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Activated Carbon-Promoted Dehydrogenation of Hydroquinones to Benzoquinones, Naphthoquinones, and Anthraquinones under Molecular Oxygen Atmosphere

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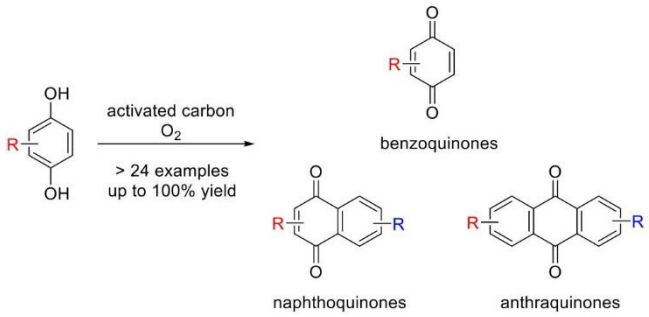
Supporting Information Placeholder

ABSTRACT: We found activated carbon-molecular oxygen system promotes the conversion of hydroquinones to benzoquinones, naphthoquinones, and anthraquinones, which are often found in natural products and pharmaceuticals. In particular, the one-pot synthesis of naphthoquinones and anthraquinones involving a Diels-Alder reaction is a useful protocol for this purpose.



Benzoquinones, naphthoquinones, and anthraquinones are remarkable scaffolds in the synthesis of natural products and pharmaceutical compounds. For example, benzoquinone has been considered a privileged structure in compounds that show antitumor, antimalarial or leishmanicidal activity, such as coenzyme Q_{10},[1] embelin,[2] and geldanamycin.[3] The naphthoquinone skeleton is also found in the precursors of bioactive molecules that have antimalarial,[4] anticancer,[5] antitumor,[6] wound healing,[7] antiparasitic[8] and antibacterial propertiess[9] (Figure 1).

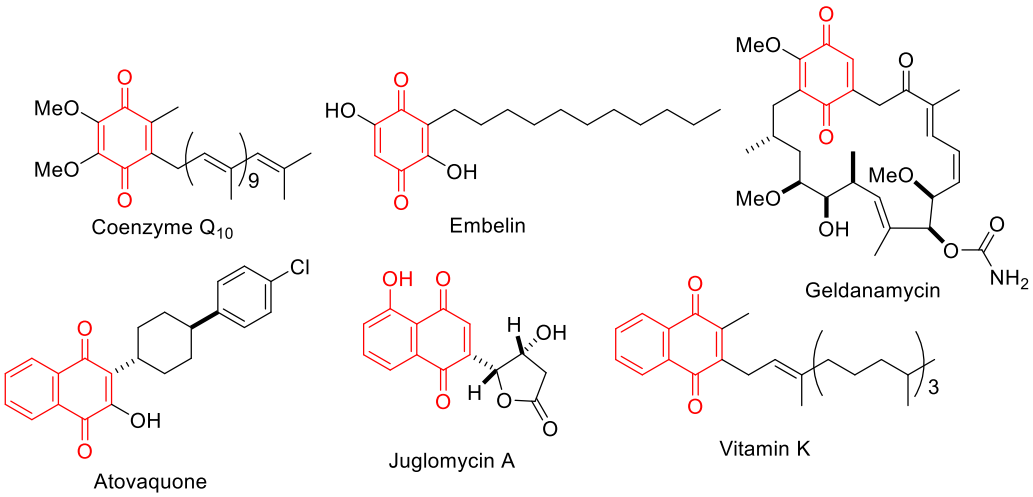
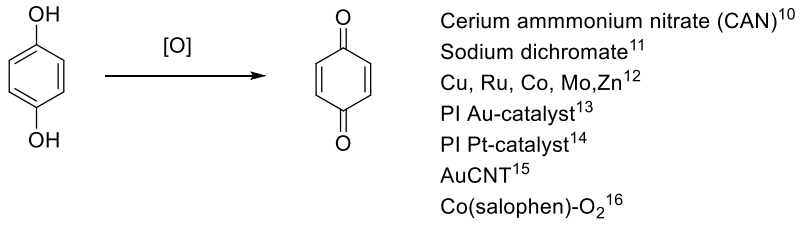


Figure 1. Benzoquinone and naphthoquinone moieties found in natural products and pharmaceuticals.

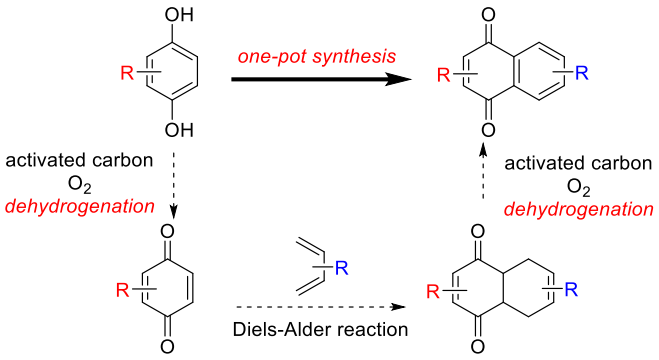
As shown in Scheme 1, numerous catalysts and promotors have been developed for the conversion of hydroquinones to benzoquinones, including cerium ammonium nitrate (CAN),[10] chromium (VI),[11] or metal complexes[12] In 2008, Kobayashi and co-workers reported the aerobic oxidation of hydroquinone derivatives to quinones catalyzed by a polymer-incarcerated gold catalyst (PI Pt).[13] They also reported a polymer incarcerated platinum catalyst (PI Au) system.[14] In 2014, Namboothiri, Doris, and co-workers reported the aerobic oxidation of phenols, and related compounds, including hydroquinones to 1,4-benzoquinones using a carbon nanotube-gold nanohybrid catalyst (AuCNT).[15] More recently, Stahl and co-workers reported the Co(salophen)-catalyzed aerobic oxidation of *p*-hydroquinones.[16]

Scheme 1. Previously reported methods for conversion of hydroquinone to benzoquinone.



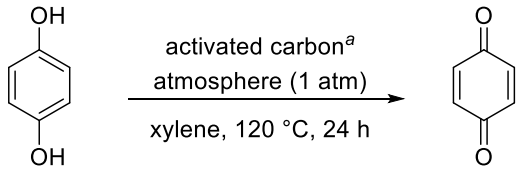
In this paper, we report the synthesis of 1,4-benzoquinones from hydroquinones to quinones using an activated carbon– molecular oxygen system.[17] Furthermore, we carried out the one-pot synthesis of naphthoquinones via a dehydrogenation, Diels-Alder reaction, and dehydrogenation sequence (Scheme 2).

Scheme 2. One-pot synthetic strategy for naphthoquinone **.**



First, we attempted the reaction of hydroquinone with activated carbon in xylene under molecular oxygen atmosphere at 120 ºC for 24 h. As shown in entries 1 to 4 in Table 1, the concentration of the hydroquinone is a crucial factor to obtain high yields of benzoquinone. This may be because of the formation of quinhydrone, which is a 1:1 molecular complex of benzoquinone and hydroquinone, in high concentration.[18] The results in entries 5 and 6 indicated that neither activated carbon nor molecular oxygen was powerful enough to promote the reaction when used alone.

Table 1. Optimization and control experiments for dehydrogenation of hydroquinone to benzoquinone



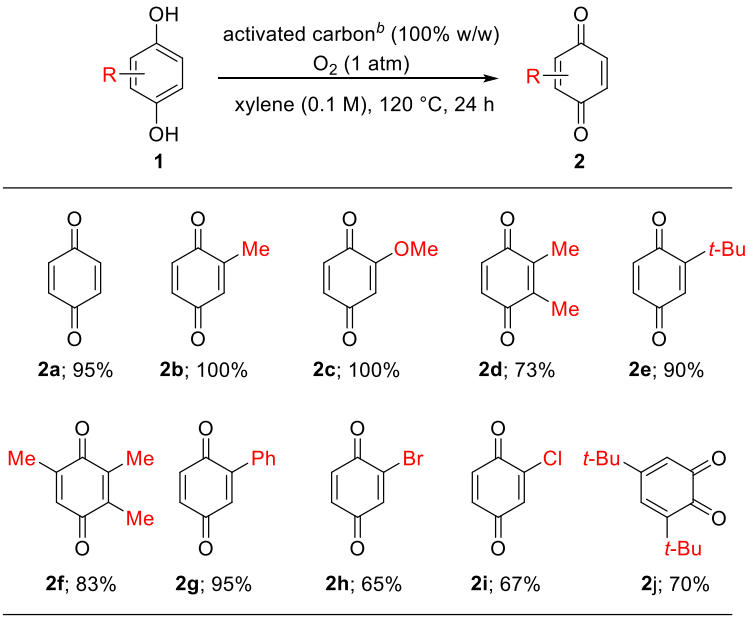
1a **2a**

entry	conc/M	activated carbon (%w/w)	atomosphere	yield/%[b]
1	1.0	100	O_2	10
2	0.5	100	O_2	33
3	0.25	100	O_2	56
4	0.1	100	O_2	95
5	0.1	100	Ar	0
6	0.1	none	O_2	trace
7	0.1	20	O_2	15
8	0.1	50	O_2	40
9	0.1	100	air	56

[a] Activated carbon (TCI-2), Tokyo Chemical Industry Co. specific surface area (~1400 m^2/g), pore volume (1.3 mL/g). [b] Isolated yield by silica-gel column chromatography.

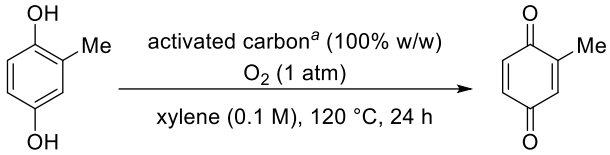
Under the optimized conditions, various substituted hydroquinones (**1a-1j**) were converted to the corresponding benzoquinones (**2a-2j**) in high to excellent yields (Table 2). Notable, 1,2-benzoquinone derivative **2j** was obtained in 70% yield. Hydroquinones possessing a variety of group, such as $COCH_3$, CO_2CH_3, OH, NO_2, CN and 1,4-dihydroxynaphthalene afforded the corresponding quinines in low yield. Then, we investigated the recyclability of the activated carbon. As shown in Table 3, the activated carbon could be recycled and reused at least five times to obtain the corresponding benzoquinone without loss of yield.

Table 2. Synthesis of benzoquinones from hydroquinones[a]



[a] Isolated yield by silica-gel column chromatography. [b] Activated carbon (TCI-2), Tokyo Chemical Industry Co.

Table 3. Recyclability of activated carbon.



1b **2b**

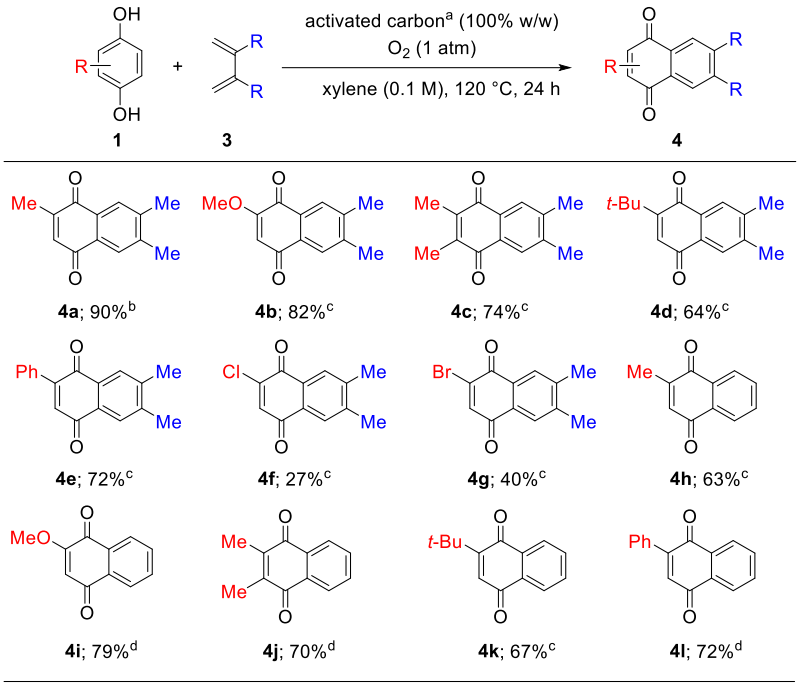
entry	recycling time	yield/%[b]
1	1	91
2	2	91
3	3	93
4	4	93
5	5	94

[a] Activated carbon (TCI-2), Tokyo Chemical Industry Co.

[b] Determined by GC analysis using pentadecane as the internal standard.

We next carried out one-pot synthesis of naphthoquinones. The reaction of benzoquinones (**1a-1j**) with 2,3-dimethyl-1,3-butadiene or 1,3-butadiene proceeded smoothly to afford the corresponding naphthoquinone derivatives (**4a-4l**) in good to high yields except for 2-chloro-6,7-dimethyl-1,4-naphthoquinone (**4f**) and 2-bromo-6,7-dimethyl-1,4-naphthoquinone (**4g**), which gave low yield (27% and 40% yield, respectively) (Table 4). The reaction involves dehydrogenation of hydroquinone by the activated carbon–molecular oxygen system to give benzoquinone, followed by Diels-Alder reaction with 1,3-butadiene to form tetrahydronaphthoquinone, and finally, dehydrogenation by the activated carbon– molecular oxygen system to give the desired naphthoquinones.

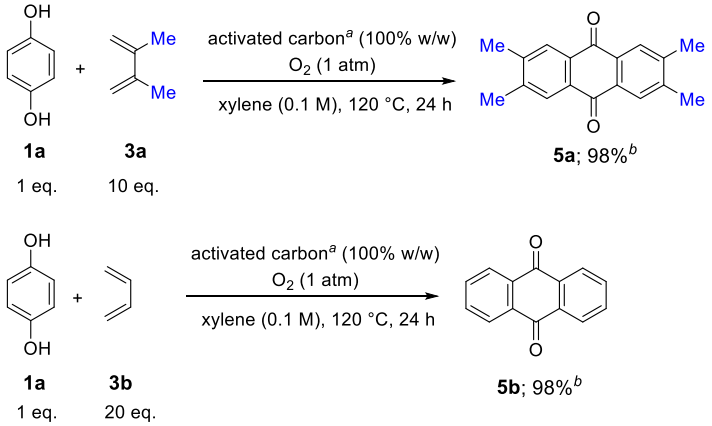
Table 4. One-pot synthesis of naphthoquinone derivatives



[a] Activated carbon (TCI-2), Tokyo Chemical Industry Co. [b] Sufficient pure without further purification. [c] Isolated yield by silica-gel column chromatography. [d] Isolated yield by recrystallization.

During the investigation of the synthesis of naphthoquinones, we found that when we used excess amount of 1,3-dienes, anthraquinone derivatives were obtained including two times of Dield-Alder reaction. After optimization, we established the conditions for one-pot synthesis of anthraquinones in excellent yield (Scheme 3).[19]

Scheme 3. One-pot synthesis of anthraquinones from hydroquinones.



[a] Activated carbon (TCI-2) Tokyo Chemical Industry Co. [b]15 % (w/w) of 1,3-butadiene

solution in toluene. [c] Isolated yield by silica-gel column chromatography.

As for the role of activated carbon, we previously reported the relationship between the nature of activated carbon and reactivity in the oxidation reaction. We have shown in a number of previous studies that the key role of activated carbon in these oxidations is not associated not with metal contaminants, specific surface area, pore volume, or the mean pore diameter. Instead, it is associated with oxygenated functional groups in the pore, for example, carbonyl and carboxyl groups.[17d]

In conclusion, we have developed a simple and environment-friendly method for the synthesis of benzoquinones, naphthoquinones, and anthraquinones from hydroquinones using an activated carbon–molecular oxygen system. Further investigation toward the application of this protocol to natural product synthesis is on-going.

EXPERIMENTAL SECTION

General experiment. All reactions were carried out in flame-dried and well cleaned glasswares with magnetic stirring. Dehydrogenation of hydroquinones to benzqouinones was conducted in a two-neck test tube with balloon which is filled with oxygen gas, unless otherwise noted. Dehydrogenation of hydroquinones to naphthoquinones and anthraquinones was conducted in a 30 mL Schlenk flask which is filled with oxygen gas. In the case of the synthesis of benzoquinones, all of reagents were added under dry argon atmosphere then the atmosphere was changed from argon to oxygen by vacuum techniques thrice. In the case of the synthesis of naphthoquinones and anthraquinones, all of the reagents were added under dry argon atmosphere then the atmosphere was changed from argon to oxygen in an ice bath to prevent evaporation of diene derivatives. All starting materials were obtained from commercial sources. Melting points were measured on a Yanaco MP-500D and are not corrected. ^{1}H and $^{13}C\{1H\}$ NMR were recorded on a Bruker Avance lll HD 400 using TMS (0 ppm) and $CDCl_3$ ($^{13}C\{1H\}$: 77.0 ppm) as an internal standard, respectively (^{1}H NMR, 400 MHz; $^{13}C\{1H\}$NMR, 100 MHz). The following abbreviations are used in connection with NMR; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet. Mass spectra were measured using an Isolera^{TM} Dalton Mass Detector. HRMS spectra were measured using a JOEL JMS-T100LP (DART ionization method, TOF analyzer). GC analyses were performed using a Hitachi G-5000 or Shimazu GC-2025 gas chromatograph equipped with GL Science InertCAP 5. Preparative column chromatography was performed using Kanto Chemical silica gel 60 N (spherical, neutral), Fuji Silysia BW: 10MH silica gel or YMC_GEL Silica gel 60

F_{254}aluminiym sheets. Safety precautions: Although we have not experienced explosion after hundreds times of oxidation experiments, mixing volatile hydrocarbons with pure oxygen has a potential risk for explosion. Safety measures against static discharge should be taken.

General Procedure

General method for the dehydrogenation of hydroquinones to benzoquinones (2a-2j)

A flame-dried two-necked test tube was prepared with balloon connected via three ways cock. After cooling down to room temperature, hydroquinone derivatives (0.5-5.0 mmol, 1.0 eq.) and activated carbon (100% w/w) were added under argon atmosphere. Then, xylene (5-50 mL, 0.1 M) was slowly added with stirring. After addition of all of reagents, the atmosphere was changed from argon to oxygen by using vacuum technique for 3 times. The reaction solution was heated up to 120 ℃ with oil bath and carefully stirred for 24 h. The reaction was monitored by TLC and GC. After confirmation of completion of the reaction, the reaction mixture was cooled down to room temperature and filtered through Celite by washing with dichloromethane. Then, the yellow solution was evaporated with reduced pressure because benzoquinone derivatives were volatile. After evaporation, the obtained residue was purified by the silica-gel column chromatography.

Recyclability of activated carbon

Firstly, substrate (**1b**) was dehydrogenated by activated carbon—O_2 promoting system and 91% of desired benzoquinone (**2b**) was obtained by gas chromatography (GC) analysis with pentadecane as an internal standard. After the reaction, the activated carbon was filtered through the Büchner funnel by washing with enough ethyl acetate and hexane. Then the washed activated carbon was dried overnight in vacuum. This recycling process was investigated for 5 times (Table 3).

General method for the dehydrogenation of hydroquinones to naphthoquinones with 2,3-dimethyl-1,3-butadiene (4a-4g)

A flame-dried 30 mL Schlenk flask was prepared. After cooling down to room temperature, hydroquinone derivatives (0.5-1.2 mmol, 1.25 eq.) and activated carbon (100% w/w) were added under argon atmosphere. Then, xylene (5-12 mL, 0.1 M based on hydroquinone derivatives) was slowly added with stirring. The reaction solution was cooled down in an ice bath before introduction of 2,3-dimethylbutadiene. After cooling down, 2.3-dimehylbutadiene (0.4-0.96 mmol, 1.0 eq.) was added dropwise into the

reaction mixture. After addition of 2,3-dimethylbutadiene, the reaction atmosphere was changed to oxygen by using three ways cock (one is for balloon with oxygen, another is for vacuum pump and the other is for Schlenk flask). The atmosphere was changed for 10 times by quickly converting the cock position. After changing the atmosphere, the reaction mixture was heated up to 120 ℃ with oil bath and carefully stirred for 36 h. The reaction was monitored by TLC and GC. After confirmation of completion of the reaction, the reaction mixture was cooled down to room temperature and filtered through Celite by washing with ethyl acetate. Then, all of solvents were removed under reduced pressure. After removal of solvents, the obtained residue was purified by recrystallization or silica-gel column chromatography.

General method for the dehydrogenation of hydroquinones to naphthoquinones with 1,3-butadiene (4h-4l)

A flame-dried 30 mL Schlenk flask was prepared. After cooling down to room temperature, hydroquinone derivatives (0.5 mmol, 1.0 eq.) and activated carbon (100% w/w) were added under argon atmosphere. Then, xylene (5 mL, 0.1 M) was slowly added with stirring. The reaction solution was cooled down in an ice bath before introduction of 1,3-butadiene. After cooling down, 15% w/w of 1.3-butadiene in toluene (2.0 mmol, 4.0 eq.) was added dropwise into the reaction mixture. After addition of 1,3-butadiene, the reaction atmosphere was changed to oxygen by using three ways cock (one is for balloon with oxygen, another is for vacuum pump and the other is for Schlenk flask). The atmosphere was changed 5 times by quickly changing the position of the cock. After changing atmosphere, the reaction mixture was heated up to 120 ℃ with oil bath and carefully stirred for 36 h. The reaction was monitored by TLC and GC. After confirmation of completion of the reaction, the reaction mixture was cooled down to room temperature and filtered through Celite by washing with ethyl acetate. Then, the solvent was removed under reduced pressure. After removal of solvents, the obtained residue was purified by recrystallization or silica-gel column chromatography.

General method for the dehydrogenation of hydroquinones to anthraquinone

A flame-dried 30 mL Schlenk flask was prepared. After cooling down to room temperature, hydroquinone derivatives (0.5 mmol, 1.0 eq.) and activated carbon (100 w/w%) were added under argon atmosphere. Then, xylene (5 mL, 0.1 M) was slowly added with stirring. The reaction solution was cooled down in ice bath before introduction of diene. After cooling down, 15 w/w% of 1.3-butadiene in toluene (10 mmol, 20 eq.) was added dropwise into the reaction mixture. After addition of diene, the reaction atmosphere change to oxygen by using three ways cock (one is for balloon with oxygen,

another is for vacuum pump and the other is for Schlenk flask). The atmosphere was changed for 5-10 times by quickly converting the cock position. After changing atmosphere, the reaction mixture were heated up to 120 ℃ with oil bath and carefully stirred for 48 h. The reaction was monitored by TLC and GC. After confirmation of completion of the reaction, the reaction mixture was cooled down to room temperature and filtered through Celite by washing with ethyl acetate. Then, the solvent was removed under reduced pressure. After evaporation, the obtained residue was purified by silica-gel column chromatography ($CHCl_3$/hexane = 1:1).

p-benzoquinone ***2a***. Yield: 95% (510 mg, 4.75 mmol). Yellow solid, Mp: 113.3─114.2 ℃ (lit.[20] Mp: 114─116 ℃); IR (neat) 501, 505, 742, 887, 941, 1072, 1082, 1305, 1342, 1364, 1590, 1641, 1677; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.79 (s, 4H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ = 187.2, 136.5.

2-methly-p-benzoquinone ***2b***. Yield: 100% (610 mg, 5.0 mmol). Yellow solid, Mp: 67.7─68.1 ℃ (lit.[21] Mp: 68─69 ℃); IR (neat) 531, 536, 680, 822, 884, 922, 998, 1094, 1141, 1300, 1347, 1372, 1597, 1643, 3055, 3071; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.72 (dd, *J* = 10.1, 2.4 Hz, 1H), 6.63 (dq, J = 3.2, 1.6 Hz, 1H), 6.77 (d, J = 10.1 Hz, 1H), 2.07 (d, J = 1.6 Hz, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ = 187.7, 187.6, 145.8, 136.5, 136.4, 133.3, 15.8.

2-methoxy-p-benzoquinone ***2c***. Yield: 100% (276 mg, 2.0 mmol). Yellow solid, Mp: 124.6─125.2 ℃ (lit.[22] Mp: 138─139 ℃); IR (neat) 556, 593, 632, 694, 793, 843, 879, 982, 1109, 1176, 1313, 1357, 1377, 1445, 1461, 1588, 1617, 1643, 1674, 2947, 2982, 3067; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.72 (d, *J* = 1.5 Hz, 2H), 5.95 (s, 1H), 3.84 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$) δ = 187.4, 181.7, 158.5, 137.2, 134.4, 107.7, 56.2.

2,3-dimethyl-p-benzoquinone ***2d***. Yield: 100% (50 mg, 0.36 mmol). Yellow solid, Mp: 51.0─52.1 ℃ (lit.[23] Mp: 54─55 ℃); IR (neat) 624, 754, 803, 840, 1064, 1136, 1307, 1365, 1380, 1600, 1651, 2955, 3052; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.72 (s, 2H), 2.03 (s, 6H); ^{13}C{1H} NMR (101 MHz, $CDCl_3$) δ = 187.2, 140.9, 136.1, 12.1.

2-tert-butyl-p-benzoquinone ***2e***. Yield: 90% (74 mg, 0.45 mmol). Yellow solid, Mp: 54.2─55.1 ℃ (lit.[24] Mp: 54─56 ℃); IR (neat) 536, 590, 652, 791, 844, 880, 934, 1010, 1042, 1107, 1116, 1198, 1257, 1289, 1337, 1365, 1391, 1459, 1482, 1589, 1651, 2869, 2960, 3055, 3254, 3297; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.68 (d, *J* = 1.2 Hz, 2H), 6.60 (t, *J* = 1.2 Hz, 1H), 1.28 (s, 9H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 188.2, 187.3, 155.8, 138.5, 134.8, 131.4, 35.1, 29.0.

2,3,6-trimethyl-p-benzoquinone ***2f***. Yield: 83% (62 mg, 0.42 mmol). Yellow solid, Mp: 36.1—36.5 ℃ (lit.[25] Mp: 36 ℃); IR (neat) 674, 697, 756, 807, 879, 990, 1030, 1101, 1187, 1260, 1314, 1374, 1434, 1616, 1643, 2918; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.55 (q, *J* = 1.6 Hz, 1H), 2.04 (d, *J* = 1.6 Hz, 3H), 2.03–2.02 (m, 3H), 2.02–1.98 (m, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 187.7, 187.3, 145.2, 140.7, 140.6, 132.9, 15.7, 12.2, 11.9.

2-phenyl-p-benzoquinone ***2g***. Yield: 95% (88 mg, 0.48 mmol). Yellow solid, Mp: 115.6—116.2 ℃ (lit.[26] Mp: 113—114 ℃); IR (neat) 534, 610, 623, 692, 799, 841, 912, 936, 976, 1000, 1077, 1099, 1254, 1276, 1297, 1314, 1342, 1444, 1492, 1572, 1589, 1643, 3036, 3058; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.52–7.41 (m, 5H), 6.88 (d, *J* = 6.7 Hz, 1H), 6.87 (d, *J* = 1.1 Hz, 1H), 6.84 (dd, *J* = 10.2, 2.2 Hz, 1H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 187.6, 186.6, 145.9, 137.0, 136.2, 132.6, 132.6, 130.1, 129.2, 128.5.

2-bromo-p-benzoquinone ***2h***. Yield: 65% (39 mg, 0.33 mmol). Brown solid, Mp: 50.2—50.7℃ (lit.[27] mp 56.5 ℃); IR (neat) 527, 532, 540, 547, 553, 559, 565, 778, 830, 915, 972, 1096, 1109, 1197, 1280, 1315, 1372, 1577, 1642, 1658, 3044, 3054; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.32 (d, *J* = 2.4 Hz, 1H), 6.97 (d, *J* = 10.1 Hz, 1H), 6.83 (dd, *J* = 10.1, 2.4 Hz, 1H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 184.5, 179.1, 138.1, 137.5, 136.6, 135.8.

2-chloro-p-benzoquinone ***2i***. Yield: 67% (476 mg, 3.4 mmol). Brown solid, Mp: 48.2—48.7 ℃ (lit.[28] Mp 51—54 ℃); IR (neat) 562, 636, 782, 829, 844, 910, 998, 1105, 1200, 1285, 1320, 1370, 1588, 1651, 1677, 3051; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.02 (d, *J* = 2.4 Hz, 1H), 6.93 (d, *J* = 10.1 Hz, 1H), 6.82 (dd, *J* = 10.1, 2.4 Hz, 1H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 184.9, 179.2, 144.0, 136.7, 136.0, 133.6.

3,5-di-tert-butyl-o-benzoquinone ***2j***. Yield: 70% (77 mg, 0.35 mmol). Darkish green solid, Mp 103.4—103.8 ℃ (lit.[29] Mp 111—112 ℃); IR (neat) 531, 541, 581, 656, 734, 811, 889, 931, 951, 1023, 1069, 1207, 1244, 1274, 1366, 1373, 1392, 1464, 1478, 1567, 1621, 1651, 1659, 1673, 2870, 2954, 3063; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 6.93 (d, *J* = 2.3 Hz, 1H), 6.21 (d, *J* = 2.3 Hz, 1H), 1.27 (s, 9H), 1.22 (s, 9H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 180.9, 179.9, 163.2, 149.7, 133.4, 121.9, 35.9, 35.3, 29.1, 27.7.

2,6,7-trimethyl-1,4-naphthoquinone ***4a***. Yield: 90% (216 mg, 1.1 mmol). Yellow solid, Mp: 107.1—107.5 ℃ (lit.[30] Mp 107.5—108.5 ℃); IR (neat) 586, 649, 680, 699, 733, 805, 876, 919, 985, 1021, 1067, 1209, 1276, 1298, 1319, 1340, 1381, 1450, 1595, 1623, 1664, 2917, 2945, 3053; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.83 (s, 1H), 7.80 (s, 1H), 6.76 (q, *J* = 1.5 Hz, 1H), 2.39 (d, *J* = 2.0 Hz, 6H), 2.17 (d, *J* = 1.6 Hz, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.5, 185.1, 147.7, 143.2, 143.2, 135.3, 130.0, 129.9, 127.3, 126.9, 20.0, 20.0, 16.3.

2-methoxy-6,7-dimethyl-1,4-naphthoquinone ***4b***. Yield: 82% (89 mg, 0.41 mmol). Brown solid, Mp: 170.6─170.8 ℃ (lit.[31] Mp: 169─171 ℃); IR (neat) 587, 673, 716, 741, 803, 873, 916, 898, 996, 1013, 1076, 1154, 1185, 1196, 1250, 1305, 1325, 1358, 1389, 1451, 1567, 1597, 1650, 1685, 2839, 2948, 3051; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.88 (s, 1H), 7.83 (s, 1H), 6.10 (s, 1H), 3.89 (s, 3H), 2.39 (d, *J* = 2.5 Hz, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.1, 180.1, 160.2, 144.2, 142.9, 129.8, 128.8, 127.6, 127.1, 109.5, 56.3, 20.2, 19.9.

2,3,6,7-tetramethyl-1,4-naphthoquinone ***4c***. Yield: 74% (79 mg, 0.37 mmol). Yellow solid, Mp: 174.5─175.0 ℃ (lit.[32] Mp: 167─168.5 ℃); IR (neat) 661, 720, 747, 895, 901, 922, 998, 1028, 1087, 1149, 1191, 1217, 1304, 1324, 1367, 1454, 1590, 1613, 1650, 2915, 2947, 3031; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.82 (s, 2H), 2.38 (s, 6H), 2.15 (s, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.2, 143.1, 143.0, 130.1, 127.2, 20.1, 12.8.

2-tert-butyl-6,7-dimethyl-1,4-naphthoquinone ***4d***. Yield: 64% (77 mg, 0.32 mmol). Yellow solid, Mp. 110.3─110.8 ℃; IR (neat) 589, 639, 685, 705, 733, 818, 890, 932, 994, 1042, 1095, 1190, 1227, 1258, 1299, 1335, 1356, 1378, 1363, 1378, 1449, 1557, 1573, 1598, 1656, 2866, 2915, 2950, 2966, 3047; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.82 (s, 1H), 7.77 (s, 1H), 6.77 (s, 1H), 2.39 (d, *J* = 3.3 Hz, 6H), 1.36 (s, 9H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 186.1, 185.1, 157.9, 143.4, 142.9, 133.6, 131.4, 129.4, 127.8, 126.4, 35.6, 29.3, 20.2, 20.0; HRMS (DART): m/z [M+H]+ calcd for $C_{16}H_{19}O_2$: 243.1385; Found: 243.1379.

2-phenyl–6,7-dimethyl-1,4-naphthoquinone ***4e***. Yield: 72% (94 mg, 0.36 mmol). Yellow solid, Mp. 83.4─84.4 ℃; IR (neat) 547, 693, 701, 715, 761, 780, 810, 843, 892, 1073, 1190, 1294, 1355, 1344, 1444, 1567, 1598, 1652, 1666, 2978, 2950, 2996, 3031; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.92 (s, 1H), 7.86 (s, 1H), 7.60–7.52 (m, 2H), 7.51–7.44 (m, 3H), 7.01 (s, 1H) 2.43 (s, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.2, 184.3, 147.6, 143.6, 143.5, 134.9, 133.5, 130.2, 129.9, 129.7, 129.3, 128.3, 127.8, 126.7, 20.1, 20.1; HRMS (DART): m/z [M+H]+ calcd for $C_{18}H_{15}O_2$: 263.1072; Found: 263.1057.

2-chloro–6,7-dimethyl-1,4-naphthoquinone ***4f***. Yield: 27% (31 mg, 0.14 mmol). Yellow solid, Mp: 141.2─142.0 ℃ (lit.[33] Mp: 145─147 ℃); IR (neat) 575, 626, 711, 891, 999, 1023, 1200, 1258, 1282, 1310, 1329, 1375, 1448, 1594, 1659, 1672, 2885, 2918, 2942, 3036, 3060; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.91 (s, 1H), 7.83 (s, 1H), 7.15 (s, 1H), 2.41 (s, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 183.0, 178.1, 146.1, 144.6, 144.1, 135.7, 129.7, 129.2, 128.5, 127.7, 20.3, 20.2.

2-bromo–6,7-dimethyl-1,4-naphthoquinone ***4g***. Yield: 40% (53 mg, 0.2 mmol). Yellow solid, Mp: 155.6─156.0 ℃ (lit.[34] Mp: 155─156 ℃); IR (neat) 560, 613, 678, 705,

797, 812, 892, 993, 1023, 1200, 1260, 1277, 1327, 1311, 1375, 1448, 1566, 1592, 1659, 1671, 2889, 2912, 2939, 3033, 3055; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.91 (s, 1H), 7.83 (s, 1H), 7.45 (s, 1H), 2.41 (s, 6H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 182.6, 177.9, 144.5, 144.1, 140.1, 139.9, 129.6, 128.8, 128.8, 127.8, 20.2, 20.2.

2-methyl-1,4-naphthoquinone ***4h***. Yield: 63% (55 mg, 0.32 mmol). Yellow solid, Mp: 104.1—104.9 ℃ (lit.[33] Mp 106—107 ℃); IR (neat) 642, 650, 666, 690, 719, 749, 777, 900, 939, 1156, 1192, 1259, 1299, 1352, 1589, 1621, 1661, 1682, 2920, 2961, 3068; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.85–7.72 (m, 2H), 7.64–7.52 (m, 2H), 3.82 (s, 1H), 1.60 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.5, 184.9, 148.1, 135.6, 133.6, 133.5, 132.2, 132.1, 126.5, 126.0, 16.5.

2-methoxy-1,4-naphthoquinone ***4i***. Yield: 83% (78 mg, 0.42 mmol). Brown solid, Mp: 153.5—154.3 ℃ (lit.[35] Mp: 147 ℃); IR (neat) 645, 670, 692, 722, 780, 865, 924, 1022, 1043, 1086, 1118, 1156, 1193, 1213, 1241, 1265, 1335, 1445, 1577, 1590, 1602, 1643, 1680, 2848, 2947, 2988, 3047; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 8.18–8.06 (m, 2H), 7.80–7.67 (m, 2H), 6.18 (s, 1H), 3.91 (s, 3H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 184.8, 180.1, 160.4, 134.3, 133.3, 132.0, 131.0, 126.7, 126.2, 109.9, 56.4.

2,3-dimethyl-1,4-naphthoquinone ***4j***. Yield: 70% (65 mg, 0.35 mmol). Yellow solid, Mp: 126.3—127.4 ℃ (lit.[36] Mp: 126 ℃); IR (neat) 533, 538, 552, 566, 617, 660, 695, 789, 889, 1004, 1189, 1258, 1292, 1313, 1371, 1334, 1592, 1620, 1656, 2848, 2923; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 8.09 (dd, *J* = 5.7, 3.3 Hz, 2H), 7.69 (dd, *J* = 5.8, 3.3 Hz, 2H), 2.19 (s, 6H); ^{13}C{1H} NMR (100 MHz, CDCl3), δ = 184.7, 143.3, 133.2, 132.0, 126.1, 12.8.

2-tert-butyl-1,4-naphthoquinone ***4k***. Yield: 67% (72 mg, 0.33 mmol). Yellow solid, Mp: 76.0—76.6 ℃ (lit.[37] Mp: 76—77 ℃); IR (neat) 626, 670, 719, 785, 891, 903, 1125, 1201, 1248, 1307, 1340, 1330, 1591, 1654, 1663, 2869, 2958, 2969, 3068; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 8.13–8.00 (m, 2H), 7.78–7.65 (m, 2H), 6.85 (s, 1H), 1.37 (s, 9H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.9, 184.9, 158.3, 133.8, 133.7, 133.5, 133.3, 131.5, 126.9, 125.6, 35.7, 29.4.

2-phenyl-1,4-naphthoquinone ***4l***. Yield: 72% (84 mg, 0.36 mmol). Yellow solid, Mp: 107.5—108.9 ℃ (lit.[38] Mp: 107—108 ℃); IR (neat) 569, 669, 694, 714, 756, 849, 898, 909, 1014, 1044, 1118, 1204, 1244, 1306, 1332, 1442, 1485, 1569, 1588, 1650, 1663; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 7.84–7.74 (m, 2H), 7.62–7.54 (m, 2H), 7.52–7.44 (m, 3H), 7.09 (s, 1H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 185.1, 184.4, 148.1, 135.2, 133.9, 133.8, 133.4, 132.4, 132.1, 130.0, 129.4, 128.4, 127.0, 126.0.

2,3,6,7-tetramethylanthraquinone ***5a***. Yield: 98% (129 mg, 0.49 mmol). Light yellow powder, Mp: 331.6─332.5 ℃ (lit.[39] Mp: 330 ℃); IR (neat) 593, 717, 908, 927, 967, 1028, 1197, 1299, 1373, 1449, 1556, 1588, 1665; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 8.03 (s, 4H), 2.43 (s, 12H); ^{13}C{1H} NMR (100 MHz, $CDCl_3$), δ = 183.6, 143.7, 131.6, 128.0, 20.2.

Anthraquinone ***5b***. Yield: 98% (102 mg, 0.49 mmol). Light yellow powder, Mp: 218.7─219.5 ℃ (lit.[40] Mp: 269─271 ℃); IR (neat) 620, 808, 817, 892, 935, 1168, 1205, 1282, 1331, 1573, 1673; ^{1}H NMR (400 MHz, $CDCl_3$), δ = 8.33 (dd, *J* = 5.8, 3.3 Hz, 4H), 7.82 (dd, *J* = 5.8, 3.3 Hz, 4H); ^{13}C NMR (100 MHz, $CDCl_3$), δ = 183.1, 134.1, 133.5, 127.2.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: copies of ^{1}H and ^{13}C NMR spectra.

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Notes

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