Synthesis of Anthraquinones by Iridium-Catalyzed [2 + 2 + 2] Cycloaddition of a 1,2-Bis(propiolyl)benzene Derivative with Alkynes

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Abstract: [2 + 2 + 2] cycloaddition of a 1,2-bis(propiolyl)benzene derivative with terminal and internal alkynes takes place in the presence of [Ir(cod)Cl]₂ (cod = 1,5-cyclooctadiene) combined with bis(diphenylphosphino)ethane (DPPE) to give anthraquinones in 42% to 93% yields with a simple experimental procedure. A fluorenone derivative can also be synthesized by iridium-catalyzed [2 + 2 + 2] cycloaddition of a benzene-linked ketodiyne with an internal alkyne to give a 94% yield.

Keywords: catalysis; cycloaddition; anthraquinones; fluorenones; diynes; iridium

1. Introduction

Anthraquinones and their derivatives are important structures found in natural products and bioactive compounds and show a broad range of bioactivities including anti-tumor [1,2], cytotoxic [3], anti-cancer [4–6], anti-bacterial [7,8], laxative [9], anti-arthritis [10], anti-fungal [11], anti-platelet [12,13], and neuroprotective effects [14]. Moreover, anthraquinones have been widely used as catalysts for producing hydrogen peroxide [15], dyes for fibers [16,17] and cells [18], a digestion catalyst for wood [19], and chemical sensors [20]. Thus, the development of synthetic methods for the formation of multi-substituted anthraquinones is an important research topic, and several synthetic methods including the oxidation of anthracene [21,22], the Friedel-Crafts reaction of phthalic anhydride [23], and the Diels-Alder reaction of naphthoquinones followed by aromatization [24] have been developed.

Transition metal-catalyzed [2 + 2 + 2] cycloaddition represents a powerful and atom-economical method to access a variety of complex aromatic carbocycles and heterocycles in short steps [25–30]. From 1,2-bis(propiolyl)benzene derivatives and alkynes, [2 + 2 + 2] cyclization has realized the synthesis of anthraquinones. After the success of stoichiometric reactions with a large amount of highly toxic Ni(CO)₄ [31] and isolated naphthoquinone-fused rhodacyclopentadiene [32], catalytic reactions were realized by the use of Ni(PPh₃)₂(CO)₂ [33], CpCo(CO)₂ [34], and RhCl(PPh₃)₃ [35]. However, the reaction systems require high reaction temperatures, and the yields of the desired anthraquinones are moderate. Yamamoto and co-workers elegantly demonstrated that Cp*RuCl(cod) (cod = 1,5-cyclooctadiene) can catalyze the [2 + 2 + 2] cycloaddition of 1,2-bis(propiolyl)benzene derivatives with terminal alkynes and methyl-substituted internal alkynes under mild reaction conditions in high yields [36–40]. On the other hand, the rhodium-catalyzed reaction reported by Tanaka realized [2 + 2 + 2] cycloaddition with aryl-substituted diynes to give anthraquinones in high yields [41]. Despite this progress with methods for the synthesis of anthraquinones, few highly atom-economical methods are available, and, thus, novel methods to efficiently obtain anthraquinones are still desired. Our laboratory has developed an iridium-catalyzed [2 + 2 + 2] cycloaddition of diynes with alkynes, nitriles, and isocyanate to provide a variety of aromatic carbocycles and...
heterocycles [42–50]. In the course of our ongoing investigation into iridium-catalyzed [2 + 2 + 2] cycloaddition, we found that an iridium/bisphosphate catalytic system catalyzed the [2 + 2 + 2] cycloaddition of 1,2-bis(propiolyl)benzene derivatives to provide anthraquinones bearing a variety of substituents in an atom-economical manner.

2. Results and Discussion

The reaction of 1,2-bis(propiolyl)benzene derivative 1 with three equivalents of 1-hexyne (2a) in the presence of 2 mol % of [Ir(cod)Cl]2 in toluene under reflux for 20 h gave the anthraquinone 3a in 20% yield (entry 1, Table 1). The phosphine ligand was found to improve the yield of anthraquinone 3a. With a monophosphine ligand, PPh₃, the cyclized product was obtained in a moderate yield (Yield 64%, entry 2). Sufficient yield was achieved with the use of 1,2-bis(diphenylphosphino)ethane (DPPE) as a ligand to give 83% yield of anthraquinone 3a (entry 3), while other representative bidentate phosphine ligands such as 1,3-bis(diphenylphosphino)propane (DPPP), 1,4-bis(diphenylphosphino)butane (DPPB), and 1,1′-bis(diphenylphosphino)ferrocene (DPPF) were ineffective at achieving a high yield (Yield 22% to 45%, entries 4 to 6).

![Chemical structure of 1,2-bis(propiolyl)benzene derivative 1 reacting with 3 equiv. of 1-hexyne (2a) with 2 mol % [Ir(cod)Cl]2 and X mol % Ligand in toluene, reflux, 20 h to yield 3a.](image)

Table 1. Ligand effects a.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand (mol %)</th>
<th>Yield of 3a (%) b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>PPh₃ (8)</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>DPPE (4)</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>DPPP (4)</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>DPPB (4)</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>DPPF (4)</td>
<td>22</td>
</tr>
</tbody>
</table>

a Reaction conditions: 1 (0.5 mmol), 2a (1.5 mmol), [Ir(cod)Cl]₂ (0.1 mmol), ligand, toluene (2.5 mL), under reflux for 20 h. b Isolated yield.

The Ir/dppe complex demonstrates high activity for [2 + 2 + 2] cycloaddition with various kinds of terminal alkynes to provide anthraquinone derivatives 3b–i in good to high yields (Table 2). Cyclized products were obtained in high yields with 1-octyne and 1-decyne, respectively (Yields 92 and 93%, 3b and 3c). A chloride group can be tolerated under the reaction conditions (Yield 73%, 3d). As well as aliphatic alkynes, the aromatic alkyne can also be used in the reaction (Yield 77%, 3e). The present iridium-catalyzed [2 + 2 + 2] cyclization can introduce a sterically hindered functional group such as a trimethylsilyl group to give the corresponding cyclized product in a moderate yield (Yield 42%, 3f). Terminal alkynes with primary, secondary, and tertiary alcohols are also good substrates for this [2 + 2 + 2] cyclization (Yields 75–85%, 3g–3i).
Unfortunately, the optimized reaction conditions in Table 2 resulted in a diminished yield for the cyclization with internal alkyne 2j, likely due to the formation of the dimer or oligomer of 1 as byproducts (Yield 36%, entry 1, Table 3). Our examination of the reaction conditions found that halogenated solvent was more suitable for the reaction than toluene. With dichloroethane (DCE) as a solvent, 62% of the cyclized product 3j was obtained (entry 2). The yield was slightly improved in dichloromethane (DCM) under reflux to give 3j in a 72% yield (entry 3).

**Table 3.** The [2 + 2 + 2] cycloaddition of 1 with internal alkyne 2j.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reaction Conditions</th>
<th>Yield of 3j (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Toluene, reflux</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>DCE, reflux</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>DCM, reflux</td>
<td>72</td>
</tr>
</tbody>
</table>

*Reaction conditions: 1 (0.5 mmol), 2j (1.5 mmol), [Ir(cod)Cl]2 (0.1 mmol), DPPE (0.2 mmol), solvent (2.5 mL) under reflux for 24 h. b Isolated yield.*
The results obtained for the iridium-catalyzed [2 + 2 + 2] cycloaddition of 1,2-bis(propioly)benzene derivative with internal alkynes are summarized in Table 4. In refluxing DCM, [2 + 2 + 2] cycloaddition with several internal alkynes proceeded to form tetra-substituted anthraquinones in good yields (Yield 72–86%, 3j–3l).

Table 4. Synthesis of tetra-substituted anthraquinones a.

<table>
<thead>
<tr>
<th>R</th>
<th>2 mol% [Ir(cod)Cl]2</th>
<th>4 mol% DPPE</th>
<th>DCM, reflux, 24 h</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Et</td>
<td></td>
<td></td>
<td></td>
<td>3j 72%</td>
</tr>
<tr>
<td>OMe</td>
<td></td>
<td></td>
<td></td>
<td>3k 82%</td>
</tr>
<tr>
<td>OH</td>
<td></td>
<td></td>
<td></td>
<td>3l 86%</td>
</tr>
</tbody>
</table>

a 1 (0.5 mmol), 2 (1.5 mmol), [Ir(cod)Cl]2 (0.1 mmol), DPPE (0.2 mmol), DCM (2.5 mL) under reflux for 24 h. Yields are isolated yields.

As shown in Scheme 1, a gram-scale reaction of 1 with 2a also proceeded smoothly. The yield was comparable as in the 0.5 mmol scale.

Scheme 1. Gram-scale synthesis of anthraquinone 3a.

Based on our previous results [45,46,48,49], we envision that the catalytic reaction is initiated by the coordination of diyne 1 to the iridium(I) complex. Oxidative addition of diyne 1 to an iridium(I) complex forms iridacyclopentadiene [51–54]. Reaction of alkyne 2 with the iridacyclopentadiene gives anthraquinone 3 and regenerates the iridium(I) complex.

Fluorenones, which have structures similar to those of anthraquinones, are also a fascinating class of compounds due to their wide range of bioactivities [55–58], and photochemical [59–62] and electronic natures [63–65]. Fortunately, the [2 + 2 + 2] cyclization of benzene-linked ketodyne 4 with alkyne 2j in the presence of [Ir(cod)Cl]2 (2 mol %), DPPE (4 mol %) in DCM under reflux for 24 h afforded the fluorenone 5j in a 43% yield (entry 1, Table 5). The proper choice of the ligand was found to be essential for the formation of fluorenone 5j in a good yield. While PPh3, 2,2′-bis(diphenylphosphino)biphenyl (BIPHEP), and DPPF were ineffective at catalyzing the formation of fluorenone 5j (Yield 28% to 63%, entries 2 to 4), excellent yield was realized with the use of 1,2-bis[bis(pentafluorophenyl)phosphino]ethane (F-DPPE) (Yield 94%, entry 5).
IR spectra were measured on a JASCO FTIR-4100A spectrometer (JASCO Corporation, Tokyo, Japan). The products were purified by column chromatography on 63–210 mesh silica gel (Silica Gel 60N) (Kanto Chemical Co., Inc., Tokyo, Japan). Inorganics 2019, 7, 138

Table 5. Synthesis of fluorenone from diyne 4 and alkyne 2j a.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand (mol %)</th>
<th>Yield of 5j (%) b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DPPE (4)</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>PPh₃ (8)</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>BIPHEP (4)</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>DPPF (4)</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>F-DPPE (4)</td>
<td>94</td>
</tr>
</tbody>
</table>

a Reaction conditions: 4 (0.5 mmol), 2j (1.5 mmol), [Ir(cod)Cl]₂ (0.1 mmol), ligand, DCM (2.5 mL) under reflux for 24 h. b Isolated yield.

3. Materials and Methods

3.1. General Methods and Materials

All anaerobic and moisture-sensitive manipulations were carried out with standard Schlenk techniques under pre-dried argon. ¹H and ¹³C NMR spectra were measured on JEOL ECX 500II spectrometers (500 MHz for ¹H, 125 MHz for ¹³C) (JEOL Ltd., Tokyo, Japan). Chemical shifts are reported in δ (ppm) referenced to the tetramethylsilane (δ 0.00) for ¹H NMR and the residual peaks of CDCl₃ (δ 77.00) for ¹³C NMR. The following abbreviations are used: s: singlet, d: doublet, t: triplet, q: quartet, sext: sextet, m: multiplet, br: broad. High-resolution mass spectra were obtained with a JEOL Mstation JMS-700 (JEOL Ltd., Tokyo, Japan). IR spectra were measured on a JASCO FTIR-4100A spectrometer (JASCO Corporation, Tokyo, Japan). The products were purified by column chromatography on 63–210 mesh silica gel (Silica Gel 60N) (Kanto Chemical Co., Inc., Tokyo, Japan).

All solvents were dried and distilled before use by the usual procedures. [Ir(cod)Cl]₂ was prepared as described in the literature [66]. Alkynes 2a (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan), 2b (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan), 2c (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 2d (Sigma-Aldrich Co. LLC., St. Louis, USA), 2e (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 2f (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 2g (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 2h (Sigma-Aldrich Co. LLC., St. Louis, USA), 2i (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 2j (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan), 2k (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan), 1,2-bis(diphenylphosphino)ethane (DPPE) (Kanto Chemical Co., Inc., Tokyo, Japan), and 1,2-bis[pentafluorophenyl]phosphino]ethane (F-DPPE) (Tokyo Chemical Industry Co., Ltd., Tokyo, Japan) were purchased and used as received. 2-(1-Hexyn-1-yl)benzaldehyde and 1,4-dimethoxybut-2-yn-1-ol (2k) were prepared by analogy to the reported procedure [67,68].

3.2. Preparation of Anthraquinone 1

To a solution of magnesium (1.632 g, 67.15 mmol) in tetrahydrofuran (THF) (120 mL) was added bromoethane (8.17 g, 75.0 mmol) dropwise at room temperature, and the mixture was stirred for 2 h. At the same temperature, 1-hexyne (5.400 g, 65.74 mmol) was added. After being stirred at 50 °C for 1 h, the reaction mixture was stirred at room temperature for 2 h. In addition, o-phthalaldehyde (4.039 g, 30.11 mmol) was added to the reaction mixture. After the mixture was stirred for 18 h, sat. NH₄Cl was added, and the mixture was extracted with EtOAc. The combined organic extracts were dried (MgSO₄), filtered, and concentrated on a rotary evaporator. The residue was subjected to column chromatography (silica gel, hexane/ethyl acetate = 8/2) to give compound S1 (8.647 g, 28.98 mmol, 96% yield, Scheme 2).
To a solution of magnesium (390.5 mg, 16.07 mmol) in THF (35 mL) bromoethane (2.059 g, 18.89 mmol) was added dropwise at room temperature, and the mixture was stirred for 2 h. At the same temperature, 1-hexyne (1.409 g, 17.16 mmol) was added. After the mixture was stirred for 18 h, the reaction mixture was filtered through a pad of Celite and subjected to column chromatography (silica gel, hexane/ethyl acetate = 8/2) to give \( \text{EtMgBr} \rightarrow \text{BrMg} \), filtered, and concentrated on a rotary evaporator. The residue was subjected to column chromatography (silica gel, hexane/ethyl acetate = 95/5) to give compound \( \text{S2} \) (2.489 g, 9.273 mmol, 93% yield, Scheme 4).

3.3. Preparation of Fluorenone 4

To a solution of magnesium (390.5 mg, 16.07 mmol) in THF (35 mL) bromoethane (2.059 g, 18.89 mmol) was added dropwise at room temperature, and the mixture was stirred for 2 h. At the same temperature, 1-hexyne (1.409 g, 17.16 mmol) was added. After the mixture was stirred for 3 h, 2-(1-hexyn-1-yl)benzaldehyde (1.853 g, 9.947 mmol) was added, and the reaction mixture was stirred for 18 h. The mixture was quenched by saturated \( \text{NH}_4\text{Cl} \) and extracted with \( \text{EtOAc} \). The combined organic extracts were dried (MgSO\(_4\)), filtered, and concentrated on a rotary evaporator. The residue was subjected to column chromatography (silica gel, hexane/ethyl acetate = 95/5) to give compound \( \text{S2} \) (2.489 g, 9.273 mmol, 93% yield, Scheme 4).
Scheme 4. Synthesis of S2.

S2: Yellow oil, Yield 93%, 2.489 g, 1H NMR (500 MHz, CDCl₃) δ 0.91 (t, J = 7.5 Hz, 3H), 0.96 (t, J = 7.5 Hz, 3H), 1.37–1.47 (m, 2H), 1.47–1.57 (m, 4H), 1.57–1.66 (m, 2H), 2.27 (td, J = 7.3, 1.8 Hz, 2H), 2.46 (t, J = 7.3 Hz, 2H), 2.66 (d, J = 5.0 Hz, 1H), 5.83 (dt, J = 5.5, 2.0 Hz, 1H), 7.23 (td, J = 7.5, 1.3 Hz, 1H), 8.41 (t, J = 6.5 Hz, 1H), 8.35 (t, J = 8.0, 1.2 Hz, 1H), 7.50 (dd, J = 7.5, 1.3 Hz, 1H), 8.04 (dd, J = 8.0, 1.3 Hz, 1H), 13C NMR (125 MHz, CDCl₃) δ 13.5, 13.6, 19.0, 19.6, 22.0, 29.8, 30.6, 79.2, 80.7, 96.5, 96.8, 123.6, 127.0, 131.5, 132.0, 134.5, 138.4, 177.9, IR (neat, cm⁻¹) 3062, 2959, 2871, 2207, 1651, 1593, 1561, 1478, 1466, 1272, 1242, 909, 756, HRMS (EI⁺) m/z [M⁺] calc for C₁₉H₂₂O 266.1671, found 266.1670.

To a solution of MnO₂ (7.960 g, 91.56 mmol) in DCM (26 mL) S2 (1.233 g, 4.595 mmol) was added at room temperature. After being stirred for 24 h, the reaction mixture was filtered through a pad of Celite and subjected to column chromatography (silica gel, hexane/ethyl acetate = 7/3) to give 4 (1.177 g, 4.418 mmol, 96% yield, Scheme 5).


4: Orange oil, Yield 96%, 1.177 g, 1H NMR (500 MHz, CDCl₃) δ 0.945 (t, J = 7.5 Hz, 3H), 0.953 (t, J = 7.5 Hz, 3H), 1.42–1.56 (m, 4H), 1.58–1.67 (m, 4H), 2.46 (t, J = 6.5 Hz, 2H), 2.48 (t, J = 6.8 Hz, 2H), 7.35 (td, J = 7.8, 1.3 Hz, 1H), 7.44 (td, J = 7.5, 1.2 Hz, 1H), 7.50 (dd, J = 7.5, 1.3 Hz, 1H), 8.04 (dd, J = 8.0, 1.3 Hz, 1H), 13C NMR (125 MHz, CDCl₃) δ 13.5, 13.6, 19.0, 19.6, 22.0, 29.8, 30.6, 79.2, 80.7, 96.5, 96.8, 123.6, 127.0, 131.5, 132.0, 134.5, 138.4, 177.9, IR (neat, cm⁻¹) 3062, 2959, 2871, 2207, 1651, 1593, 1561, 1478, 1466, 1272, 1242, 909, 756, HRMS (EI⁺) m/z [M⁺] calc for C₁₉H₂₂O 266.1671, found 266.1670.

3.4. General Procedure for the Reaction of 1,2-Bis(propiolyl)benzene Derivative 1 with Alkyne

Representative Procedure for the Reaction of 1,2-Bis(propiolyl)benzene Derivative 1 with Alkyne 2a (Tables 1 and 2).

To a solution of [Ir(cod)Cl]₂ (6.7 mg, 0.010 mmol) and DPPE (8.0 mg, 0.020 mmol) in toluene (1.0 mL), 1-hexyne (125.7 mg, 1.530 mmol) and a solution of 1 (148.1 mg, 0.5031 mmol) in toluene (1.5 mL) were added. The mixture was stirred under reflux for 20 h. After removal of the solvent on a rotary evaporator, the residue was subjected to column chromatography (silica gel, hexane/EtOAc = 99/1) to give compound 1,2,4-tributyllanthracene-9,10-dione (3a) (157.8 mg, 0.4191 mmol, 83% yield, Scheme 6).
A procedure for the Gram-Scale Synthesis of Anthraquinone 3a from 1,2-Bis(propionyloxy)benzene Derivative 1 and Alkyne 2a.

To a solution of [Ir(cod)Cl]2 (45.6 mg, 0.068 mmol) and DPPE (53.8 mg, 0.135 mmol) in toluene (6.8 mL), 1-hexyne (0.838 g, 10.2 mmol) and a solution of 1 (1.019 g, 3.46 mmol) in toluene (10.1 mL) were added, and the mixture was stirred under reflux for 20 h. After removal of the solvent on a rotary evaporator, the residue was subjected to column chromatography (silica gel, hexane/EtOAc = 99/1) to give compound 1,2,4-tributylanthracene-9,10-dione (3a) (1.032 g, 2.740 mmol, 79% yield, Scheme 7).

3.5. Characterization of 3a–3l

1,2,4-Tributylanthracene-9,10-dione (3a, Scheme 8). Brown solid, mp 42.0–43.0 °C, Yield 83%, 157.8 mg. \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 0.99 (t, \(J = 7.5\) Hz, 6H), 1.02 (t, \(J = 6.8\) Hz, 3H), 1.40–1.53 (m, 4H), 1.52–1.70 (m, 8H), 2.68–2.72 (m, 2H), 3.02–3.18 (m, 4H), 7.32 (s, 1H), 7.65–7.73 (m, 2H), 8.07–8.15 (m, 2H), 13C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 13.9, 14.0, 14.1, 22.9, 23.1, 23.5, 29.9, 33.0, 33.1, 33.4, 33.5, 35.7, 126.1, 126.3, 131.1, 133.0, 133.9, 134.3, 135.0, 138.2, 142.5, 144.0, 148.4, 185.9, 187.1, IR (KBr, cm\(^{-1}\)) 2956, 2927, 2869, 1665, 1590, 1536, 1456, 1320, 1288, 1262, 1102, 1020, 898, 802, 726, HRMS (EI\(^+\)) m/z [M]+ calcd for C\(_{26}\)H\(_{32}\)O\(_2\) 376.2402, found 376.2401.

1,4-Dibutyl-2-hexylanthracene-9,10-dione (3b, Scheme 9). Yellow solid, mp 41.0–41.5 °C, 188.0 mg, Yield 92%. \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 0.91 (t, \(J = 6.8\) Hz, 3H), 0.98 (t, \(J = 7.0\) Hz, 3H), 1.02 (t, \(J = 7.0\) Hz, 3H), 1.29–1.38 (m, 4H), 1.38–1.45 (m, 2H), 1.45–1.68 (m, 2H), 1.53–1.68 (m, 8H), 2.67–2.76 (m, 2H), 3.03–3.17 (m, 4H), 7.32 (s, 1H), 7.68 (t, \(J = 3.8\) Hz, 1H), 7.70 (t, \(J = 4.0\) Hz, 1H), 8.07–8.15 (m, 2H), 13C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 14.0, 14.1, 22.6, 23.1, 23.5, 29.5, 29.9, 31.3, 31.6, 33.1, 33.3, 33.4, 35.7, 126.1, 126.3, 131.1, 133.0, 133.9, 134.4, 135.0, 138.3, 142.5, 144.0, 148.4, 185.9, 187.1, IR (KBr, cm\(^{-1}\)) 2959,
2927, 2854, 1668, 1595, 1539, 1462, 1320, 1288, 1265, 727; HRMS (EI+) m/z [M]+ calcd for C_{28}H_{36}O_{2} 404.2715, found 404.2722.


1,4-Dibutyl-2-octylanthracene-9,10-dione (3c, Scheme 10). Brown solid, mp 39.5–39.8 °C, 200.0 mg, Yield 93%. $^1$H NMR (500 MHz, CDCl$_3$) δ 0.89 (t, $J$ = 7.0 Hz, 3H), 1.02 (t, $J$ = 7.0 Hz, 3H), 1.21–1.38 (m, 8H), 1.38–1.45 (m, 2H), 1.45–1.53 (m, 2H), 1.53–1.69 (m, 8H), 2.68–2.75 (m, 2H), 3.01–3.17 (m, 4H), 7.32 (s, 1H), 7.68 (t, $J$ = 7.1 Hz, 2H), 1.39–1.54 (m, 4H), 3.05–3.17 (m, 2H), 7.35 (s, 1H), 7.69 (t, $J$ = 3.8 Hz, 1H), 7.71 (t, $J$ = 4.0 Hz, 1H), 8.08–8.16 (m, 2H), $^{13}$C NMR (125 MHz, CDCl$_3$) δ 14.0, 14.1, 23.1, 23.4, 29.9, 30.3, 33.2, 33.4, 33.7, 35.6, 44.4, 126.1, 126.3, 131.5, 133.1, 133.2, 134.3, 134.4, 135.0, 138.3, 142.5, 144.0, 148.4, 185.9, 187.1, IR (KBr, cm$^{-1}$) 3460, 2964, 2925, 2856, 1668, 1595, 1540, 1461, 1324, 1288, 1262, 996, 904, 728, HRMS (EI+) m/z [M]+ calcd for C$_{30}$H$_{40}$O$_{2}$ 432.3028, found 432.3024.

Scheme 10. Characterization of 3c.

1,4-Dibutyl-2-(3-chloropropyl) anthracene-9,10-dione (3d, Scheme 11). Yellow oil, 144.4 mg, Yield 73%, $^1$H NMR (500 MHz, CDCl$_3$) δ 0.99 (t, $J$ = 7.5 Hz, 3H), 1.02 (t, $J$ = 7.0 Hz, 3H), 1.49 (sext, $J$ = 6.8 Hz, 2H), 1.53–1.70 (m, 6H), 2.05–2.14 (m, 2H), 2.92 (t, $J$ = 7.3 Hz, 2H), 3.05–3.17 (m, 4H), 3.63 (t, $J$ = 6.3 Hz, 2H), 7.35 (s, 1H), 7.69 (t, $J$ = 3.8 Hz, 1H), 7.71 (t, $J$ = 4.0 Hz, 1H), 8.08–8.16 (m, 2H), $^{13}$C NMR (125 MHz, CDCl$_3$) δ 14.0, 14.1, 23.1, 23.4, 29.9, 30.3, 33.2, 33.4, 33.7, 35.6, 44.4, 126.1, 126.3, 131.5, 133.1, 133.2, 134.1, 134.3, 134.9, 138.3, 142.6, 144.2, 146.2, 185.9, 186.9, IR (neat, cm$^{-1}$) 2956, 2934, 2860, 1669, 1595, 1541, 1456, 1392, 1331, 1287, 1251, 997, 904, 798, 727, 653, HRMS (EI+) m/z [M]+ calcd for C$_{25}$H$_{29}$O$_{2}$Cl 396.1856, found 396.1863.

Scheme 11. Characterization of 3d.

1,4-Dibutyl-2-phenylanthracene-9,10-dione (3e, Scheme 12). Yellow oil, 152.6 mg, Yield 77%, $^1$H NMR (500 MHz, CDCl$_3$) δ 0.75 (t, $J$ = 7.5 Hz, 3H), 0.97 (t, $J$ = 7.5 Hz, 3H), 1.24 (sext, $J$ = 7.1 Hz, 2H), 1.39–1.54 (m, 4H), 1.62–1.72 (m, 2H), 3.01–3.09 (m, 2H), 3.12–3.20 (m, 2H), 7.29 (d, $J$ = 7.0 Hz, 2H), 7.36 (s, 1H), 7.38–7.48 (m, 3H), 7.71 (t, $J$ = 3.8 Hz, 1H), 7.75 (t, $J$ = 3.8 Hz, 1H), 8.11–8.19 (m, 2H), $^{13}$C NMR (125 MHz, CDCl$_3$) δ 13.7, 14.0, 23.0, 23.1, 30.8, 33.2, 33.4, 35.6, 126.2, 126.4, 127.5, 128.1, 128.8, 132.4, 133.2, 133.3,
133.8, 134.3, 135.0, 138.6, 141.0, 142.6, 143.7, 149.1, 186.0, 186.7, IR (neat, cm\(^{-1}\)) 3059, 3022, 2958, 2931, 2862, 1672, 1595, 1535, 1458, 1324, 1256, 1018, 886, 723, 703, HRMS (EI+) m/z [M]+ calcd for C\(_{28}\)H\(_{26}\)O\(_2\) 396.2089, found 396.2087.

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\text{1,4-Dibutyl-2-(trimethylsilyl) anthracene-9,10-dione (3f, Scheme 13). Brown oil, 83.0 mg, Yield 42%, } \\
\text{\(^1\)H NMR (500 MHz, CDCl\(_3\)) } \delta \text{ 0.41 (s, 9H), 1.00 (t, } J = 7.3 \text{ Hz, 6H), 1.44–1.60 (m, 6H), 1.61–1.70 (m, 2H), } \\
\text{3.10–3.17 (m, 2H), 3.32 (br, 2H), 7.64 (s, 1H), 7.68–7.75 (m, 2H), 8.10–8.17 (m, 2H). } \\
\text{\(^{13}\)C NMR (125 MHz, CDCl\(_3\)) } \delta \text{ 0.7, 14.0, 14.1, 23.1, 23.5, 33.5, 34.5, 35.7, 35.8, 126.1, 126.4, 132.1, 133.1, 133.3, 133.7, 134.2, } \\
\text{135.0, 142.7, 143.8, 148.1, 150.8, 186.5, 186.9, IR (neat, cm\(^{-1}\)) 2960, 2934, 2866, 1669, 1595, 1457, 1312, } \\
\text{1287, 1255, 1103, 959, 887, 883, 841, 800, 727, 659, HRMS (EI+) m/z [M]+ calcd for C\(_{25}\)H\(_{28}\)O\(_3\) Si 392.2172, found 392.2172.}

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\text{1,4-Dibutyl-2-(hydroxynethyl) anthracene-9,10-dione (3g, Scheme 14). Yellow solid, mp 123.5–124.0 °C,} \\
\text{134.3 mg, Yield 76%, } \text{\(^1\)H NMR (500 MHz, CDCl\(_3\)) } \delta \text{ 0.98 (t, } J = 7.5 \text{ Hz, 3H), 1.01 (t, } J = 6.5 \text{ Hz, 3H), } \\
\text{1.43–1.53 (m, 2H), 1.53–1.70 (m, 6H), 1.94 (t, } J = 5.3 \text{ Hz, 1H), 3.00–3.12 (m, 2H), 3.12–3.21 (m, 2H), 4.89} \\
\text{(d, } J = 5.5 \text{ Hz, 2H), 7.66–7.74 (m, 3H), 8.08–8.15 (m, 2H). } \\
\text{\(^{13}\)C NMR (125 MHz, CDCl\(_3\)) } \delta \text{ 13.96, 14.05, } \\
\text{23.1, 23.4, 29.5, 32.7, 33.4, 35.8, 62.3, 126.2, 126.4, 132.1, 133.2, 133.3, 133.5, 134.3, 134.9, 135.5, 141.9, } \\
\text{144.6, 145.1, 185.9, 186.7, IR (KBr, cm\(^{-1}\)) 3371, 3320, 2956, 2927, 2859, 1666, 1591, 1469, 1319, 1287, 1259, } \\
\text{1046, 981, 907, 730, HRMS (EI+) m/z [M]+ calcd for C\(_{25}\)H\(_{28}\)O\(_3\) 350.1882, found 350.1882.}

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\text{1,4-Dibutyl-2-(1-hydroxyethyl) anthracene-9,10-dione (3h, Scheme 15). Brown oil, 156.4 mg, Yield 85%,} \\
\text{\(^1\)H NMR (500 MHz, CDCl\(_3\)) } \delta \text{ 0.98 (t, } J = 7.0 \text{ Hz, 3H), 1.01 (t, } J = 7.3 \text{ Hz, 3H), 1.42–1.60 (m, 8H), 1.60–1.71} \\
\text{(m, 3H), 2.00 (s, 1H), 2.78–2.92 (m, 1H), 3.16 (t, } J = 8.0 \text{ Hz, 2H), 3.20–3.31 (m, 1H), 5.35 (q, } J = 5.8 \text{ Hz,} \\
\text{1H), 7.69 (t, } J = 3.5 \text{ Hz, 1H), 7.70 (t, } J = 3.8 \text{ Hz, 1H), 7.80 (s, 1H), 8.06–8.13 (m, 2H). } \\
\text{\(^{13}\)C NMR (125 MHz, CDCl\(_3\)) } \delta \text{ 13.96, 14.05, 23.1, 23.4, 25.3, 29.2, 33.4, 33.5, 35.9, 65.7, 126.1, 126.3, 132.1, 133.17, 133.24,}
133.8, 134.0, 134.2, 135.0, 140.4, 144.8, 150.6, 185.9, 186.9, IR (neat, cm\(^{-1}\)) 3453, 3073, 2957, 2862, 1672, 1594, 1542, 1462, 1291, 1123, 1062, 908, 759, 727, HRMS (EI\(^+\)) m/z [M]\(^+\) calcd for C\(_{24}\)H\(_{28}\)O\(_3\) 364.2038, found 364.2044.

**Scheme 15.** Characterization of 3h.

1,4-Dibutyl-2-(2-hydroxypropan-2-yl) anthracene-9,10-dione (3i, Scheme 16). Brown solid, mp 77.5–82.2 °C, 140.3 mg, Yield 75%, \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 0.96 (t, \(J = 7.3\) Hz, 3H), 0.98 (t, \(J = 7.5\) Hz, 3H), 1.39–1.59 (m, 6H), 1.59–1.68 (m, 2H), 1.75 (s, 6H), 1.94 (s, 1H), 3.08–3.16 (m, 2H), 3.54 (br, 2H), 7.66–7.73 (m, 2H), 7.75 (s, 1H), 8.02–8.09 (m, 2H); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 13.9, 14.0, 23.1, 23.6, 30.3, 31.9, 33.6, 35.4, 36.0, 74.0, 125.9, 126.3, 132.4, 133.0, 133.3, 134.1, 134.2, 135.5, 135.6, 143.6, 143.7, 151.8, 186.0, 187.8, IR (KBr, cm\(^{-1}\)) 3372, 2956, 2931, 2872, 1666, 1592, 1462, 1316, 1291, 1142, 728, HRMS (EI\(^+\)) m/z [M]\(^+\) calcd for C\(_{25}\)H\(_{30}\)O\(_3\) 378.2196, found 378.2195.

**Scheme 16.** Characterization of 3i.

1,4-Dibutyl-2,3-diethylanthracene-9,10-dione (3j, Scheme 17). Yellow oil, 134.6 mg, Yield 72%, \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 1.02 (t, \(J = 7.3\) Hz, 6H), 1.22 (t, \(J = 7.3\) Hz, 6H), 1.50–1.69 (m, 8H), 2.82 (q, \(J = 7.5\) Hz, 4H), 3.11 (br, 4H), 7.63–7.69 (m, 2H), 8.02–8.09 (m, 2H); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 14.0, 15.3, 22.5, 23.5, 30.1, 33.6, 125.9, 132.2, 132.8, 135.1, 142.4, 147.9, 187.3, IR (neat, cm\(^{-1}\)) 3156, 3065, 2961, 2934, 2870, 1669, 1595, 1536, 1458, 1401, 1377, 1328, 1287, 1265, 1102, 1055, 907, 797, 730, HRMS (EI\(^+\)) m/z [M]\(^+\) calcd for C\(_{26}\)H\(_{32}\)O\(_2\) 376.2401, found 376.2401.

**Scheme 17.** Characterization of 3j.

1,4-Dibutyl-2,3-bis(methoxymethyl)anthracene-9,10-dione (3k, Scheme 18). Yellow solid, mp 86.2–86.5 °C, 167.5 mg, Yield 82%, \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 1.03 (t, \(J = 7.3\) Hz, 6H), 1.53–1.70 (m, 8H), 3.18 (br, 4H), 3.52 (s, 6H), 4.58 (s, 4H), 7.65–7.72 (m, 2H), 8.03–8.10 (m, 2H); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 14.0, 23.5, 30.1, 33.7, 59.0, 67.8, 126.1, 133.1, 134.1, 134.9, 142.6, 144.1, 186.8, IR (KBr, cm\(^{-1}\)) 2953, 2927, 2870, 2807, 1670, 1593, 1462, 1320, 1288, 1191, 1097, 947, HRMS (EI\(^+\)) m/z [M]\(^+\) calcd for C\(_{26}\)H\(_{32}\)O\(_4\) 408.2301, found 408.2300.
3.6. Procedure for the Reaction of Diyne 4 with Alkyne 2j

To a solution of [Ir(cod)Cl]2 (6.7 mg, 0.010 mmol) and F-DPPE (15.2 mg, 0.0200 mmol) in DCM (1.0 mL), 3-hexyne (125.9 mg, 1.530 mmol) and a solution of diyne (133.5 mg, 0.5012 mmol) in DCM (1.5 mL) were added. The mixture was stirred under reflux for 24 h. After removal of the solvent on a rotary evaporator, the residue was subjected to column chromatography (silica gel, hexane/EtOAc = 99.5/0.5) to give compound 1,4-dibutyl-2,3-diethyl-9H-fluoren-9-one (5j) (164.1 mg, 0.4708 mmol, 94% yield, Scheme 20).

Scheme 20. Synthetic procedure for 5j.

1,4-Dibutyl-2,3-diethyl-9H-fluoren-9-one (5j, Scheme 21). Yellow oil, 164.1 mg, Yield 94%. 1H NMR (500 MHz, CDCl3) δ 0.99 (t, J = 7.0 Hz, 3H), 1.03 (t, J = 7.3 Hz, 3H), 1.18 (t, J = 7.8 Hz, 3H), 1.21 (t, J = 7.5 Hz, 3H), 1.45–1.66 (m, 8H), 2.67 (q, J = 7.5 Hz, 2H), 2.71 (q, J = 7.5 Hz, 2H), 2.84–2.92 (m, 2H), 3.00–3.14 (m, 2H), 7.22 (t, J = 7.0 Hz, 1H), 7.43 (td, J = 7.5, 1.0 Hz, 1H), 7.54 (d, J = 8.0 Hz, 1H), 7.61 (d, J = 7.0 Hz, 1H), 13C NMR (125 MHz, CDCl3) δ 14.0, 15.5, 15.6, 21.4, 22.3, 23.3, 23.5, 27.3, 29.1, 32.2, 33.3, 122.8, 123.5, 127.7, 129.3, 134.1, 135.4, 135.5, 140.7, 141.5, 142.2, 144.3, 147.8, 195.1, IR (neat, cm\(^{-1}\)) 2963, 2876, 1704, 1606, 1564, 1464, 1261, 1098, 1058, 1026, 800, HRMS (EI\(^+\)) m/z [M]+ calcd for C\(_{25}\)H\(_{32}\)O\(_3\) 348.2453, found 348.2453.
4. Conclusions

In summary, we have developed an efficient and convenient method for the synthesis of anthraquinones ranging from a 42% yield to a 93% yield through an iridium/dppe complex-catalyzed [2 + 2 + 2] cycloaddition of a 1,2-bis(propioly)benzene derivative with a broad range of terminal and internal alkynes. The use of dichloromethane as a solvent is important for the success of [2 + 2 + 2] cyclization with internal alkynes to lead to the desired anthraquinones in 72–86% yields. Furthermore, the synthesis of the fluorenone was also achieved by [2 + 2 + 2] cyclization with the iridium/dppe catalytic system to give a 94% yield.

**Author Contributions:** Conceptualization, R.T. Methodology, Y.T. Investigation, Y.T. and T.S. Writing-Original Draft Preparation, T.S. Writing-Review & Editing, T.S. and R.T. Visualization, T.S. Supervision, R.T. Project Administration, R.T. Funding Acquisition, R.T.

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