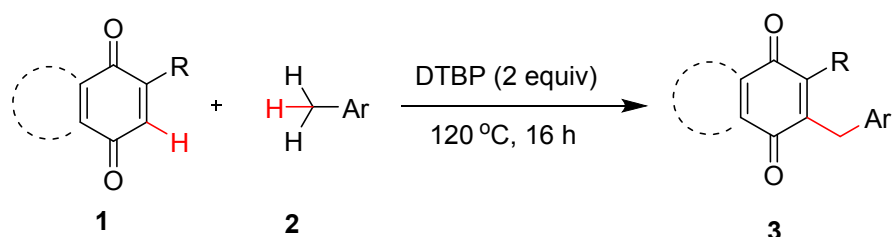
**7. Copies of ^1H and ^{13}C NMR spectra for all
compounds**S18

1. General information.

All reactions were carried out under sealed tube. Chemicals and analytical grade solvents were purchased from commercial suppliers and used without further purification unless otherwise stated. All reagents were weighed and handled in air at room temperature. Analytical thin-layer chromatography was performed on glass plates of Silica Gel GF-254 with detection by UV light (254 and 365 nm). Column chromatography was carried out on silica gel (200–300 mesh). ^1H NMR spectra were recorded at 400 MHz and ^{13}C NMR spectra were recorded at 101 MHz by using Agilent 400 MHz NMR spectrometer. Chemical shifts were calibrated using residual undeuterated solvent as an internal reference (^1H NMR: CDCl_3 7.26 ppm, $\text{DMSO-}d_6$ 2.50 ppm, ^{13}C NMR: CDCl_3 77.16 ppm, $\text{DMSO-}d_6$ 39.52 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, br s = broad singlet, d = doublet, t = triplet, q = quartet, m = multiplet), Coupling constants (J) were reported in Hertz (Hz). HRMS were performed on a Thermo Scientific LTQ Orbitrap XL instrument. Melting points were measured with micro melting point apparatus.

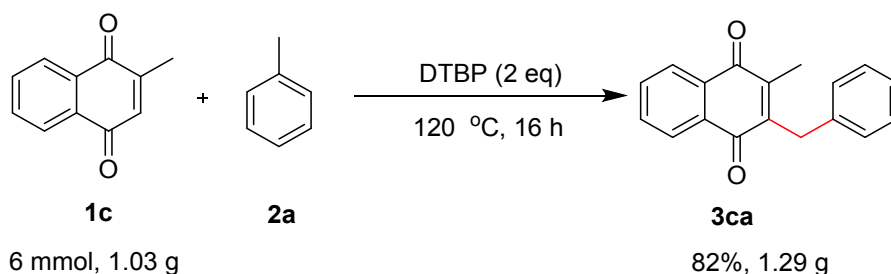
2. Experimental Section.

General procedures for the synthesis of benzylquinones.



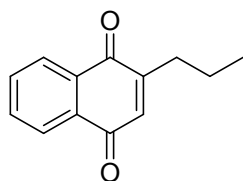
A 10 mL oven-dried Schlenk tube was charged with quinones **1** (0.4 mmol, 1.0 equiv.) in benzylic hydrocarbons **2** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. After the completion of the reaction (monitored by TLC), the mixture was extracted with EtOAc (3 × 5 mL). The combined organic layers were washed with brine, dried over Na₂SO₄ and the solvent was removed in vacuo. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc) to afford the desired pure product **3**.

3. Procedure for gram-scale reaction.

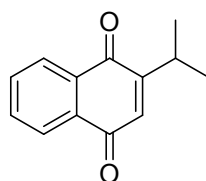


A 100 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone **1c** (6 mmol, 1.0 equiv.) in toluene **2a** (30 mL). DTBP (12 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. After the completion of the reaction (monitored by TLC), the mixture was extracted with EtOAc (3 × 50 mL). The combined organic layers were washed with brine, dried over Na₂SO₄ and the solvent was removed in vacuo. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc) to give 1.29 g of **3ca** in 82 % yield.

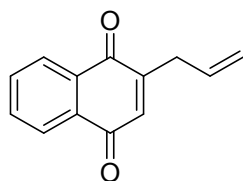
4. Typical procedure for the synthesis of starting materials.



2-propylnaphthalene-1,4-dione¹: A solution of 0.9 g $(\text{NH}_4)_2\text{S}_2\text{O}_8$ in 10 ml distilled water was added dropwise over 25-120 min to a stirred suspension of 10 ml H_2O , 20 ml CH_3CN 0.24 g AgNO_3 , 0.4 g 1,4-naphthoquinone and 3.2 mmol propionic acid at 65-75°C. After stirring for 5-10 min. The reaction mixture was diluted with EtOAc (20 mL) and washed with H_2O (3×10 mL). The aqueous phase was extracted with EtOAc (3×10 mL), and the combined organic phase was dried over Na_2SO_4 . After filtration and evaporation of the solvents in vacuo, the crude product was purified by column chromatography on silica gel (petroleum ether/EtOAc = 30/1) to give analytically pure product (0.28 g) as yellow needles; yield: 55%; $^1\text{H NMR}$ (300 MHz, CDCl_3) δ 8.06 – 7.95 (m, 2H), 7.72 – 7.63 (m, 2H), 6.72 (s, 1H), 2.56 – 2.40 (m, 2H), 1.57 (dd, $J = 15.1, 7.4$ Hz, 2H), 0.96 (t, $J = 7.3$ Hz, 3H).

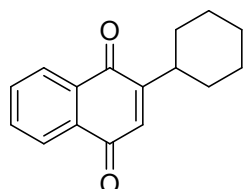


2-isopropylnaphthalene-1,4-dione¹: A solution of 0.9 g $(\text{NH}_4)_2\text{S}_2\text{O}_8$ in 10 ml distilled water was added dropwise over 25-120 min to a stirred suspension of 10 ml H_2O , 20 ml CH_3CN 0.24 g AgNO_3 , 0.4 g 1,4-naphthoquinone and 3.2 mmol Isopropyl acid at 65-75 °C. After stirring for 5-10 min. The reaction mixture was diluted with EtOAc (20 mL) and washed with H_2O (3×10 mL). The aqueous phase was extracted with EtOAc (3×10 mL), and the combined organic phase was dried over Na_2SO_4 . After filtration and evaporation of the solvents in vacuo, the crude product was purified by column chromatography on silica gel (petroleum ether/EtOAc = 30/1) to give analytically pure product (0.31 g) as yellow needles; yield: 61%; $^1\text{H NMR}$ (300 MHz, CDCl_3) δ 8.12 – 8.00 (m, 2H), 7.73 – 7.67 (m, 2H), 6.75 (s, 1H), 3.29 – 3.15 (m, 1H), 1.18 (d, $J = 6.9$ Hz, 6H).

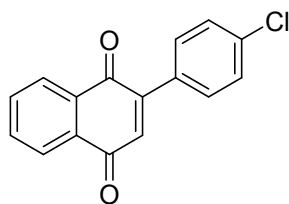


2-allylnaphthalene-1,4-dione²: A mixture of 1,4-naphthoquinone (2 mmol) and $\text{Bi}(\text{OTf})_3$ (0.05 mmol) and allyltrimethylsilane (4 mmol) in dichloromethane (10 mL)

was stirred at room temperature for the 1 h. After completion of the reaction as indicated by TLC, the reaction mixture was quenched with water (15 mL) and extracted with dichloromethane (3×10 mL). Evaporation of the solvent followed by purification on silica gel (petroleum ether/EtOAc = 40/1) afforded analytically pure product (0.19 g) as light yellow solid; yield: 48%; ¹H NMR (300 MHz, CDCl₃) δ 8.08 – 7.98 (m, 2H), 7.73 – 7.67 (m, 2H), 6.77 (s, 1H), 5.98 – 5.78 (m, 1H), 5.22 (dd, *J* = 1.5, 1.0 Hz, 1H), 5.19 – 5.16 (m, 1H), 3.30 (ddd, *J* = 6.8, 2.6, 1.4 Hz, 2H).



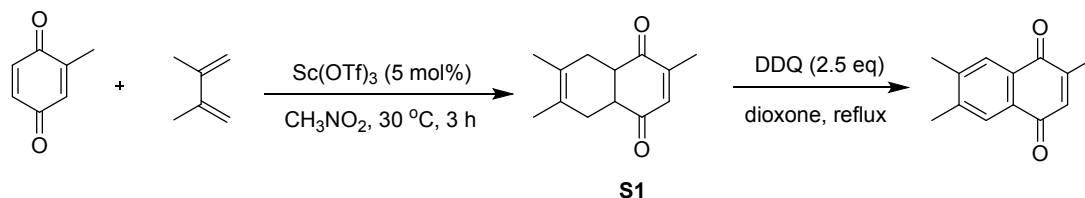
2-cyclohexylnaphthalene-1,4-dione³: To a nitrogen or argon backfilled Shlenk tube substrate 1,4-naphthoquinone (1.5 mmol, 237 mg, 1 equiv.), cyclohexanecarboxylic acid (15 mmol, 1920 mg, 10 equiv.) and ammonium persulfate (685 mg, 3 mmol) were added. After a final backfill, DMSO/water (30 mL/50 μL degassed by bubbling with argon (2 balloons/15 mins) was added and the reaction was sealed and stirred overnight at 40 ° C. The reaction mixture was diluted with DCM (150 mL) and washed with sat. NaHCO₃ solution. The aqueous layer was then extracted with DCM (3 x 10 mL) and the combined organic layers were washed with brine (20 mL), dried (Na₂SO₄) and concentrated to give the crude product; yellow paste (251 mg, 70%); ¹H NMR (300 MHz, CDCl₃) δ 8.09 – 7.96 (m, 2H), 7.68 (dt, *J* = 3.9, 3.4 Hz, 2H), 6.69 (s, 1H), 2.89 (dd, *J* = 24.8, 13.0 Hz, 1H), 1.78 (t, *J* = 17.0 Hz, 5H), 1.51 – 1.35 (m, 2H), 1.20 (q, *J* = 12.4 Hz, 3H).



2-(4-chlorophenyl)naphthalene-1,4-dione⁴: To a solution of 1,4-naphthoquinone (2 mmol, 316 mg) in trifluorotoluene (15 mL) was added 4-Chlorophenylboronic acid (3 mmol, 603 mg), water (10 mL), and silver(I) nitrate (0.1 M solution in water, 0.4 mmol, 67.9 mg). Potassium persulfate (6 mmol, 1620 mg) was then added and the solution was stirred vigorously at room temperature for 24 h and monitored by thin-layer chromatography analysis of the organic layer. Upon consumption of quinone, the reaction was diluted with dichloromethane (20 mL) and washed with 5% sodium bicarbonate. The layers were separated, and the aqueous layer was extracted with dichloromethane (3×20 mL), dried over sodium sulfate, and evaporated in vacuo. Purification was performed by silica gel chromatography to yield chromatographically using petroleum ether–ethyl acetate (30 :1) and spectroscopically pure product. Yellow solid, 58% yield. ¹H NMR (300 MHz, CDCl₃) δ 8.17 (s, 1H),

8.12 (d, $J = 3.2$ Hz, 1H), 7.84 – 7.75 (m, 2H), 7.53 (d, $J = 8.8$ Hz, 2H), 7.46 (d, $J = 8.7$ Hz, 2H), 7.07 (s, 1H).

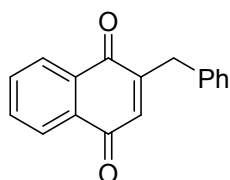
Procedure for the preparation of 2,6,7-trimethyl-1,4-naphthoquinone⁵.



2,3-Dimethyl-1,3-dibutene (1.1 mL, 10 mmol) was added to a mixture of 2-methylbenzoquinone (244.2 mg, 2.0 mmol) and Sc(OTf)₃ (49.2 mg, 0.1 mmol) in CH₃NO₂ (25 mL). The mixture was stirred at room temperature for 2 h, and then filtered through celite. Evaporation of the solvent under vacuum afforded crude **S1** without further purification. 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone (DDQ, 1.135 g, 5 mmol) was added to the solution of **S1** in dioxane (30 mL). The mixture was refluxed under 110 °C overnight. After purification by column chromatography on silica gel with petroleum ether/ethyl acetate (10:1) as eluent, 2,6,7-trimethyl-1,4-naphthoquinone was obtained as a yellow solid (295mg, 74%). ¹H NMR (300 MHz, CDCl₃) δ 7.78 (d, $J = 11.0$ Hz, 2H), 6.74 (d, $J = 1.5$ Hz, 1H), 2.37 (s, 6H), 2.15 (d, $J = 1.4$ Hz, 3H).

5. Characterization data of products.

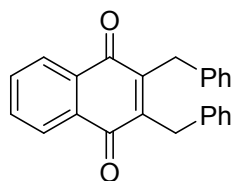
2-benzyl-naphthalene-1,4-dione (**3aa**)⁶



A 10 mL oven-dried Schlenk tube was charged with 1,4-naphthoquinone (**1a**, 63.3 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3aa** as a yellow solid (45% yield), mp 85-87 °C. R_f = 0.50 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.06 (d, $J = 3.2$ Hz, 1H), 8.00 (d, $J = 3.3$ Hz, 1H), 7.69 (d, $J = 2.8$ Hz, 2H), 7.32 (t, $J = 7.1$ Hz, 2H), 7.24 (d, $J = 7.2$ Hz, 3H), 6.58 (s, 1H), 3.88 (s, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 185.02, 184.94, 150.84, 138.89, 135.69, 133.78, 133.71, 132.09, 132.01, 129.47, 128.87, 126.97, 126.63, 126.07, 35.73.

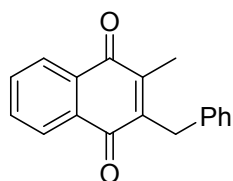
2,3-dibenzyl-naphthalene-1,4-dione (**3ba**)⁷



A 10 mL oven-dried Schlenk tube was charged with 2-benzyl-1,4-naphthoquinone (**1b**, 99.3 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ba** as a yellow solid (78% yield), mp 64-66 °C. Rf = 0.60 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.09 (d, *J* = 2.4 Hz, 2H), 7.70 (d, *J* = 2.3 Hz, 2H), 7.27 – 7.16 (m, 10H), 4.09 (s, 4H). ¹³C NMR (101 MHz, CDCl₃) δ 185.17, 146.18, 137.93, 133.64, 132.00, 128.67, 128.63, 126.49, 32.45.

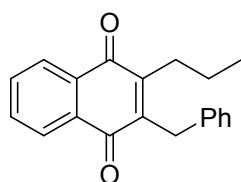
2-benzyl-3-methylnaphthalene-1,4-dione (**3ca**)⁸



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ca** as a yellow solid (86% yield), mp 78-80 °C. Rf = 0.60 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.10 – 8.04 (m, 2H), 7.72 – 7.66 (m, 2H), 7.28 – 7.16 (m, 5H), 4.03 (s, 2H), 2.24 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.37, 184.63, 145.30, 144.40, 138.02, 133.47, 133.44, 132.08, 132.00, 128.62, 128.56, 126.45, 126.40, 126.24, 32.40, 13.28.

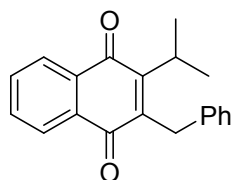
2-benzyl-3-propylnaphthalene-1,4-dione (**3da**)



A 10 mL oven-dried Schlenk tube was charged with 2-propyl-1,4-naphthoquinone (**1d**, 80.1 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3da** as a yellow solid (81% yield), mp 85-87°C. Rf = 0.60 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.09 (s, 2H), 7.71 (s, 2H), 7.30 – 7.17 (m, 5H), 4.05 (s, 2H), 2.75 – 2.65 (m, 2H), 1.52 – 1.41 (m, 2H), 1.00 (t, *J* = 7.2 Hz, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.22, 185.10, 148.35, 144.92, 138.53, 133.45, 132.17, 132.02, 128.80, 128.41, 126.39, 126.126.25, 32.16, 29.55, 22.62, 14.58. HRMS calcd. For C₂₀H₁₉O₂⁺ (M+H)⁺ 291.1380 Found 291.1379.

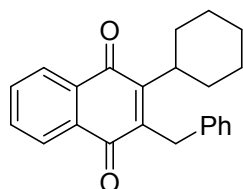
2-benzyl-3-isopropyl-naphthalene-1,4-dione (**3ea**)



A 10 mL oven-dried Schlenk tube was charged with 2-isopropyl-1,4-naphthoquinone (**1e**, 80.1 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ea** as a yellow solid (75% yield), mp 81-83 °C. Rf = 0.60 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 7.92 (s, 2H), 7.56 (s, 2H), 7.14 (s, 2H), 7.07 (d, *J* = 6.8 Hz, 3H), 3.96 (s, 2H), 3.16 – 3.07 (m, 1H), 1.18 (d, *J* = 6.9 Hz, 6H). ¹³C NMR (101 MHz, CDCl₃) δ 185.30, 185.23, 152.27, 144.45, 138.65, 133.49, 133.35, 133.21, 133.09, 132.86, 131.57, 128.59, 128.29, 126.28, 128.24, 31.61, 30.67, 29.70, 20.74. HRMS calcd. For C₂₀H₁₉O₂⁺ (M+H)⁺ 291.1380 Found 291.1385.

2-benzyl-3-cyclohexyl-naphthalene-1,4-dione (**3fa**)

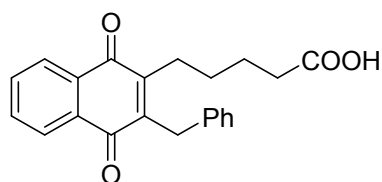


A 10 mL oven-dried Schlenk tube was charged with 2-cyclohexyl-1,4-naphthoquinone (**1f**, 96.1 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column

chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3fa** as a yellow solid (72% yield), mp 92-94 °C. Rf = 0.60 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.03 (t, *J* = 7.0 Hz, 2H), 7.67 (s, 2H), 7.26 (d, *J* = 8.2 Hz, 2H), 7.19 (d, *J* = 7.0 Hz, 3H), 4.08 (s, 2H), 2.88 (t, *J* = 10.9 Hz, 1H), 2.05 (dd, *J* = 24.4, 12.2 Hz, 2H), 1.75 (t, *J* = 13.6 Hz, 2H), 1.44 (d, *J* = 12.6 Hz, 2H), 1.35 – 1.18 (m, 4H). ¹³C NMR (101 MHz, CDCl₃) δ 185.63, 185.41, 151.46, 144.98, 139.00, 133.47, 133.19, 133.09, 132.81, 131.56, 128.57, 128.37, 126.27, 126.20, 41.93, 31.75, 30.10, 29.85, 26.98, 26.88, 25.79. HRMS calcd. For C₂₃H₂₃O₂⁺ (M+H)⁺ 353.1512 Found 353.1517.

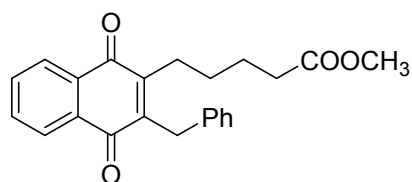
5-(3-benzyl-1,4-dioxo-1,4-dihydronaphthalen-2-yl)pentanoic acid (**3ga**)



A 10 mL oven-dried Schlenk tube was charged with 2-pentanoic acid-1,4-naphthoquinone (**1g**, 103.3 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 3 : 1) to the desired product **3ga** as a white solid (73% yield), mp 107-109 °C. Rf = 0.30 (1:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, DMSO-*d*₆) δ 12.17 (s, 1H), 8.12 (s, 2H), 7.97 (s, 2H), 7.48 – 7.18 (m, 5H), 4.11 (s, 2H), 2.79 – 2.67 (m, 2H), 2.29 (t, *J* = 7.2 Hz, 2H), 1.65 (dd, *J* = 14.6, 7.3 Hz, 2H), 1.44 (d, *J* = 6.6 Hz, 2H). ¹³C NMR (101 MHz, DMSO-*d*₆) δ 184.92, 184.69, 174.68, 148.12, 144.87, 139.17, 134.42, 132.10, 131.90, 128.93, 128.65, 126.67, 126.40, 126.33, 33.82, 31.86, 28.42, 27.14, 25.20. HRMS calcd. For C₂₂H₂₁O₄⁺ (M+H)⁺ 349.1440 Found 349.1441.

methyl 5-(3-benzyl-1,4-dioxo-1,4-dihydronaphthalen-2-yl)pentanoate (**3ha**)



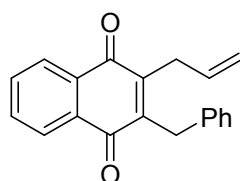
A 10 mL oven-dried Schlenk tube was charged with methyl 5-(1,4-dioxo-1,4-dihydronaphthalen-2-yl)pentanoate (**1h**, 108.8 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and

the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 50 : 1) to the desired product **3ha** as a yellow solid (79% yield), mp 111-113 °C. Rf = 0.50 (3:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.10 – 8.02 (m, 2H), 7.69 (d, *J* = 3.0 Hz, 2H), 7.29 – 7.08 (m, 5H), 4.02 (s, 2H), 3.64 (s, 3H), 2.71 – 2.63 (m, 2H), 2.29 (t, *J* = 7.5 Hz, 2H), 1.70 (dd, *J* = 14.9, 7.6 Hz, 2H), 1.46 – 1.35 (m, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 185.08, 184.99, 173.78, 147.90, 145.07, 138.46, 133.50, 133.35, 132.10, 131.98, 128.63, 128.40, 126.43, 126.41, 51.54, 33.71, 32.08, 28.48, 27.25, 25.26. HRMS calcd.

For C₂₃H₂₃O₄⁺ (M+H)⁺ 363.1596 Found 363.1592.

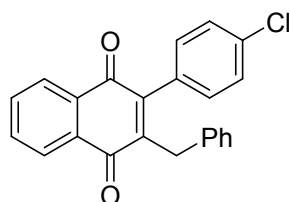
2-allyl-3-benzyl-naphthalene-1,4-dione (**3ia**)



A 10 mL oven-dried Schlenk tube was charged 2-allyl-1,4-naphthoquinone (**1i**, 79.3 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 50 : 1) to the desired product **3ia** as a yellow solid (65% yield), mp 93-95 °C. Rf = 0.50 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.08 (s, 2H), 7.70 (d, *J* = 2.5 Hz, 2H), 7.31 – 7.10 (m, 5H), 5.87 – 5.74 (m, 1H), 5.06 (dd, *J* = 13.4, 6.5 Hz, 2H), 4.04 (s, 2H), 3.47 (d, *J* = 6.2 Hz, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 185.01, 184.76, 145.85, 145.35, 138.15, 133.56, 133.46, 132.06, 132.01, 128.62, 128.61, 126.47, 126.44, 126.35, 117.04, 32.06, 31.19. HRMS calcd. For C₂₀H₁₇O₂⁺ (M+H)⁺ 289.1223 Found 289.1229.

2-benzyl-3-(4-chlorophenyl)naphthalene-1,4-dione (**3ja**)

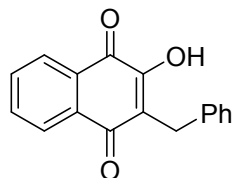


A 10 mL oven-dried Schlenk tube was charged 2-(4-chlorophenyl)naphthalene-1,4-dione (**1j**, 107.5 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 50 : 1) to the desired product

3ja as a yellow solid (58% yield), mp 143-145 °C. Rf = 0.60 (7:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.15 (s, 2H), 7.77 (s, 2H), 7.28 (dd, *J* = 25.4, 6.6 Hz, 9H), 4.16 (s, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 185.15, 146.18, 137.93, 133.61, 133.48, 132.02, 128.65, 128.57, 128.62, 126.48, 126.25, 32.44.

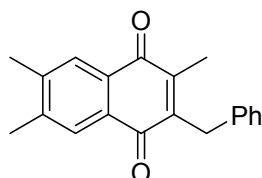
2-benzyl-3-hydroxynaphthalene-1,4-dione (**3ka**)⁹



A 10 mL oven-dried Schlenk tube was charged with 2-hydroxy-1,4-naphthoquinone (**1k**, 69.6 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ka** as a yellow solid (78% yield), mp 175-177 °C. Rf = 0.3 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.13 (d, *J* = 7.3 Hz, 1H), 8.08 (d, *J* = 7.2 Hz, 1H), 7.77 (t, *J* = 7.0 Hz, 1H), 7.69 (t, *J* = 7.1 Hz, 1H), 7.46 (s, 1H), 7.41 (d, *J* = 7.0 Hz, 2H), 7.25 (dd, *J* = 33.9, 7.1 Hz, 4H), 3.97 (s, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 184.36, 181.63, 152.99, 138.86, 135.00, 132.98, 129.31, 129.17, 128.43, 126.89, 126.31, 126.12, 123.00, 29.08.

2-benzyl-3,6,7-trimethylnaphthalene-1,4-dione (**3la**)

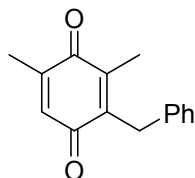


A 10 mL oven-dried Schlenk tube was charged with 2,6,7-trimethylnaphthalene-1,4-dione (**1l**, 80.1 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3la** as a yellow solid (85% yield), mp 102-104 °C. Rf = 0.5 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 7.79 (s, 2H), 7.23 (q, *J* = 7.4 Hz, 5H), 3.99 (s, 2H), 2.35 (s, 6H), 2.20 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.57, 184.85, 144.97, 144.07, 143.17, 143.14, 138.23, 130.09, 130.00, 128.58, 127.45, 127.23, 126.30,

32.31, 20.13, 13.20, 12.84. HRMS calcd. For $C_{20}H_{18}NaO_2^+$ ($M+Na$) $^+$ 313.1204 Found 313.1205.

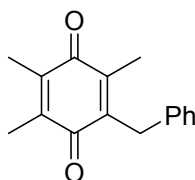
2-benzyl-3,5-dimethylcyclohexa-2,5-diene-1,4-dione (**3ma**)



A 10 mL oven-dried Schlenk tube was charged with 2,6-dimethylnaphthalene-1,4-dione (**1m**, 54.5 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ma** as a yellow solid (81% yield), mp 79-81 °C. Rf = 0.6 (10:1 petroleum ether/EtOAc).

1H NMR (400 MHz, $CDCl_3$) δ 7.24 (td, J = 7.1, 1.2 Hz, 2H), 7.22 – 7.01 (m, 3H), 6.57 (dd, J = 3.1, 1.5 Hz, 1H), 3.84 (s, 2H), 2.08 (s, 3H), 2.03 (d, J = 1.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 188.28, 187.13, 145.40, 142.72, 141.77, 138.00, 133.07, 128.67, 128.62, 126.34, 31.69, 15.85, 12.70. HRMS calcd. For $C_{15}H_{15}O_2^+$ ($M+H$) $^+$ 227.1072 found 227.1075.

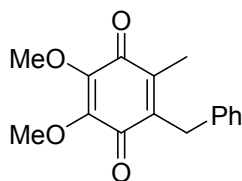
2-benzyl-3,5,6-trimethylcyclohexa-2,5-diene-1,4-dione (**3na**)



A 10 mL oven-dried Schlenk tube was charged with 2,3,5-trimethylcyclohexa-2,5-diene-1,4-dione (**1n**, 60.0 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3na** as a yellow solid (78% yield), mp 83-85 °C. Rf = 0.5 (10:1 petroleum ether/EtOAc).

1H NMR (400 MHz, $CDCl_3$) δ 7.26 (t, J = 7.1 Hz, 2H), 7.18 (d, J = 6.7 Hz, 3H), 3.87 (s, 2H), 2.11 (s, 3H), 2.02 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 187.82, 187.02, 142.39, 141.28, 140.57, 140.43, 138.30, 128.56, 128.52, 126.30, 32.05, 12.78, 12.44, 12.41. HRMS calcd. For $C_{16}H_{17}O_2^+$ ($M+H$) $^+$ 241.1223 found 241.1223.

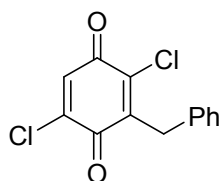
2-benzyl-5,6-dimethoxy-3-methylcyclohexa-2,5-diene-1,4-dione (**3oa**)



A 10 mL oven-dried Schlenk tube was charged with 2,3-dimethoxy-5-methylcyclohexa-2,5-diene-1,4-dione (**1o**, 72.8 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3oa** as a red solid (72% yield), mp 92-94 °C. Rf = 0.5 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 7.24 (t, *J* = 7.2 Hz, 2H), 7.16 (t, *J* = 6.9 Hz, 3H), 3.96 (s, 6H), 3.82 (s, 2H), 2.06 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 184.57, 184.01, 144.34, 144.31, 140.90, 139.87, 137.81, 128.61, 128.59, 128.16, 126.43, 61.16, 31.71, 12.49. HRMS calcd. For C₁₆H₁₇O₄⁺ (M+H)⁺ 273.1127 found 273.1124.

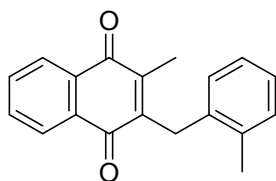
3-benzyl-2,5-dichlorocyclohexa-2,5-diene-1,4-dione (**3pa**)



A 10 mL oven-dried Schlenk tube was charged with 2,5-dichlorocyclohexa-2,5-diene-1,4-dione (**1p**, 70.4 mg, 0.4 mmol), toluene **2a** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3pa** as a yellow solid (67% yield), mp 73-75 °C. Rf = 0.4 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 7.27 (dd, *J* = 16.4, 9.0 Hz, 5H), 7.08 (s, 1H), 4.06 (s, 2H). ¹³C NMR (101 MHz, CDCl₃) δ 177.36, 144.23, 144.07, 141.41, 135.87, 132.81, 129.20, 128.79, 127.18, 33.92. HRMS calcd. For C₁₃H₈Cl₂NaO₂⁺ (M+Na)⁺ 288.9794 Found 288.9790.

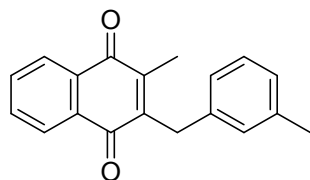
2-methyl-3-(2-methylbenzyl)naphthalene-1,4-dione (**3ab**)



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), *o*-xylene **2b** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ab** as a yellow solid (79% yield), mp 113-115 °C. R_f = 0.6 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.11 (dd, *J* = 20.1, 5.8 Hz, 2H), 7.72 (d, *J* = 3.8 Hz, 2H), 7.20 (d, *J* = 7.2 Hz, 1H), 7.12 (t, *J* = 7.2 Hz, 1H), 7.05 (t, *J* = 7.4 Hz, 1H), 6.84 (d, *J* = 7.4 Hz, 1H), 3.98 (s, 2H), 2.46 (s, 3H), 2.16 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.17, 184.42, 145.47, 145.35, 136.23, 135.97, 133.61, 133.47, 132.18, 132.07, 130.31, 126.63, 126.35, 29.55, 20.00, 13.23. HRMS calcd. For C₁₉H₁₇O₂⁺ (M+H)⁺ 277.1223 found: 277.1228.

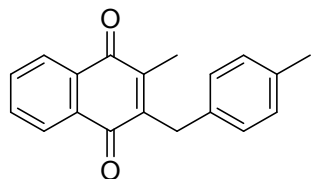
2-methyl-3-(3-methylbenzyl)naphthalene-1,4-dione (**3ac**)



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), *m*-xylene **2c** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ac** as a yellow solid (84% yield), mp 118-120 °C. R_f = 0.6 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.07 (s, 2H), 7.68 (d, *J* = 1.5 Hz, 2H), 7.15 (t, *J* = 7.6 Hz, 1H), 7.07 – 6.96 (m, 3H), 3.99 (s, 2H), 2.29 (s, 3H), 2.24 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.40, 184.65, 145.36, 144.37, 138.28, 137.91, 133.48, 133.44, 132.06, 131.99, 129.30, 128.50, 127.20, 126.47, 126.23, 125.60, 32.32, 21.46, 13.33. HRMS calcd. For C₁₉H₁₇O₂⁺ (M+H)⁺ 277.1223 found: 277.1218.

2-methyl-3-(4-methylbenzyl)naphthalene-1,4-dione (**3ad**)¹⁰

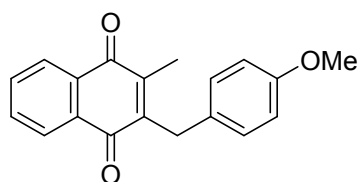


A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), *para*-xylene **2d** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was

added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ad** as a yellow solid (88% yield), mp 105-107 °C. Rf = 0.5 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.06 (s, 2H), 7.68 (d, *J* = 2.0 Hz, 2H), 7.09 (dd, *J* = 22.0, 7.5 Hz, 4H), 3.98 (s, 2H), 2.28 (s, 3H), 2.24 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.43, 184.67, 145.49, 144.19, 135.99, 134.93, 133.47, 133.43, 133.32, 132.04, 131.99, 129.33, 128.49, 126.44, 126.22, 32.00, 21.02, 13.30.

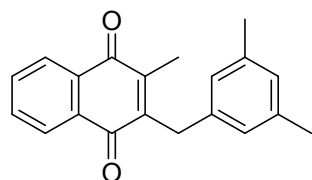
2-(4-methoxybenzyl)-3-methylnaphthalene-1,4-dione (**3ae**)¹⁰



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), 4-Methylanisole **2e** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ae** as a yellow solid (85% yield), mp 113-115 °C. Rf = 0.5 (10:1 petroleum ether/EtOAc).

¹H NMR (400 MHz, CDCl₃) δ 8.05 (d, *J* = 1.2 Hz, 2H), 7.67 (s, 2H), 7.14 (d, *J* = 8.2 Hz, 2H), 6.79 (d, *J* = 8.4 Hz, 2H), 3.94 (s, 2H), 3.74 (s, 3H), 2.24 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 185.46, 184.72, 158.07, 145.55, 144.01, 133.47, 133.44, 129.98, 129.61, 126.42, 126.22, 113.99, 77.39, 55.22, 31.54, 13.26.

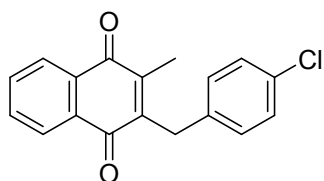
2-(3,5-dimethylbenzyl)-3-methylnaphthalene-1,4-dione (**3af**)



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), Mesitylene **2f** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3af** as a yellow solid (75% yield), mp 117-119 °C. Rf = 0.6 (10:1 petroleum ether/EtOAc).

^1H NMR (400 MHz, CDCl_3) δ 8.08 (s, 2H), 7.69 (d, $J = 2.3$ Hz, 2H), 6.81 (s, 3H), 3.95 (s, 2H), 2.24 (s, 9H). ^{13}C NMR (101 MHz, CDCl_3) δ 185.49, 184.70, 145.44, 144.36, 138.15, 137.81, 133.47, 133.42, 132.09, 132.03, 128.10, 126.50, 126.30, 126.23, 32.22, 21.31, 13.33. HRMS calcd. For $\text{C}_{20}\text{H}_{19}\text{O}_2^+$ ($\text{M}+\text{H}$) $^+$ 291.1380 found: 291.1378.

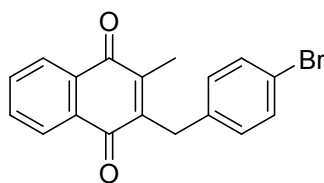
2-(4-chlorobenzyl)-3-methylnaphthalene-1,4-dione (**3ag**)¹⁰



A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), 4-Chlorotoluene **2g** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ag** as a yellow solid (67% yield), mp 135-137 °C. $R_f = 0.5$ (10:1 petroleum ether/EtOAc).

^1H NMR (400 MHz, CDCl_3) δ 8.07 (s, 2H), 7.69 (s, 2H), 7.25 – 7.20 (m, 2H), 7.15 (d, $J = 8.1$ Hz, 2H), 3.97 (s, 2H), 2.22 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 185.23, 184.55, 144.79, 144.52, 136.48, 133.59, 132.22, 132.01, 131.87, 129.91, 128.73, 126.47, 126.32, 31.83, 13.32.

2-(4-bromobenzyl)-3-methylnaphthalene-1,4-dione (**3ah**)¹¹



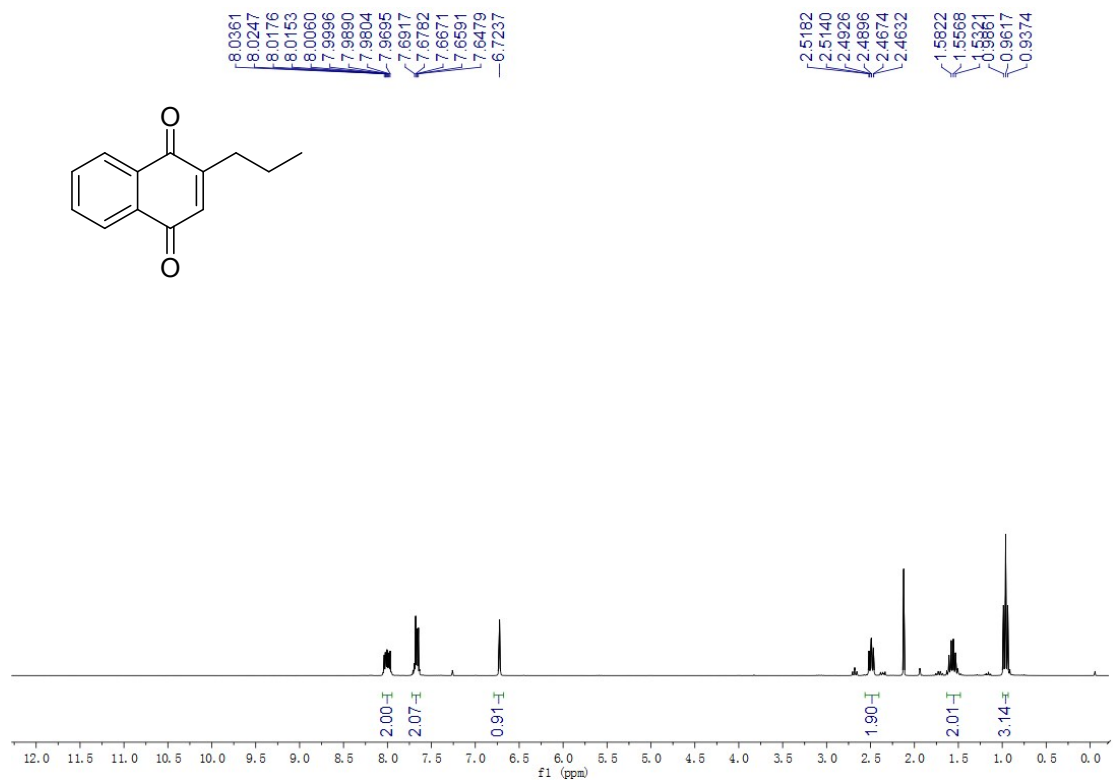
A 10 mL oven-dried Schlenk tube was charged with 2-methyl-1,4-naphthoquinone (**1c**, 68.9 mg, 0.4 mmol), 4-bromotoluene **2h** (2 mL). DTBP (0.8 mmol, 2.0 equiv.) was added by syringe. The tube was then sealed, and the reaction mixture was stirred in an oil bath preheated at 120 °C for 16 h. The residue was purified by column chromatography on silica gel (petroleum ether/EtOAc = 100 : 1) to the desired product **3ah** as a yellow solid (62% yield), mp 121-123 °C. $R_f = 0.5$ (10:1 petroleum ether/EtOAc).

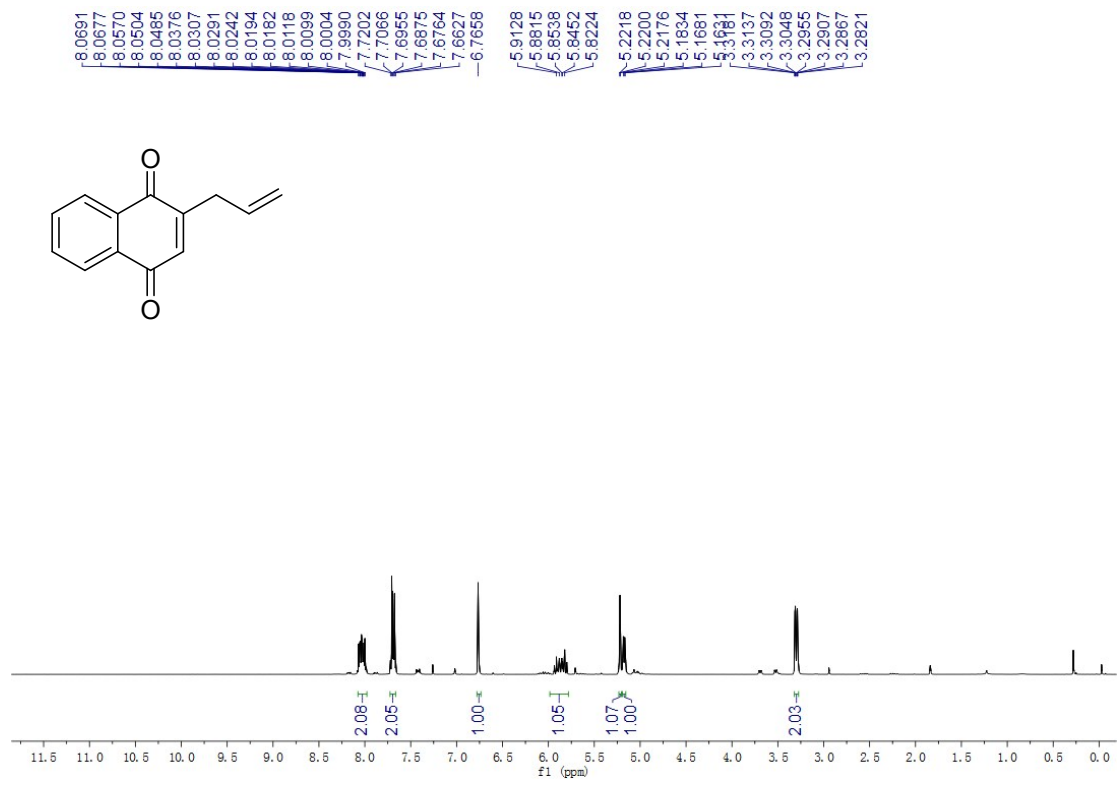
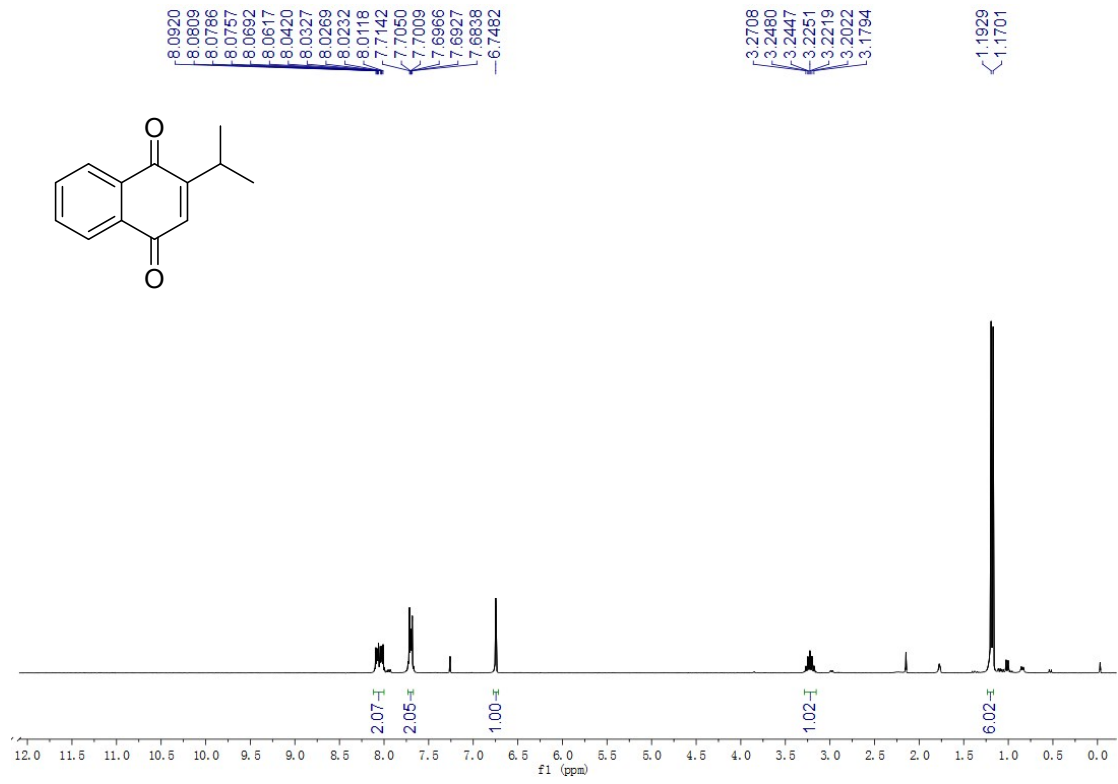
^1H NMR (400 MHz, CDCl_3) δ 8.07 (s, 2H), 7.70 (s, 2H), 7.37 (d, $J = 8.2$ Hz, 2H), 7.10 (d, $J = 8.0$ Hz, 2H), 3.96 (s, 2H), 2.23 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 185.22, 184.55, 144.72, 144.67, 137.02, 133.70, 133.67, 132.02, 131.87, 131.69, 131.66, 130.30, 130.27, 126.48, 126.34, 120.28, 31.90, 13.34.

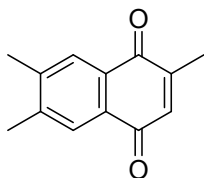
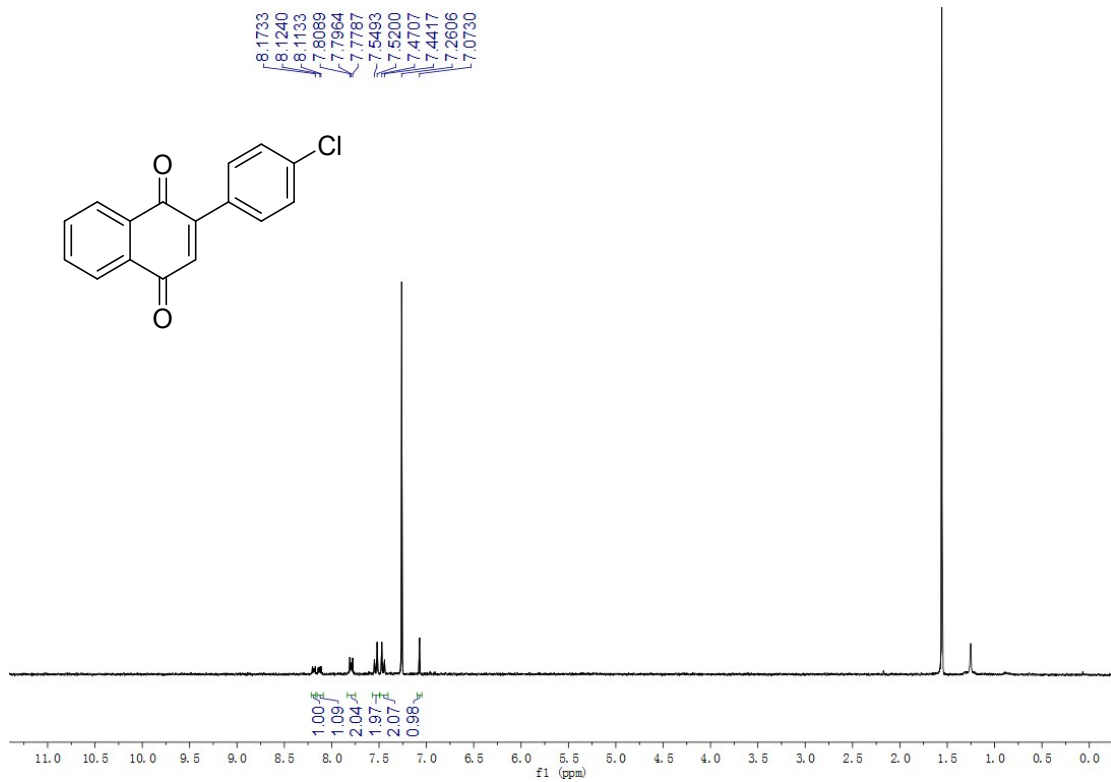
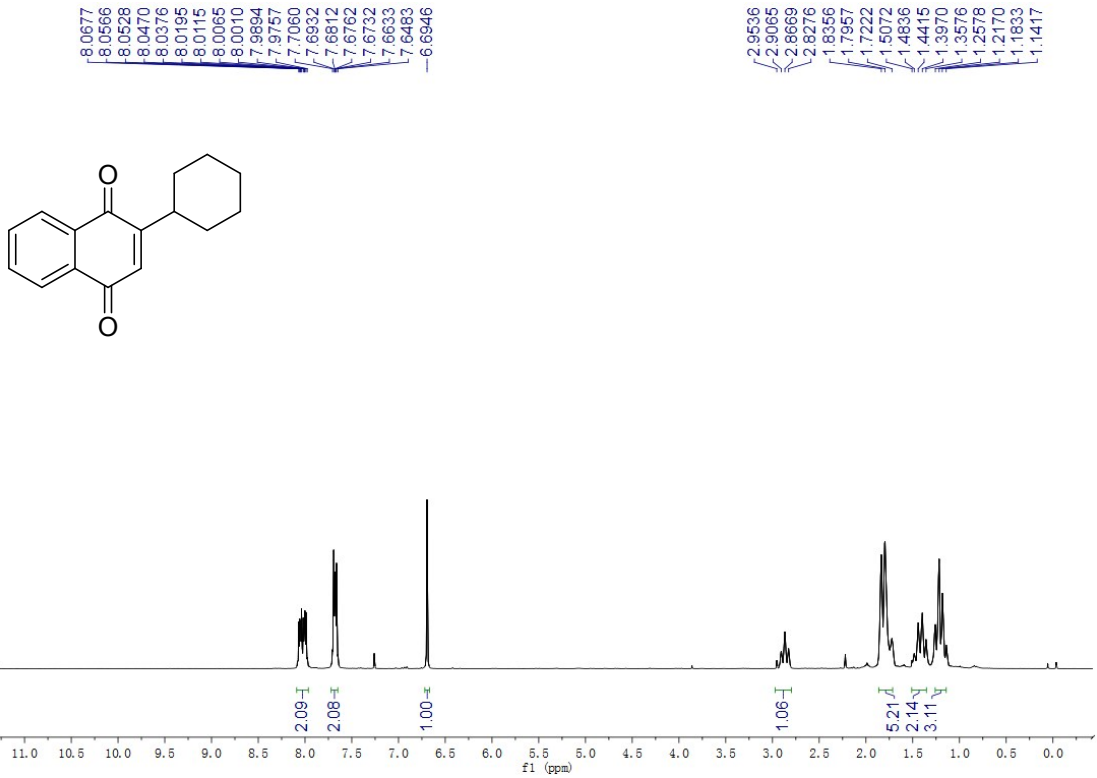
6. References

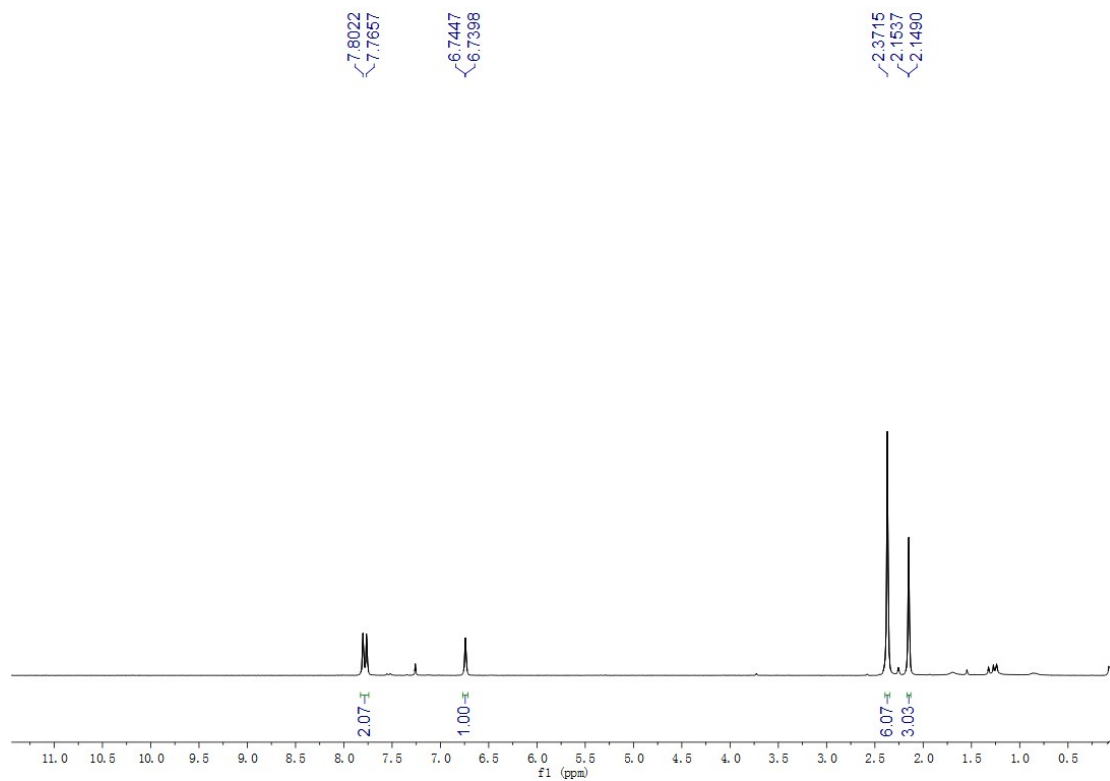
- 1 B. Liu, L. Gu, J. Zhang, *Recueil des Travaux Chimiques des Pays-Bas*, 1991, **110**, 99.
- 2 J. S. Yadav, B. V. S. Reddy, T. Swamy, *Tetrahedron Lett*, 2003, **44**, 4861.
- 3 D. R. Sutherland, M. Veguillas, C. L. Oates, A.-L. Lee, *Org. Lett*, 2018, **20**, 6863.
- 4 Y. Fujiwara, V. Domingo, I. B. Seiple, R. Gianatassio, M. Del Bel, P. S. Baran, *J. Am. Chem. Soc.*, 2011, **133**, 3292.
- 5 X.-L. Zhou, P.-S. Wang, D.-W. Zhang, P. Liu, C.-M. Wang, L.-Z. Gong, *Org. Lett*, 2015, **17**, 5120.
- 6 A. Śkrzyńska, M. Romaniszyn, D. Pomikło, Ł. Albrecht, *J. Org. Chem*, 2018, **83**, 5019.
- 7 S. Yamago, M. Hashidume, J. Yoshida, *Tetrahedron*, 2002, **58**, 6805.
- 8 S.-L. Zhou, L.-N. Guo, X.-H. Duan, *Eur. J. Org. Chem*, 2014, **2014**, 8094.
- 9 D. B. Ramachary, *Org. Biomol. Chem*, 2010, **8**, 2859.
- 10 P. Sidorov, I. Desta, M. Chessé, D. Horvath, G. Marcou, A. Varnek, E. Davioud-Charvet, M. Elhabiri, *ChemMedChem*, 2016, **11**, 1339.
- 11 T. Müller, L. Johann, B. Jannack, M. Brückner, D. A. Lanfranchi, H. Bauer, C. Sanchez, V. Yardley, C. Deregnacourt, J. Schrével, M. Lanzer, R. H. Schirmer, E. Davioud-Charvet, *J. Am. Chem. Soc*, 2011, **133**, 11557.

7. Copies of ^1H and ^{13}C NMR spectra for all compounds

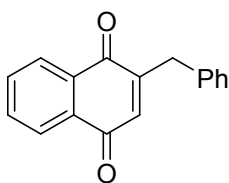
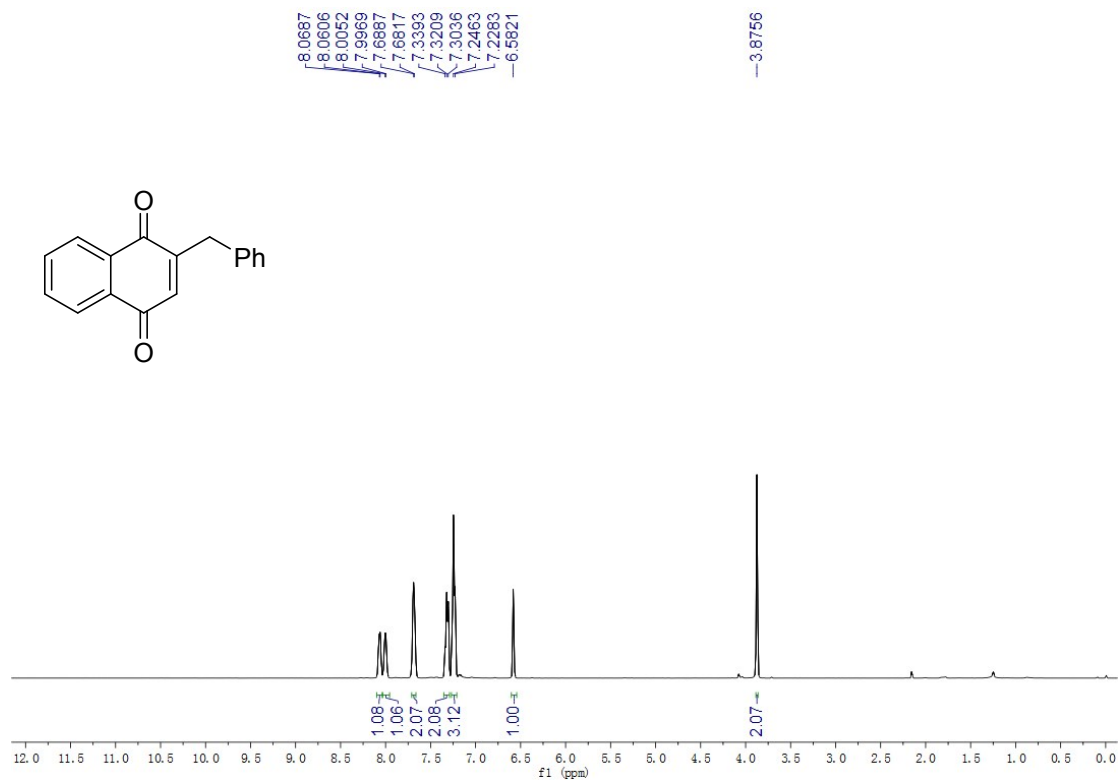


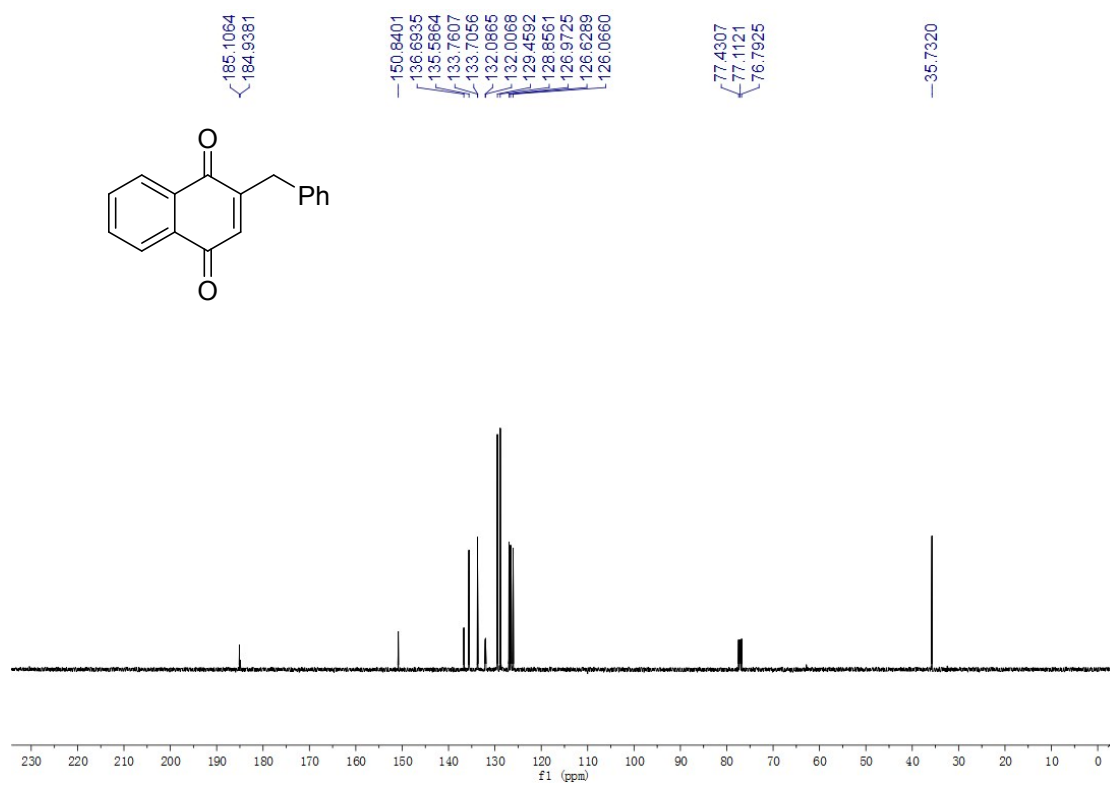




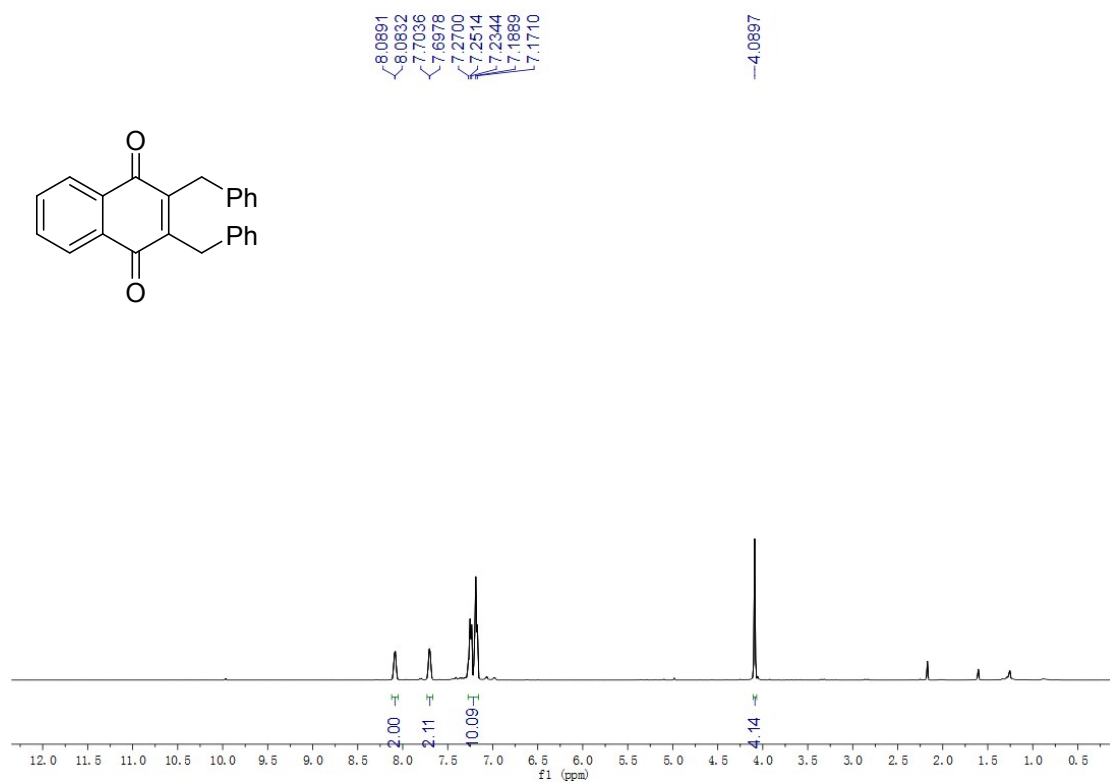


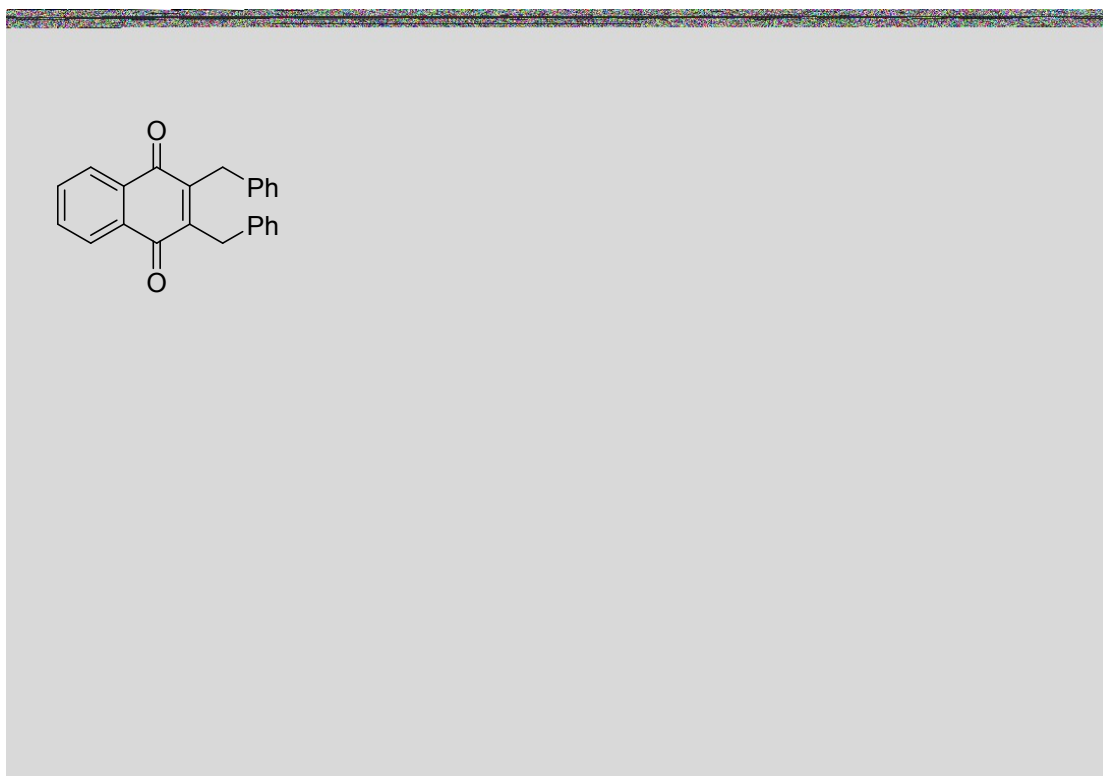
2-benzyl-1,4-naphthoquinone (3aa)



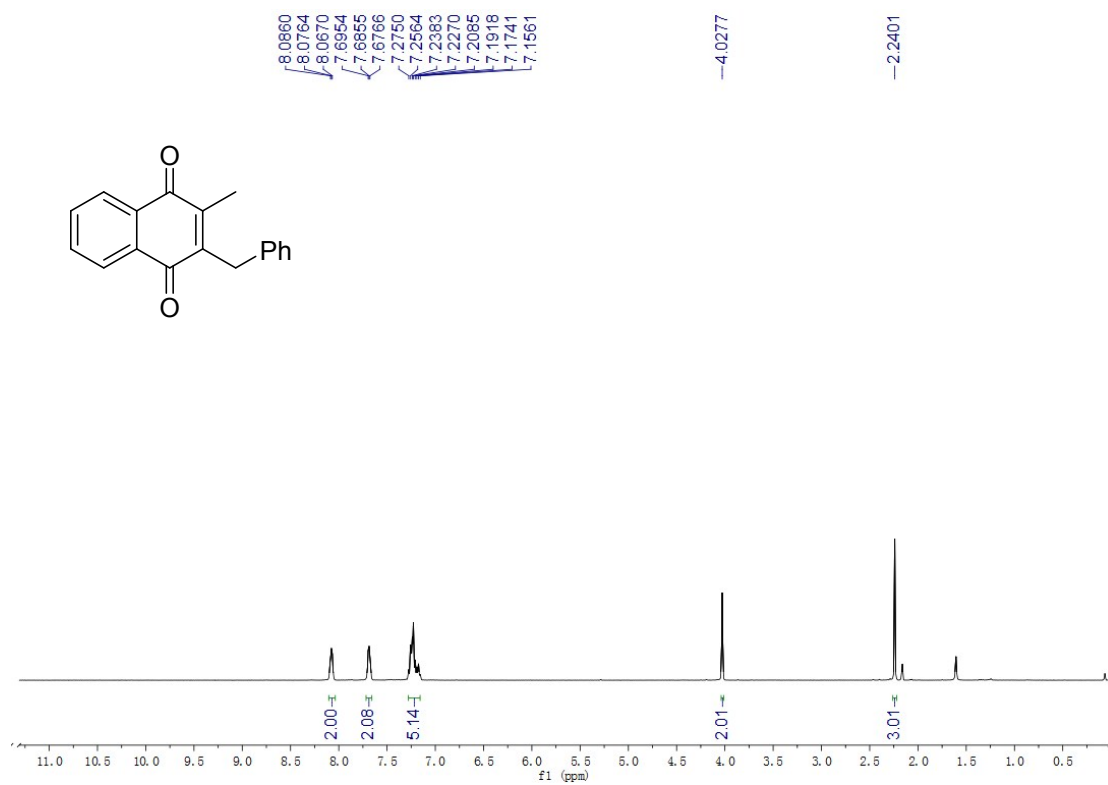


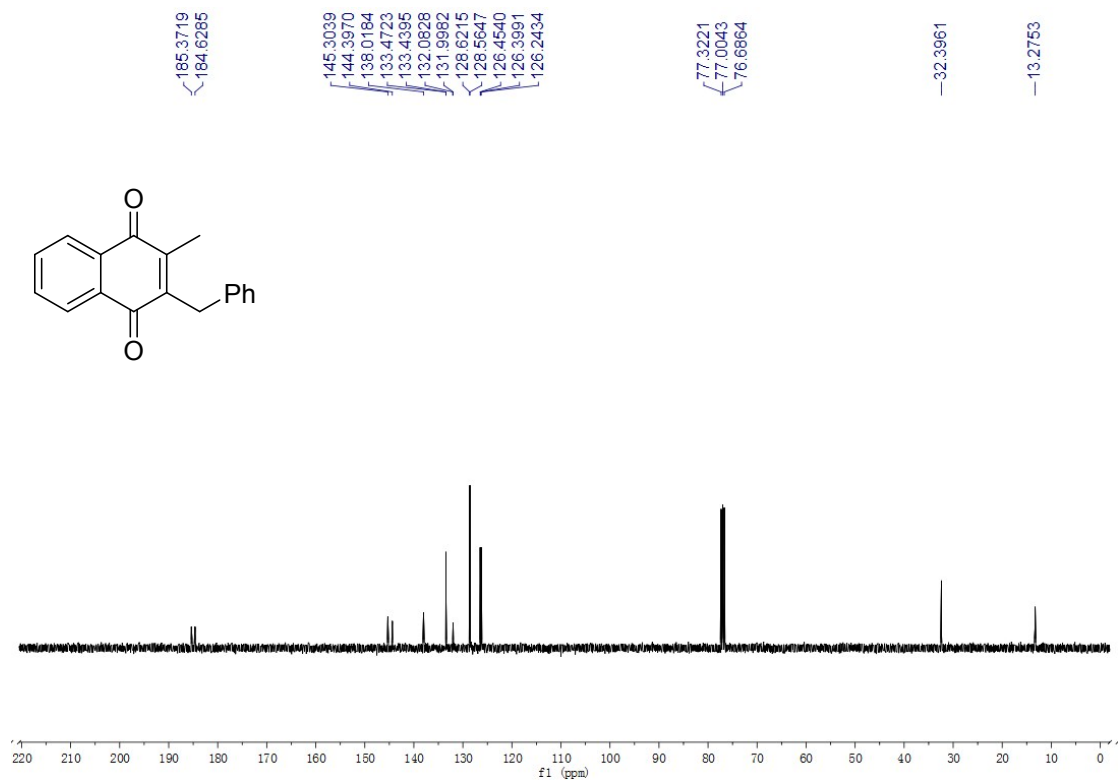
2,3-dibenzyl-1,4-naphthoquinone (3ba)





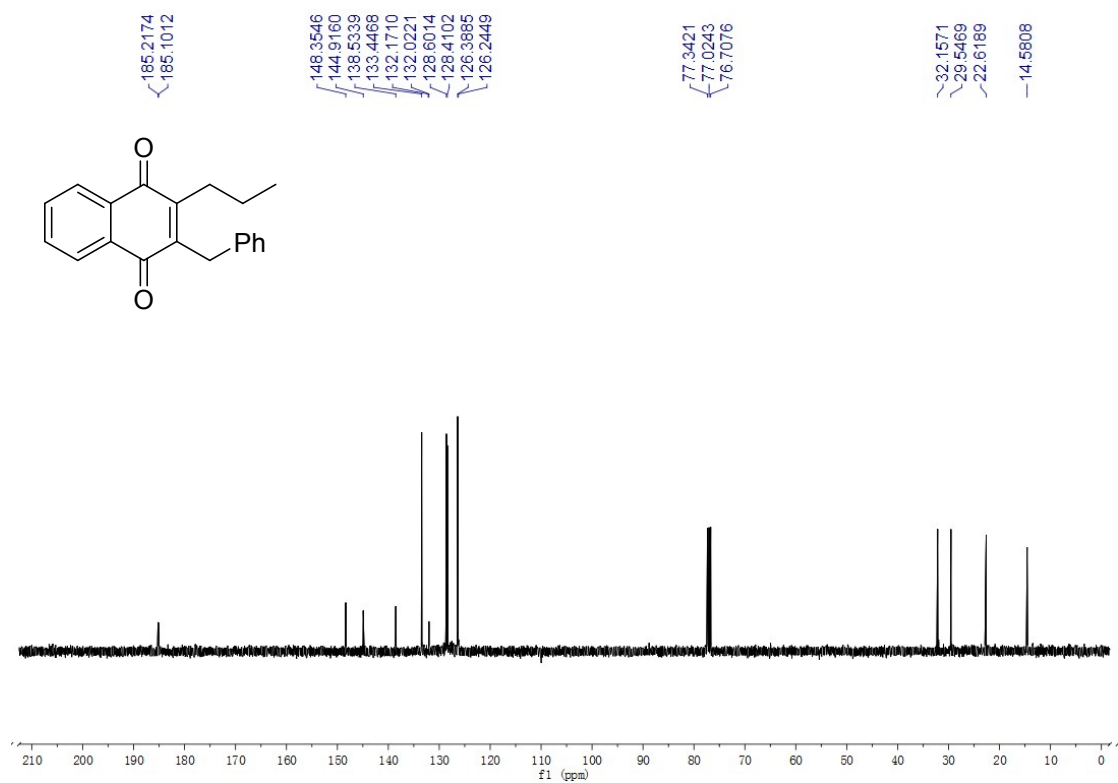
2-benzyl-3-methylnaphthalene-1,4-dione (3ca)



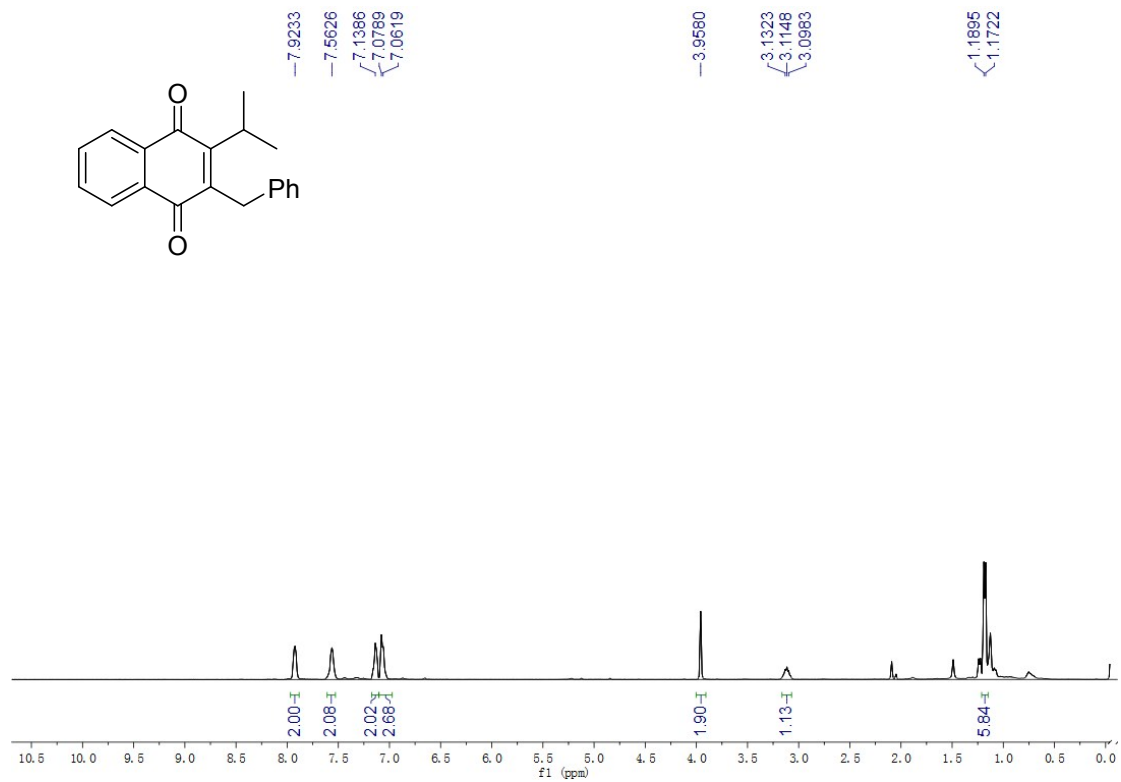


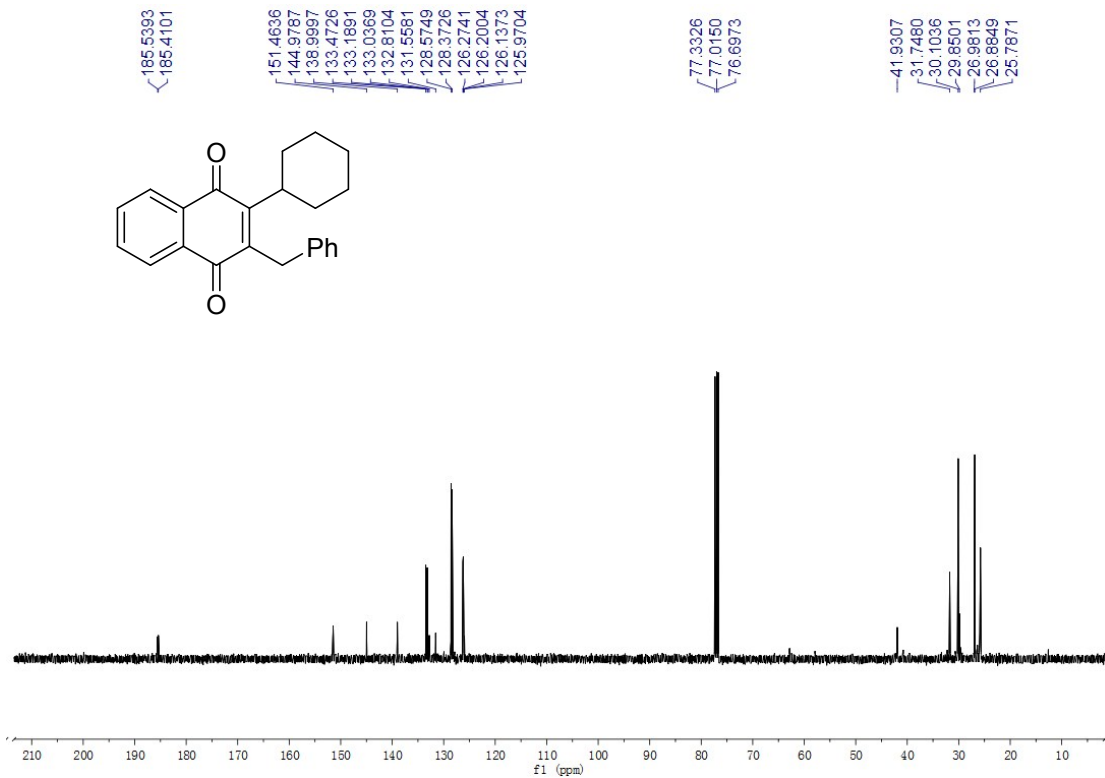
2-benzyl-3-propylnaphthalene-1,4-dione (3da)



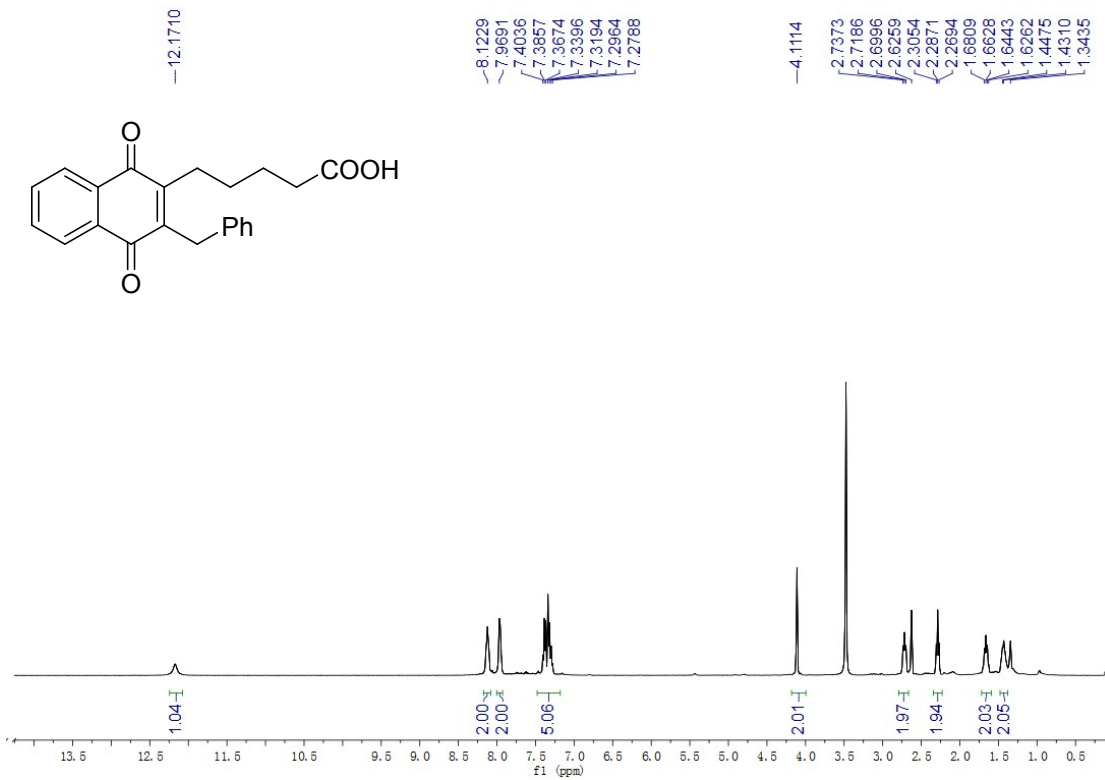


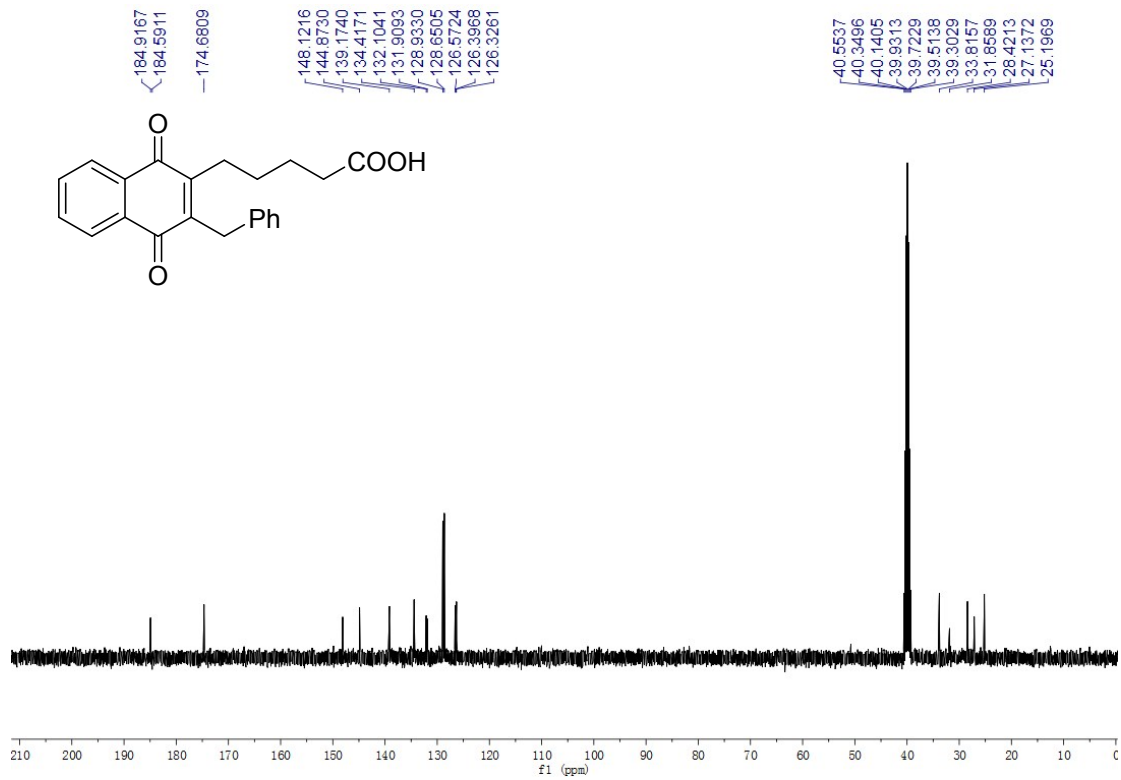
2-benzyl-3-isopropylnaphthalene-1,4-dione (3ea)



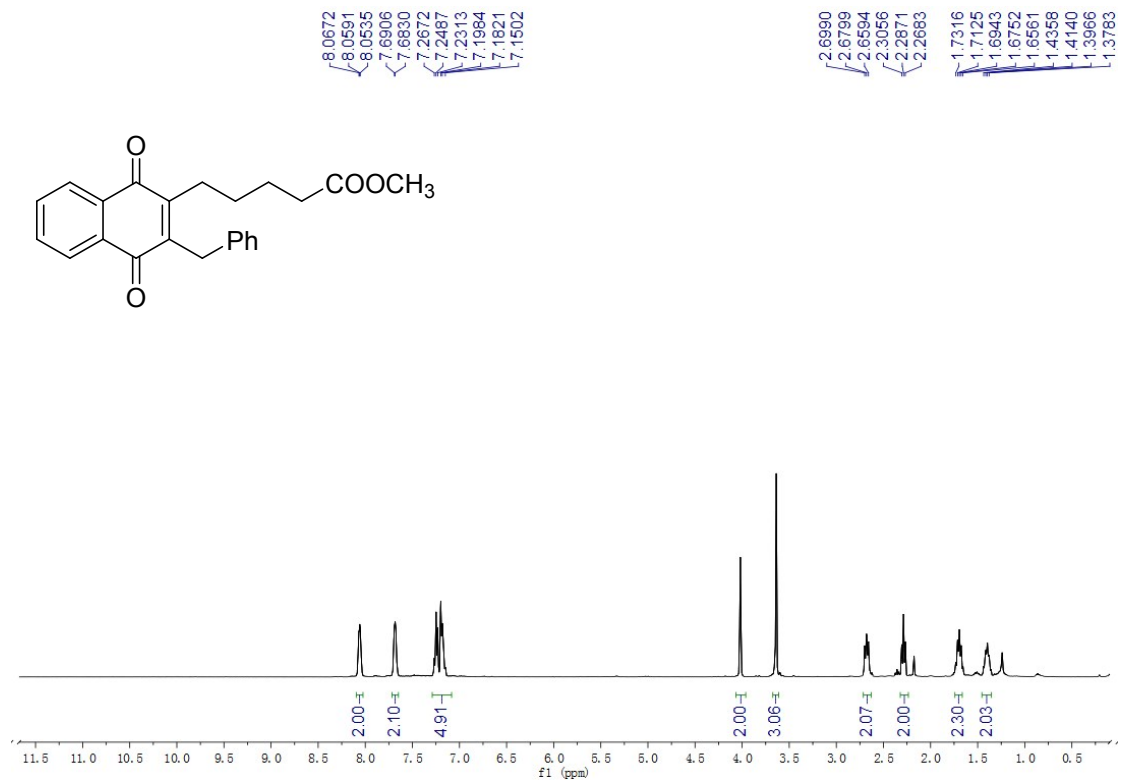


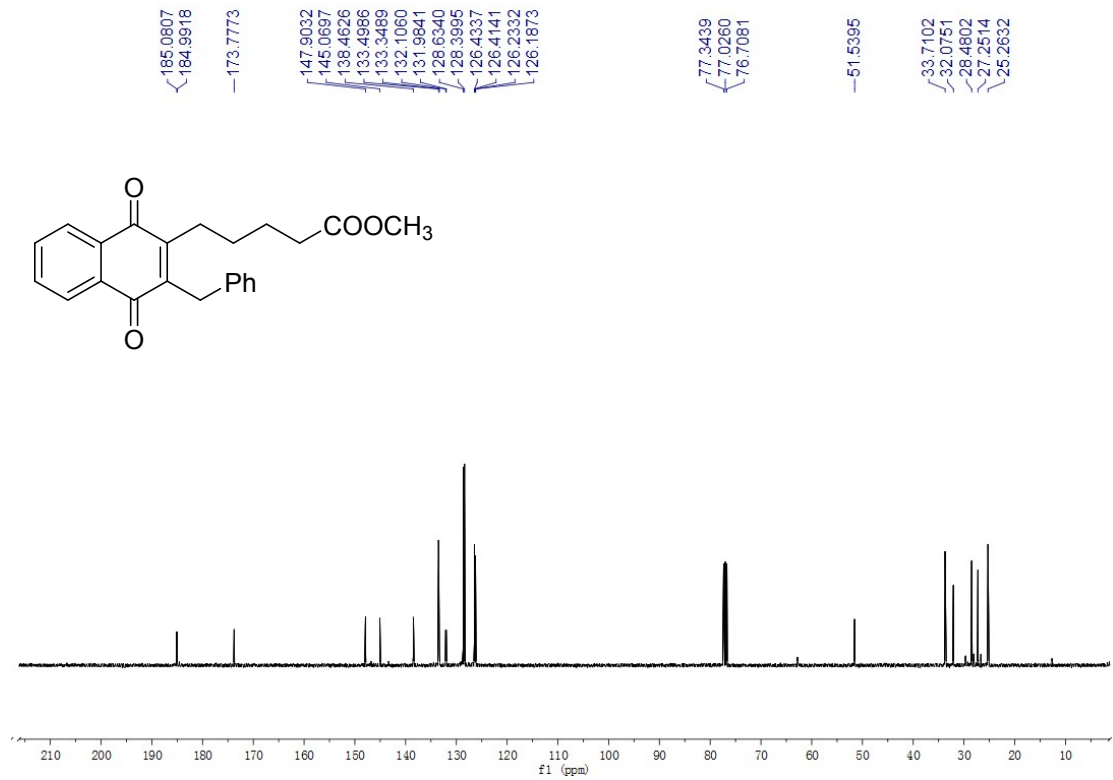
5-(3-benzyl-1,4-dioxo-1,4-dihydronaphthalen-2-yl)pentanoic acid (3ga)





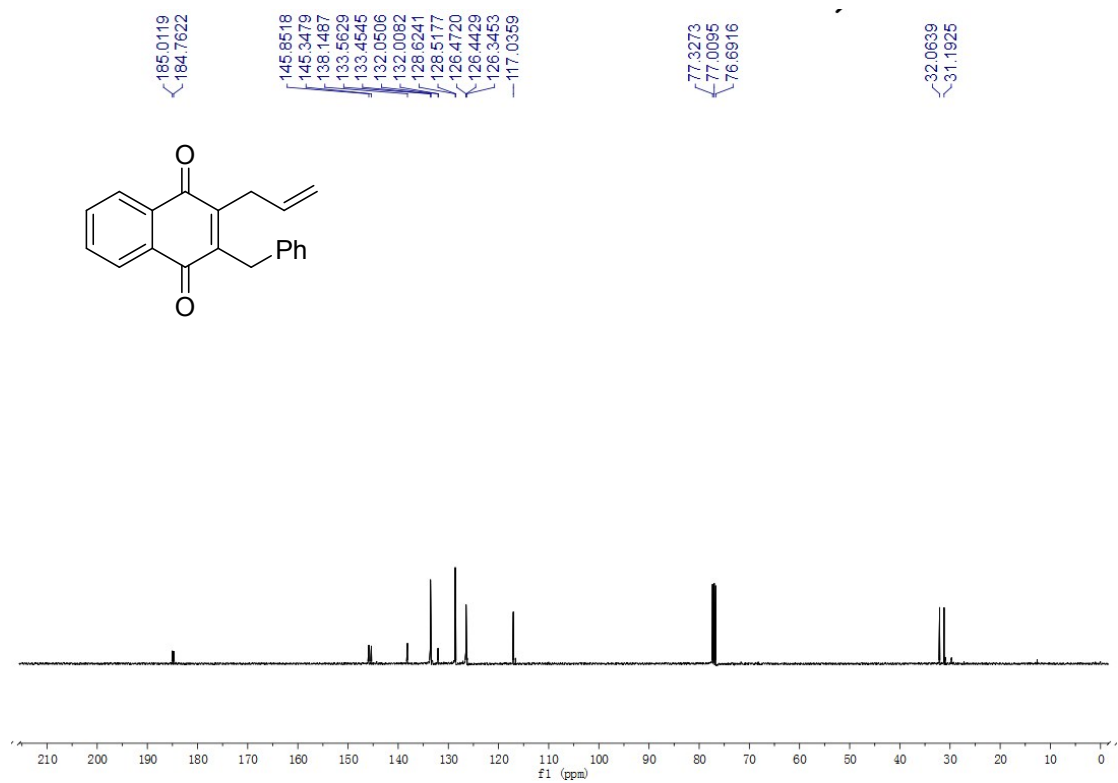
methyl 5-(3-benzyl-1,4-dioxo-1,4-dihydronaphthalen-2-yl)pentanoate (3ha)



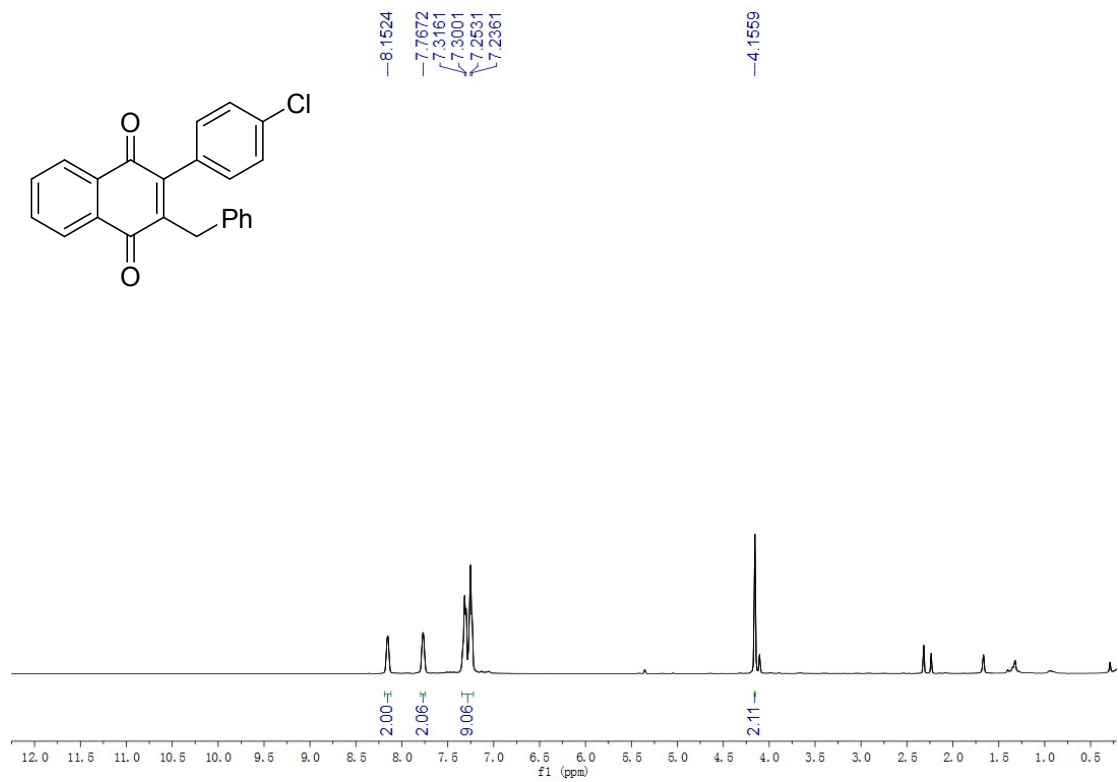


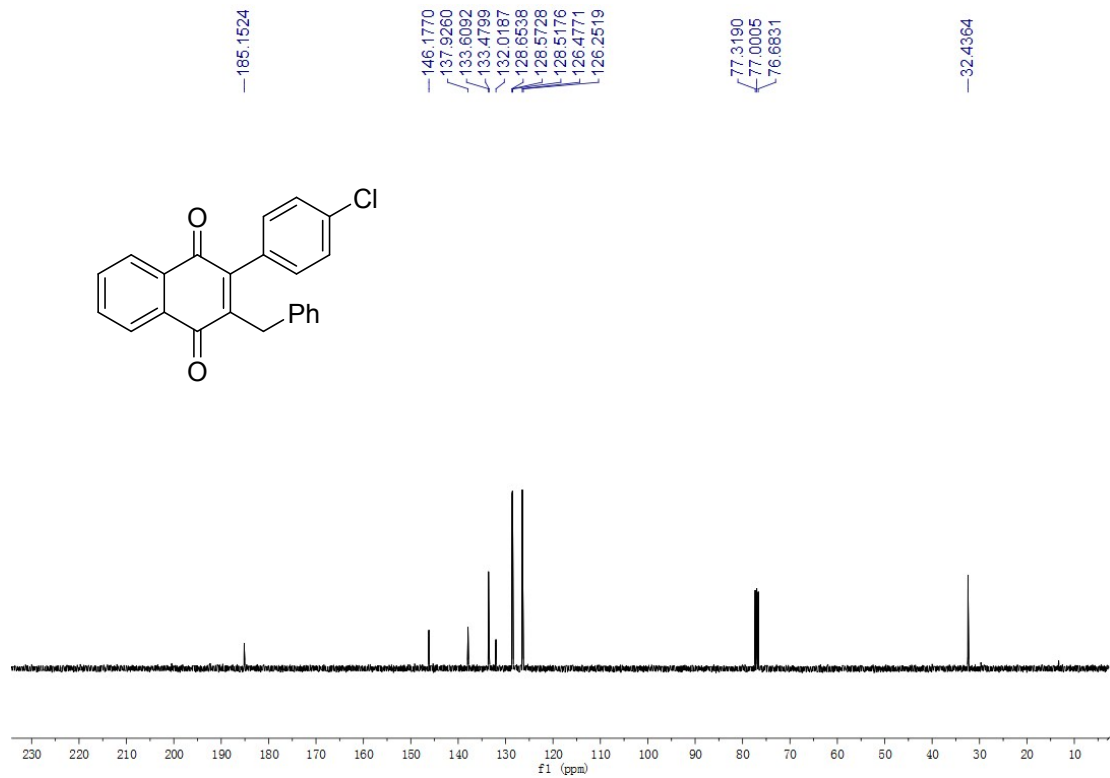
2-allyl-3-benzyl-1,4-naphthoquinone (**3ia**)



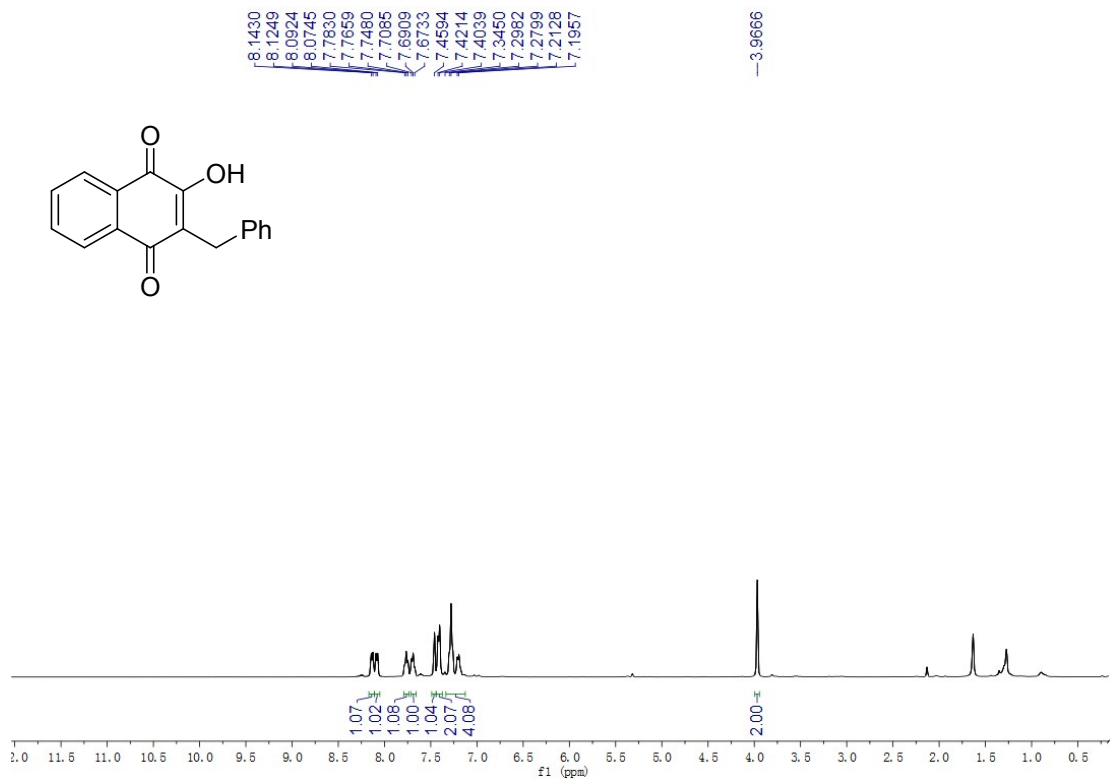


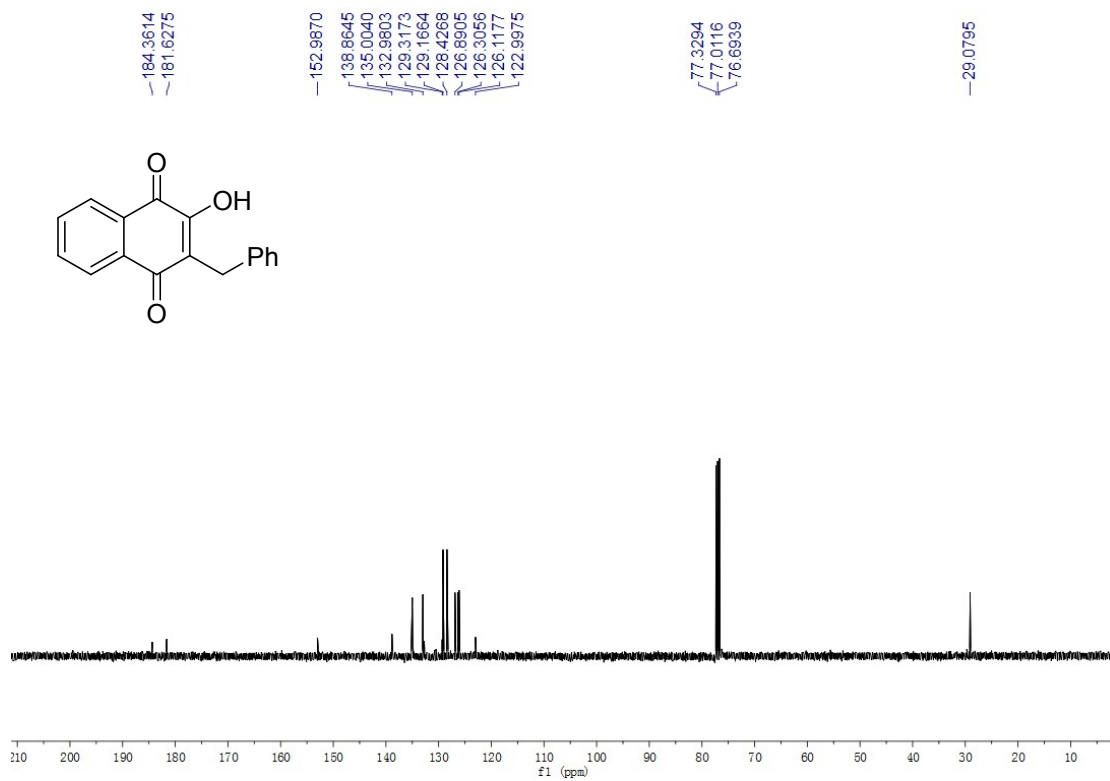
2-benzyl-3-(4-chlorophenyl)naphthalene-1,4-dione (3ja)



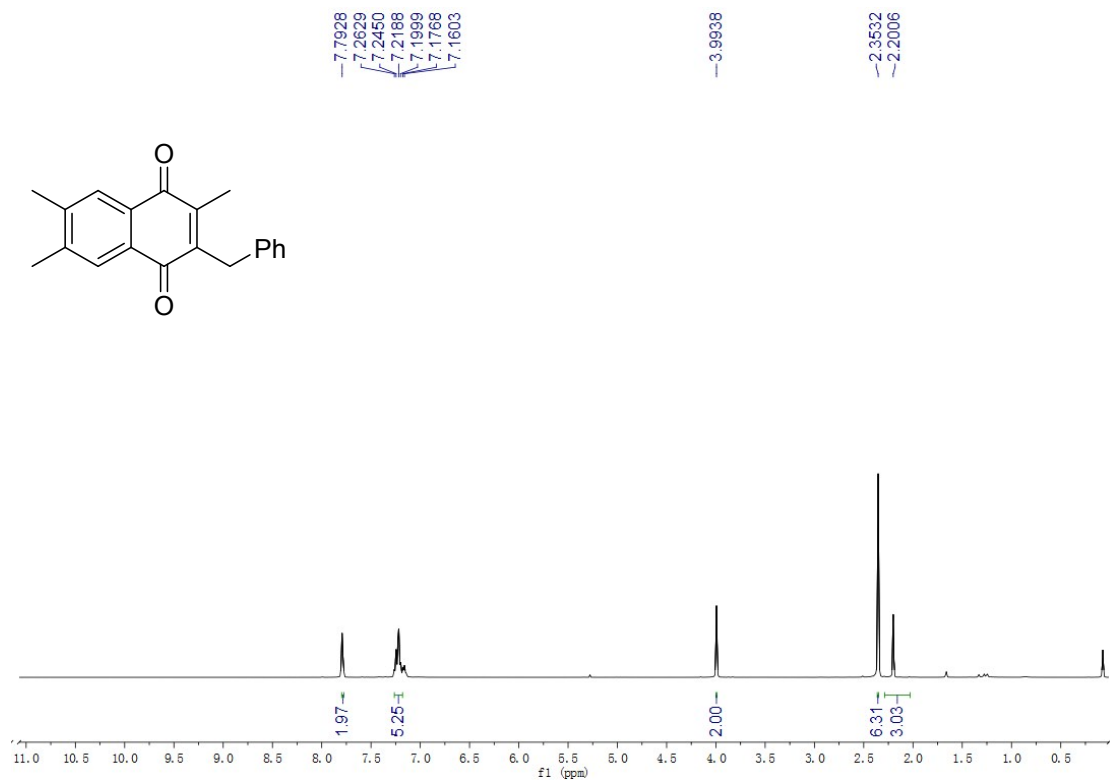


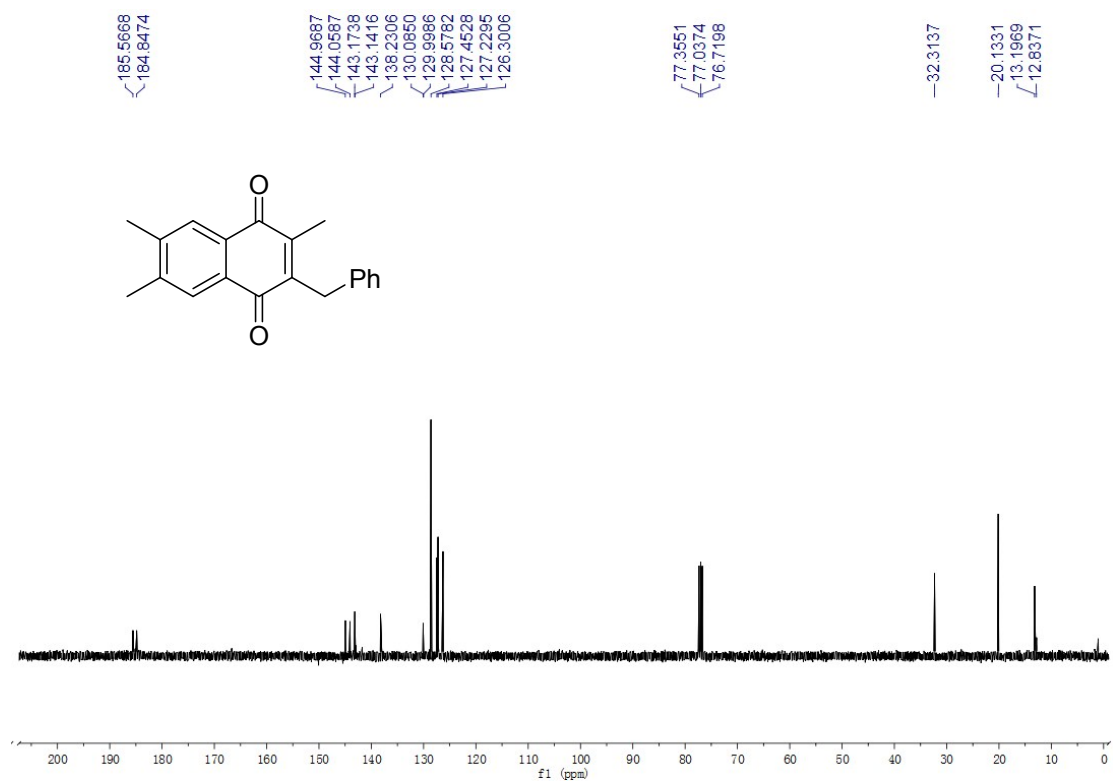
2-benzyl-3-hydroxynaphthalene-1,4-dione (3ka)



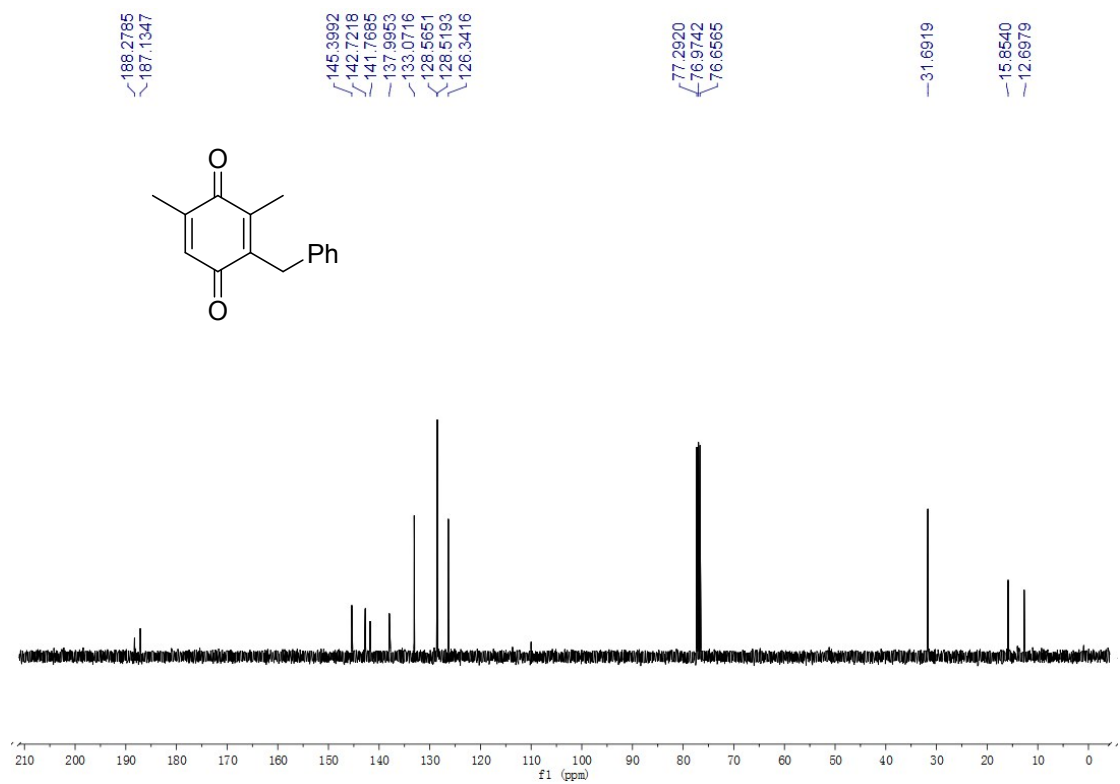
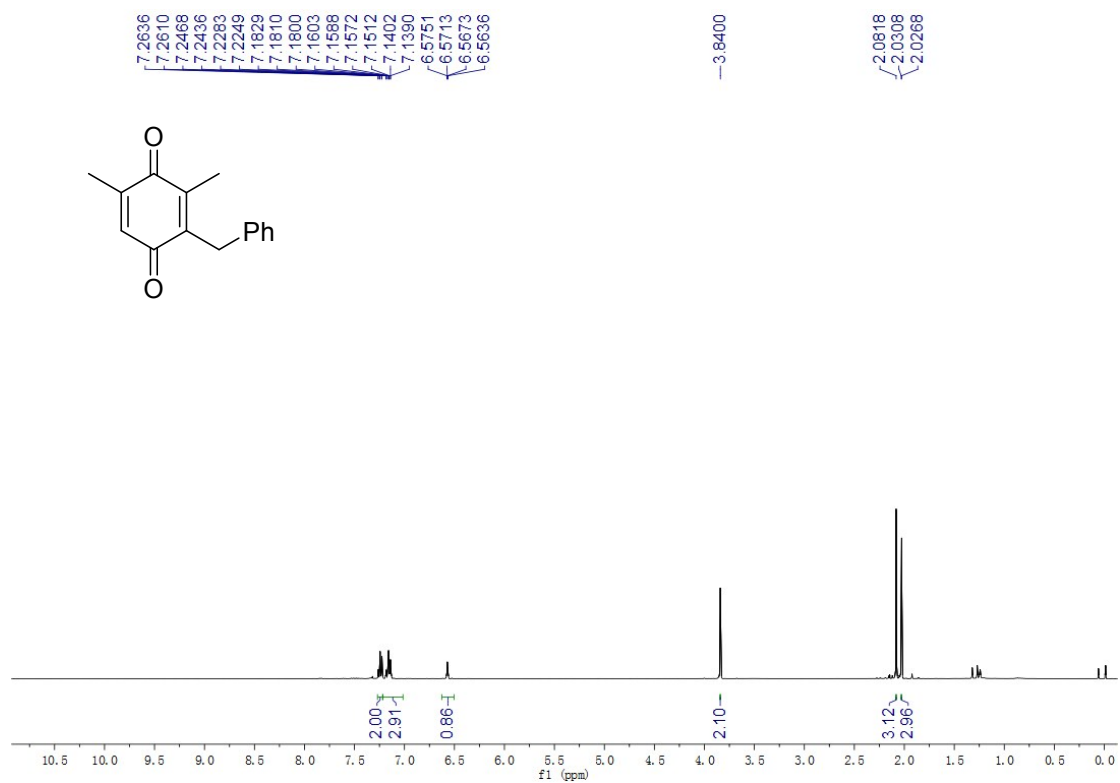


2-benzyl-3,6,7-trimethylnaphthalene-1,4-dione (3la)

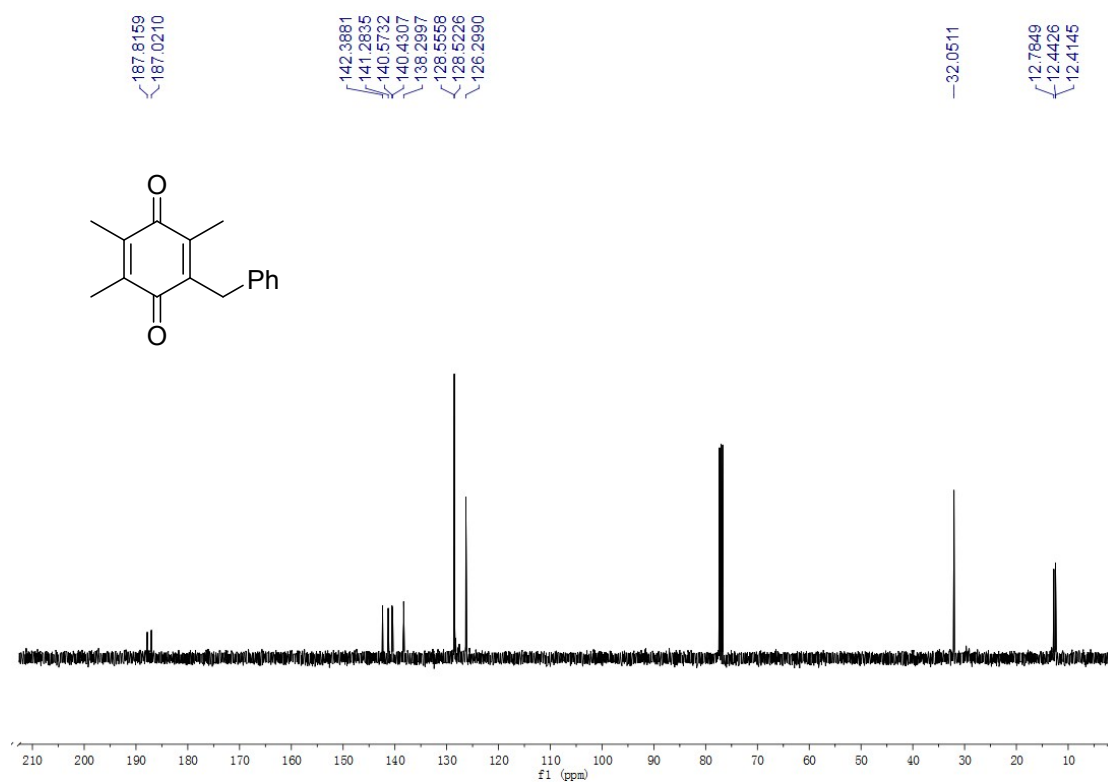
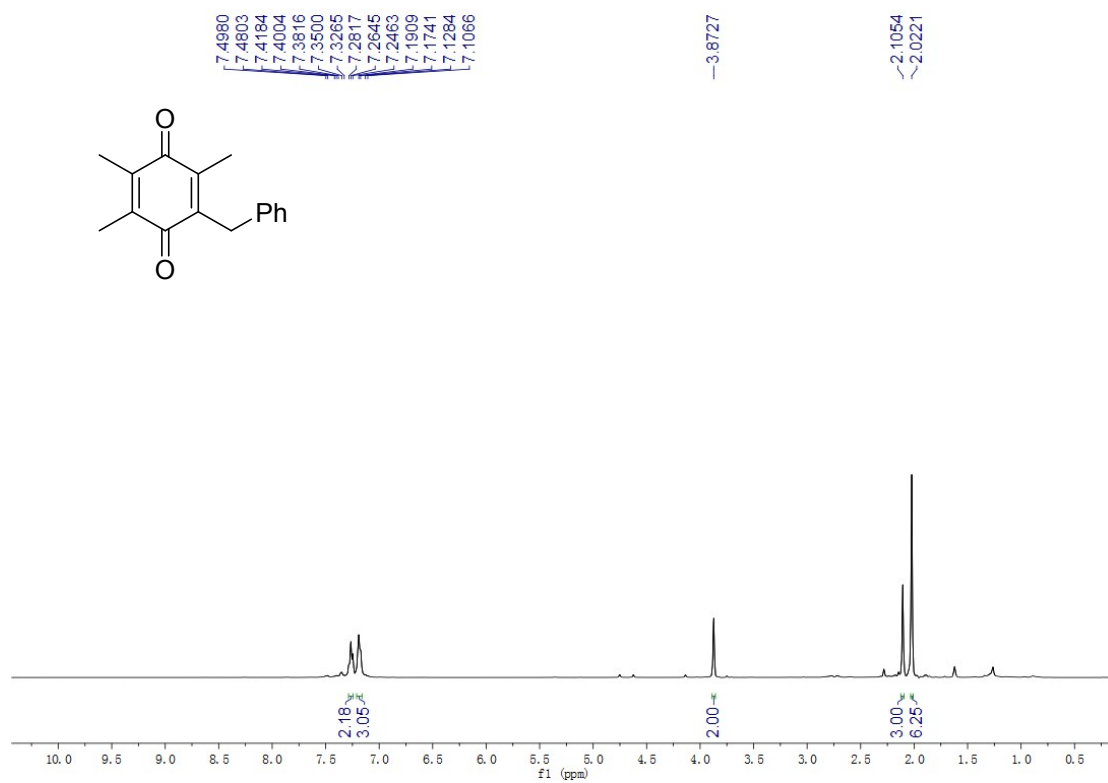




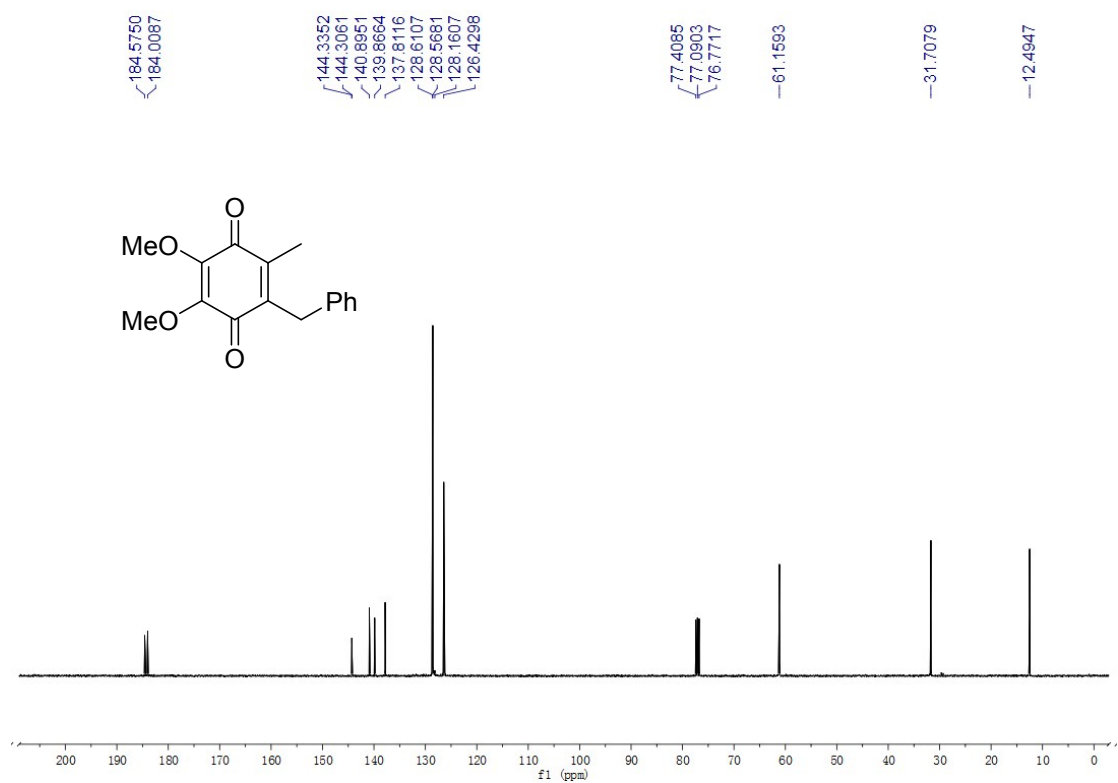
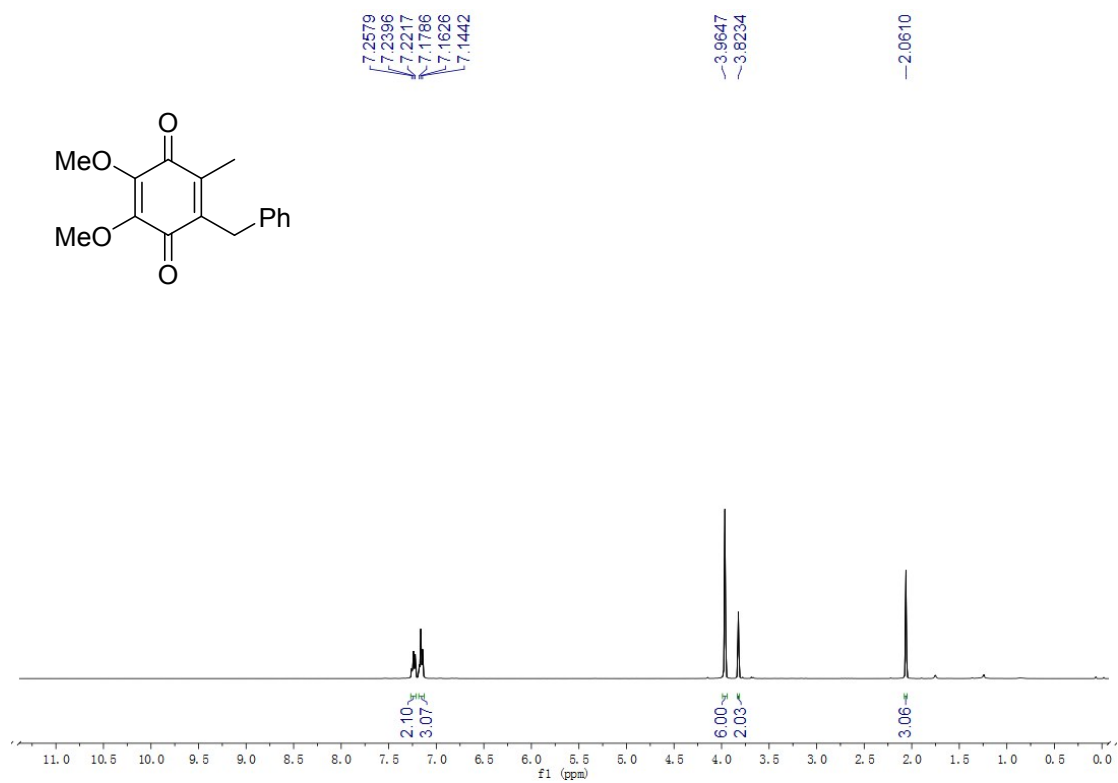
2-benzyl-3,5-dimethylcyclohexa-2,5-diene-1,4-dione (3ma)



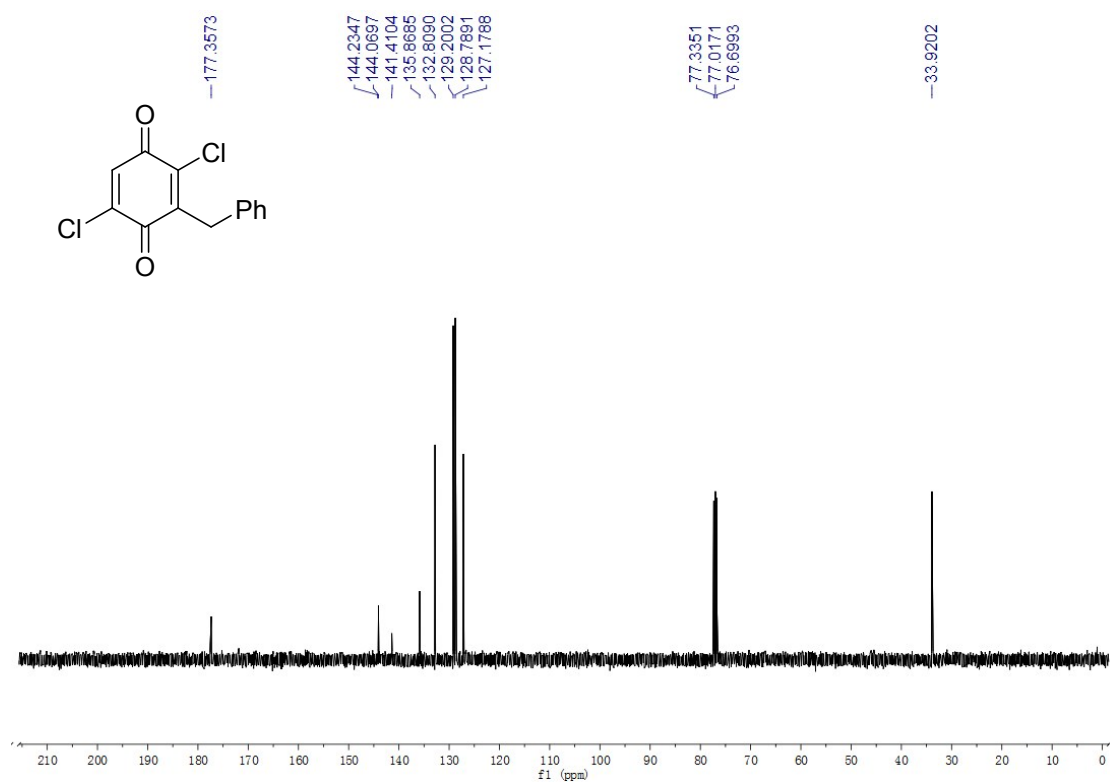
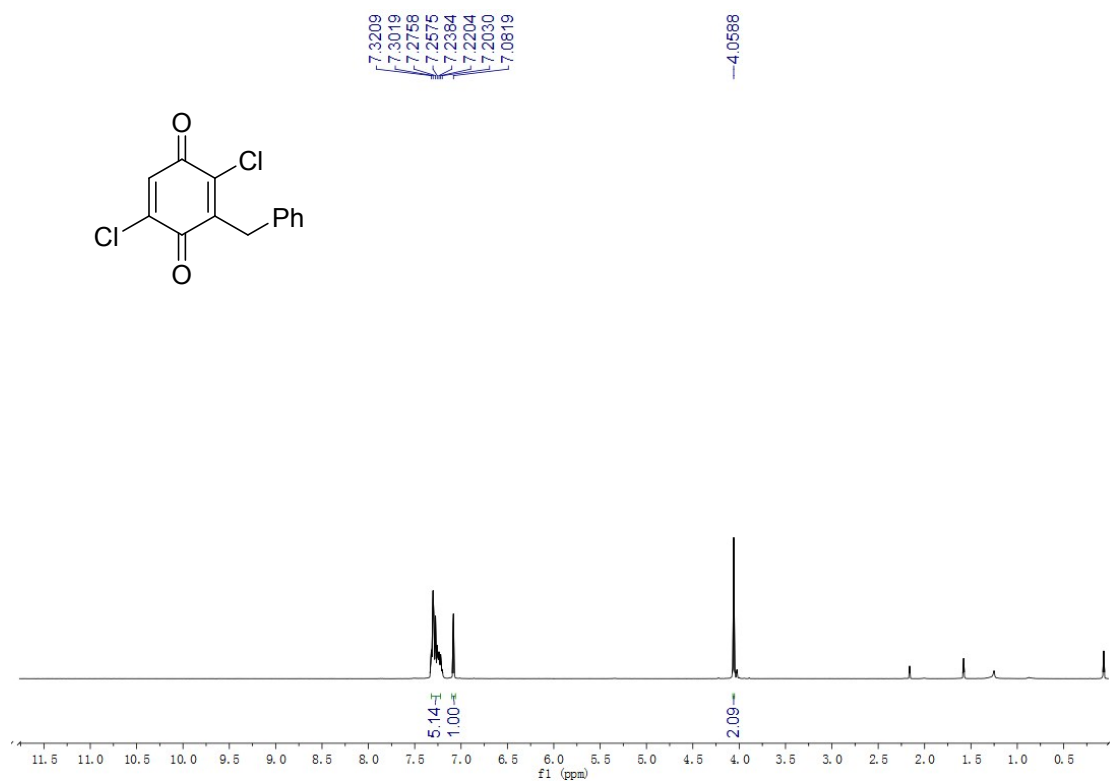
2-benzyl-3,5,6-trimethylcyclohexa-2,5-diene-1,4-dione (3na)



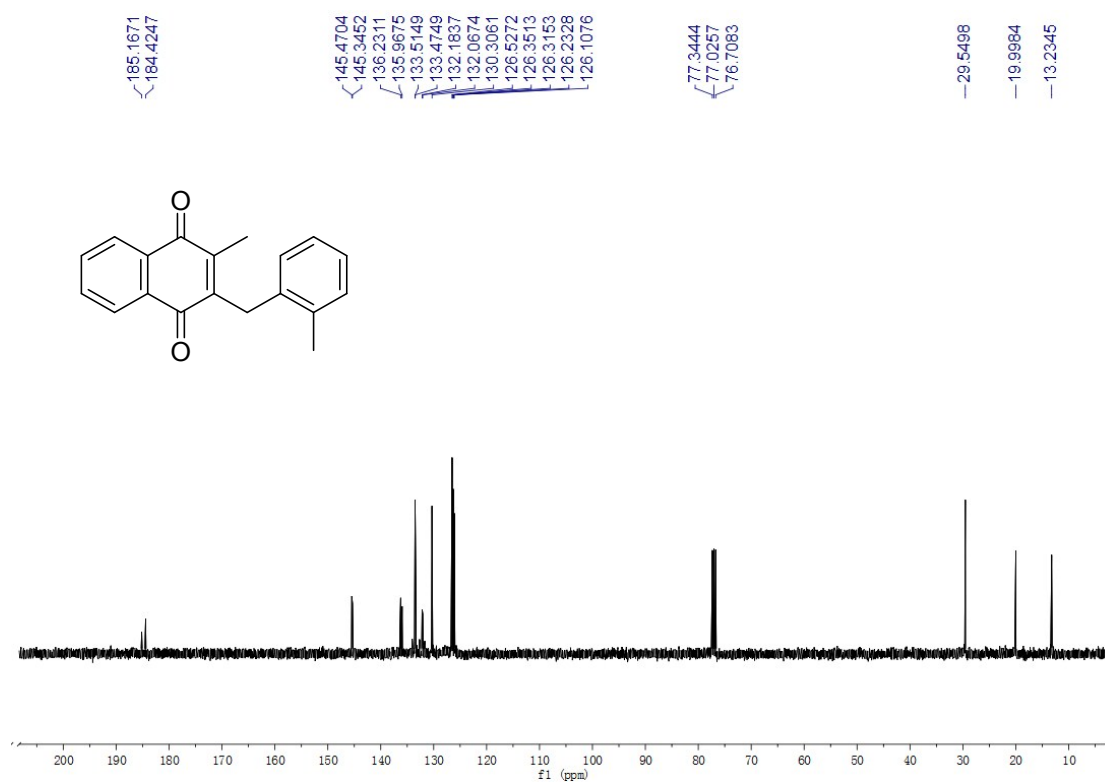
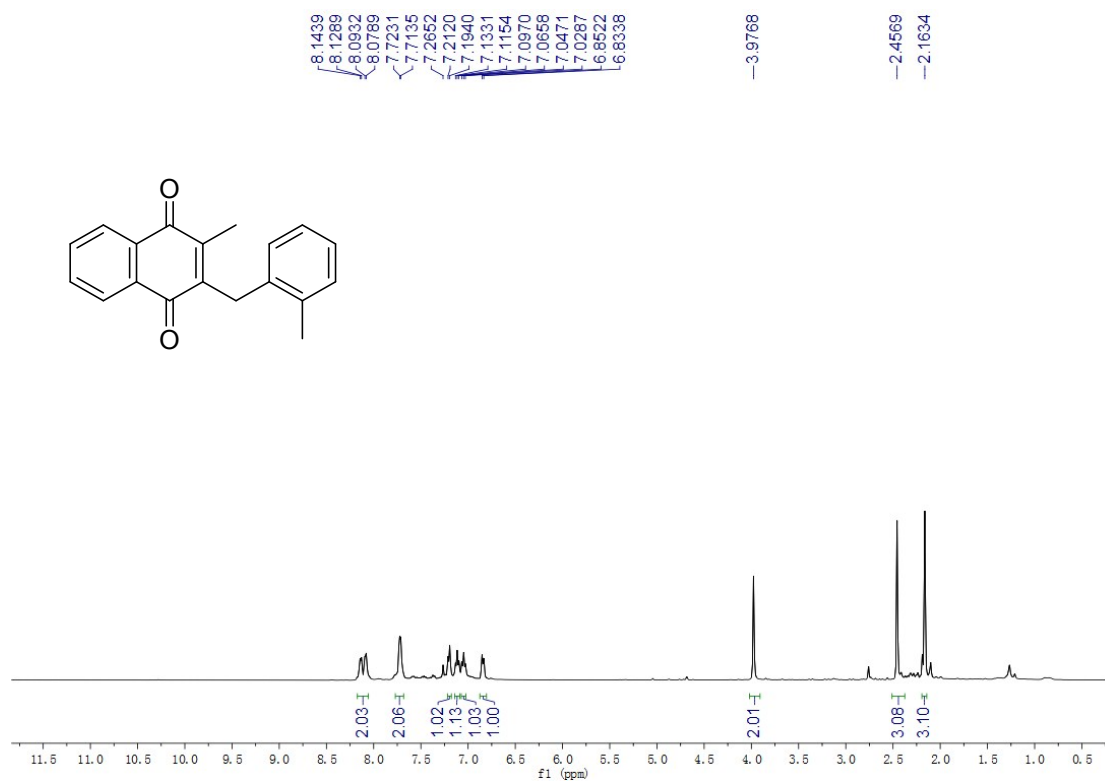
2-benzyl-5,6-dimethoxy-3-methylcyclohexa-2,5-diene-1,4-dione (30a)



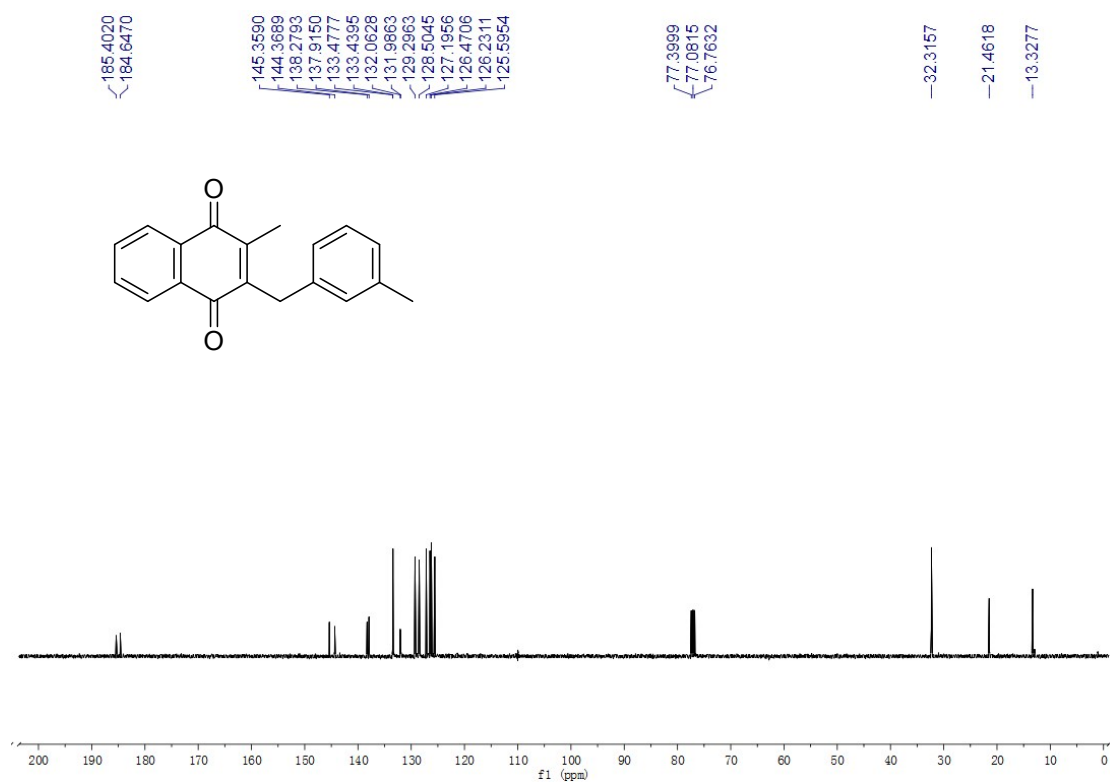
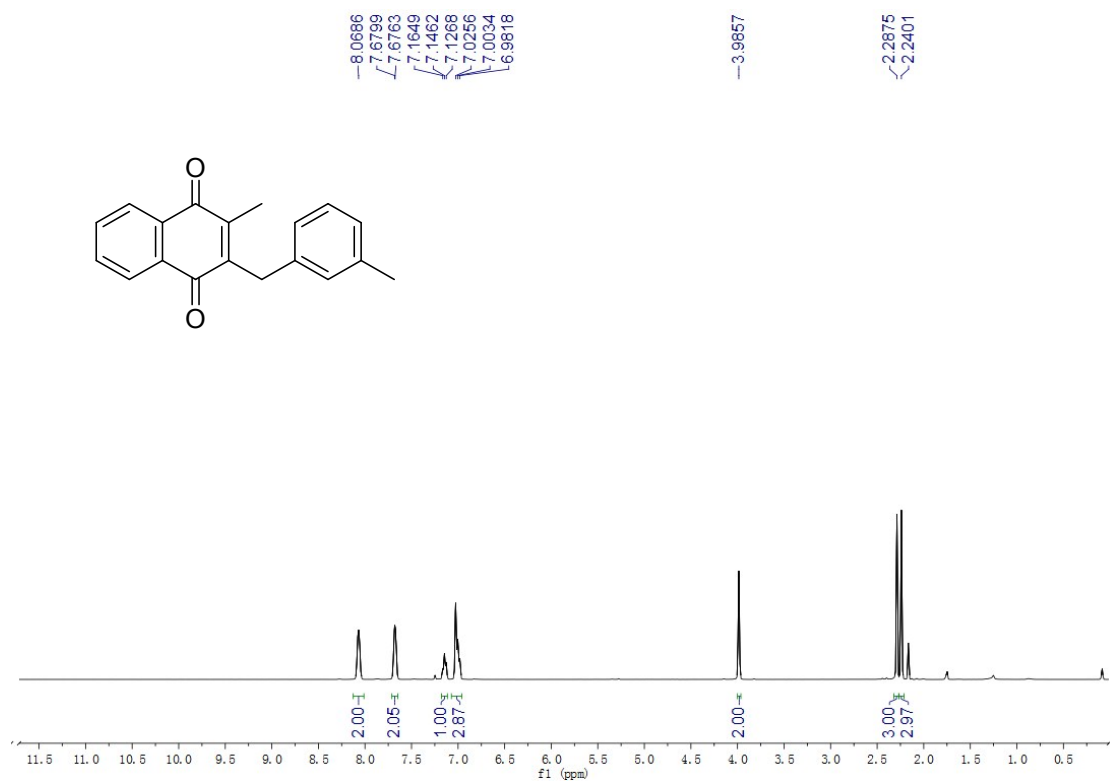
3-benzyl-2,5-dichlorocyclohexa-2,5-diene-1,4-dione (3pa)



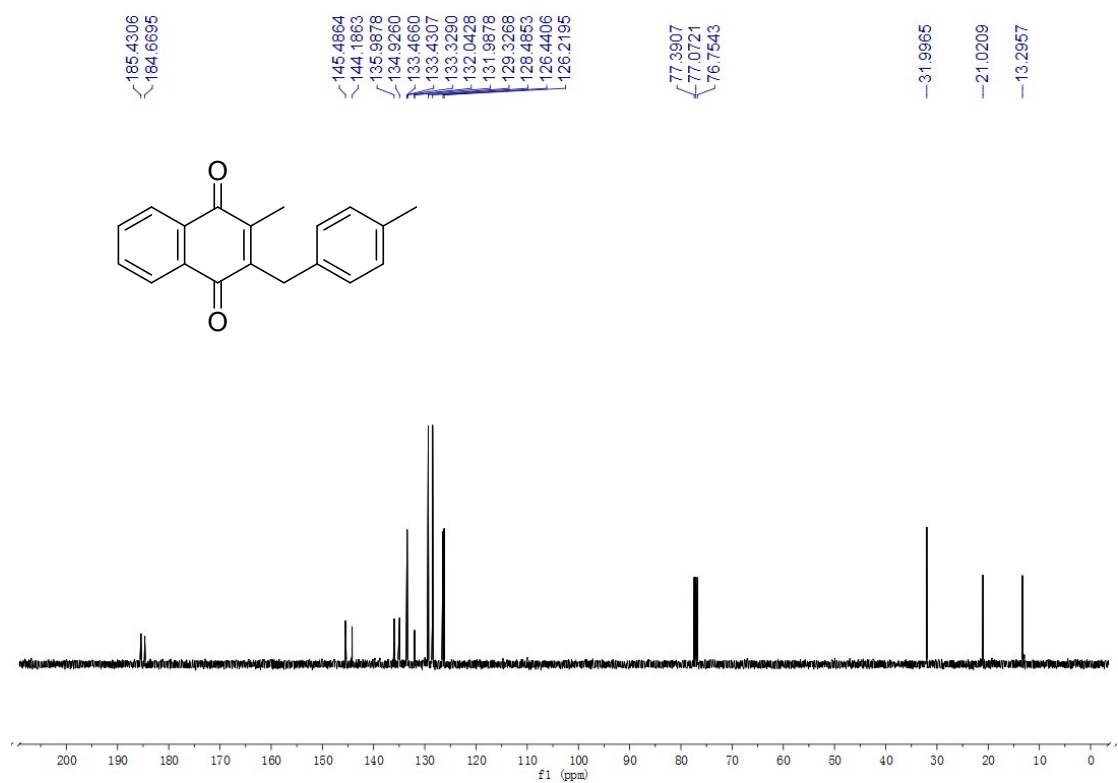
2-methyl-3-(2-methylbenzyl)naphthalene-1,4-dione (3ab)



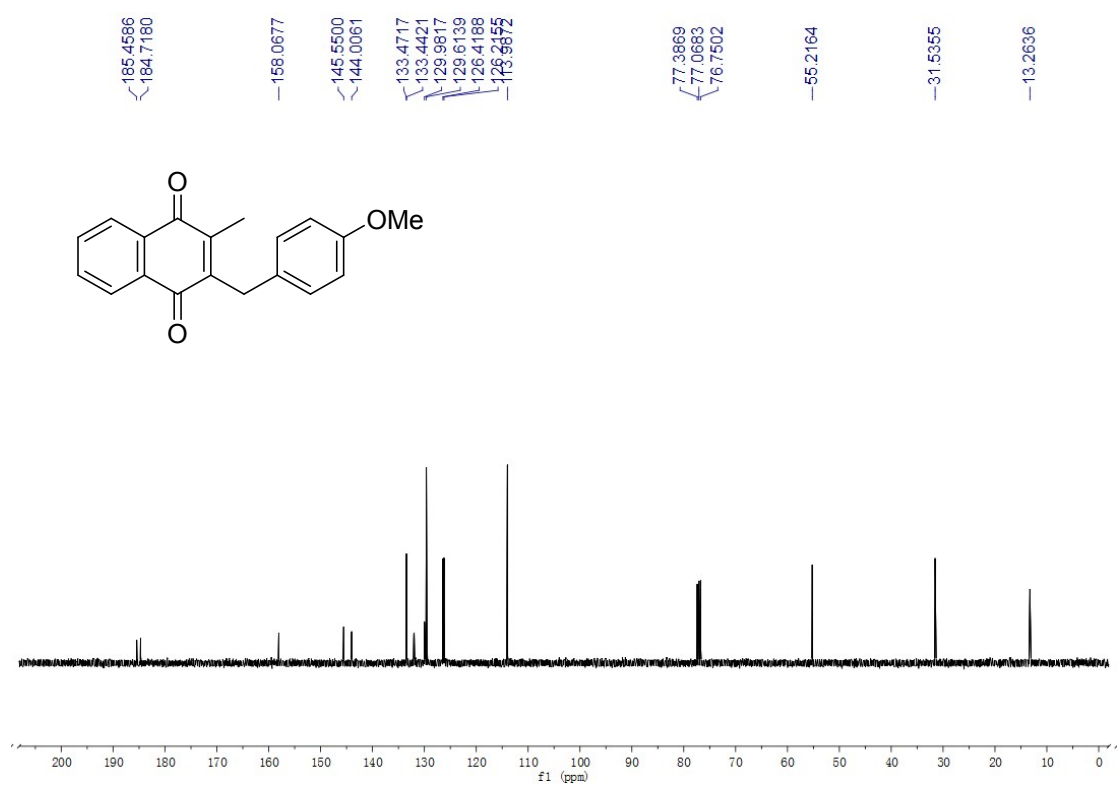
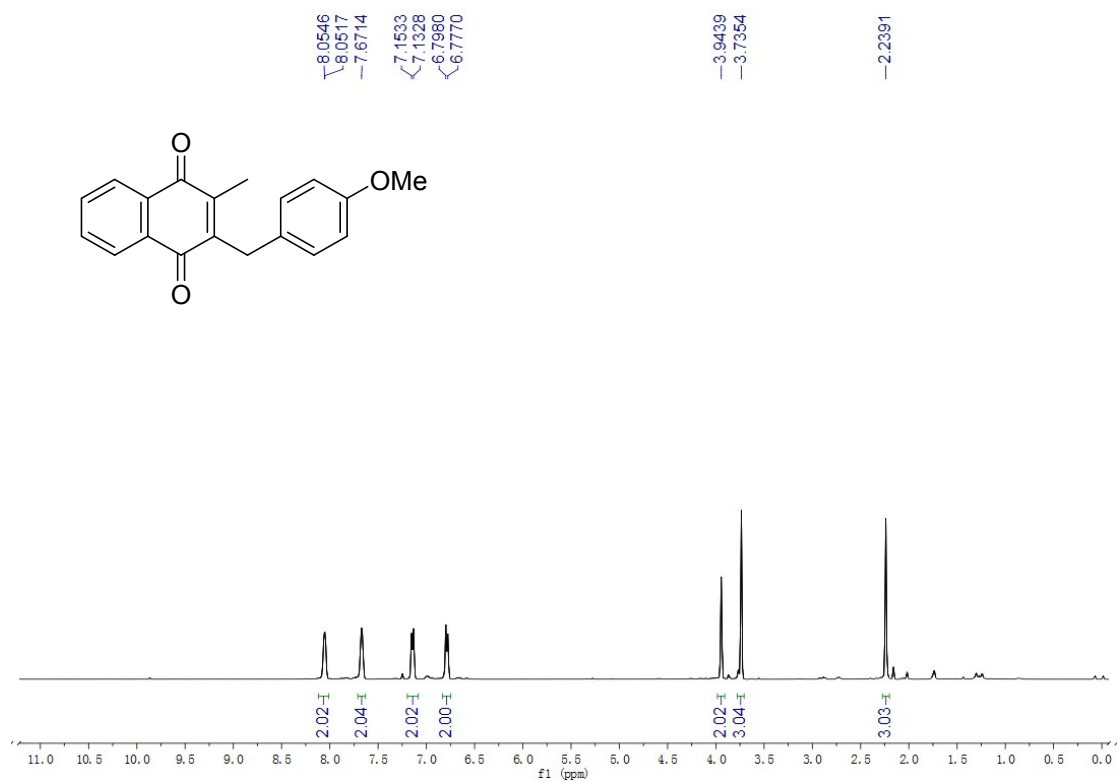
2-methyl-3-(3-methylbenzyl)naphthalene-1,4-dione (3ac)



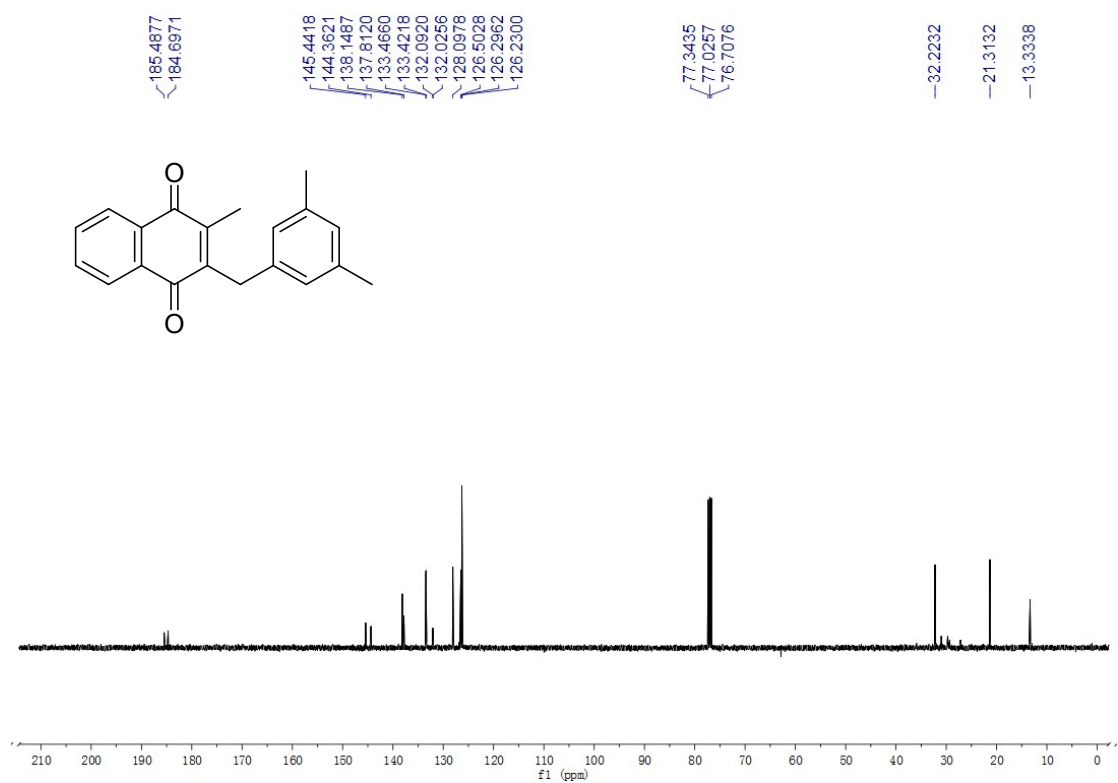
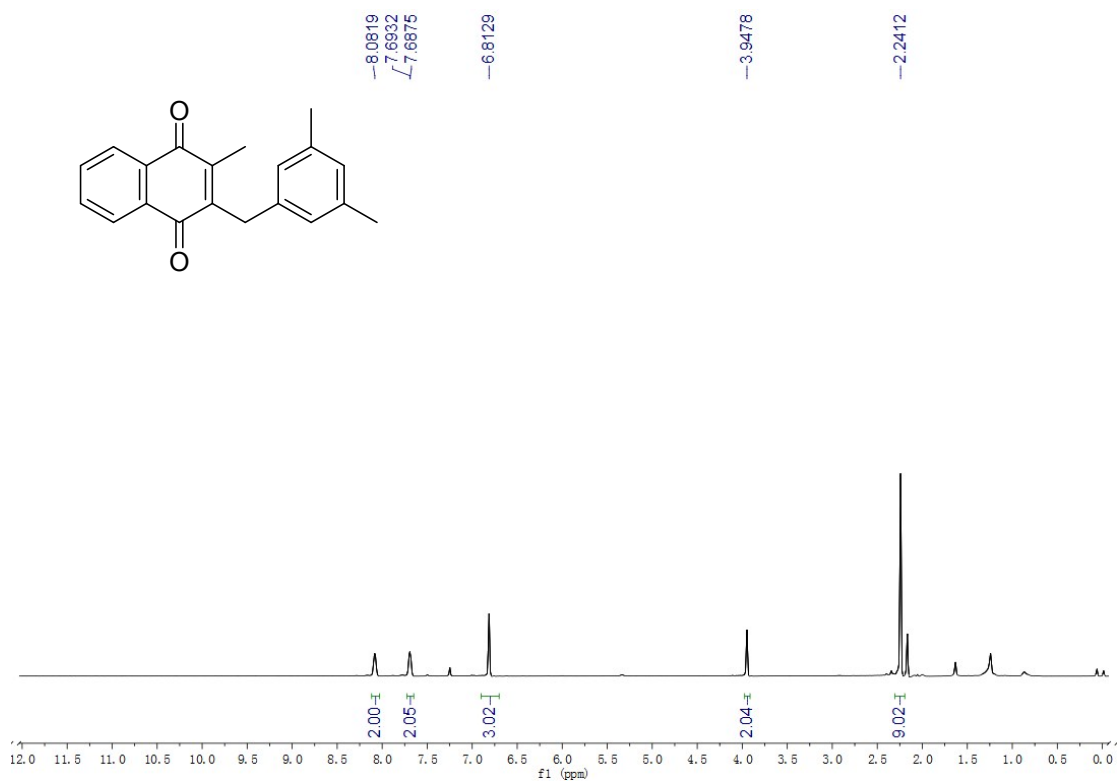
2-methyl-3-(4-methylbenzyl)naphthalene-1,4-dione (3ad)



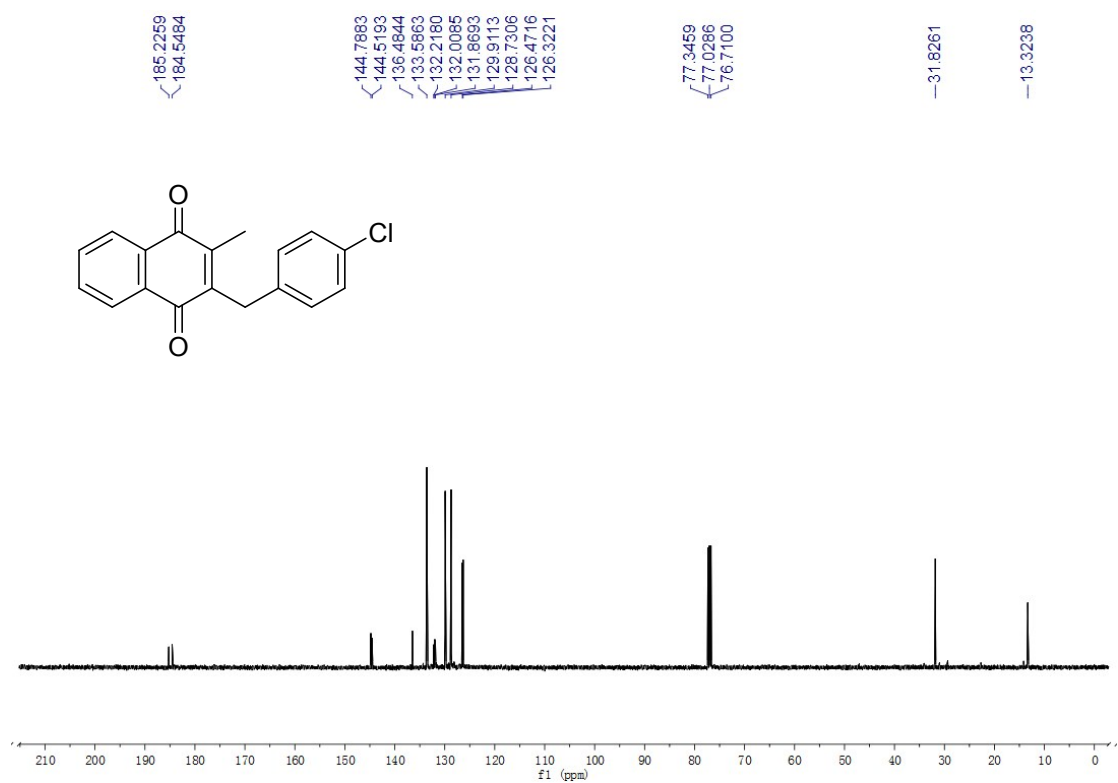
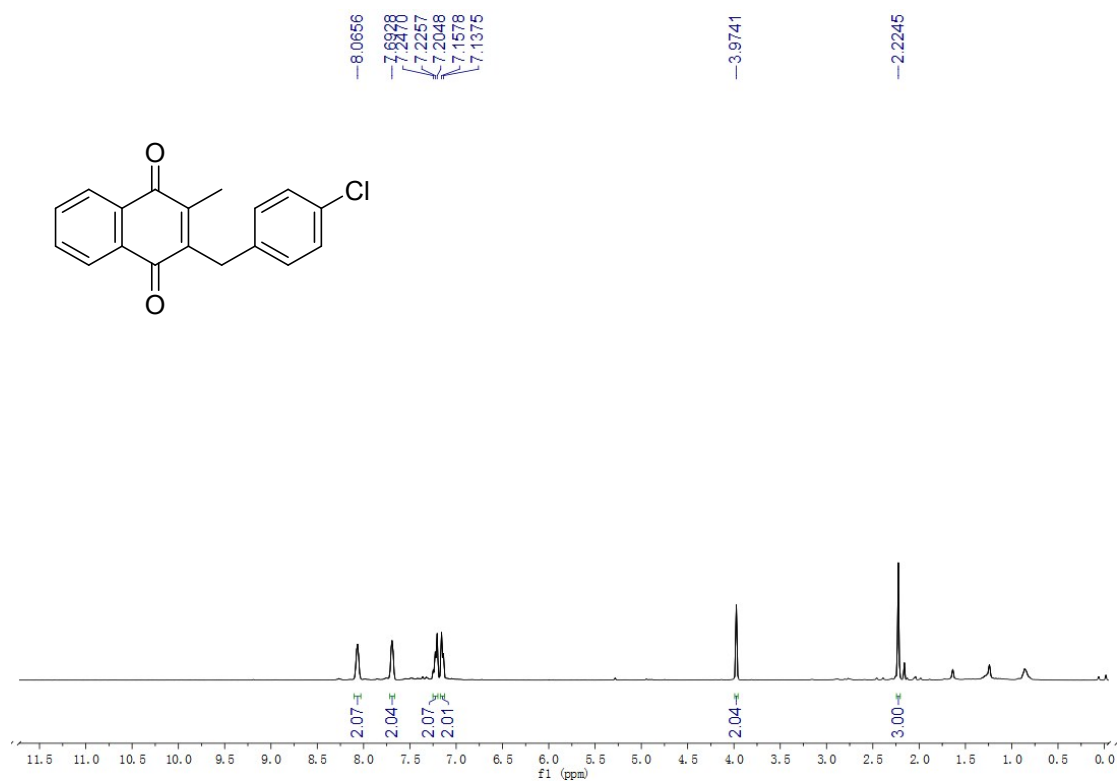
2-(4-methoxybenzyl)-3-methylnaphthalene-1,4-dione (3ae)



2-(3,5-dimethylbenzyl)-3-methylnaphthalene-1,4-dione (3af)



2-(4-chlorobenzyl)-3-methylnaphthalene-1,4-dione (3ag)



2-(4-bromobenzyl)-3-methylnaphthalene-1,4-dione (3ah)

