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Palladium-Catalyzed Direct Acylation: One-Pot Relay Synthesis of Anthraquinones

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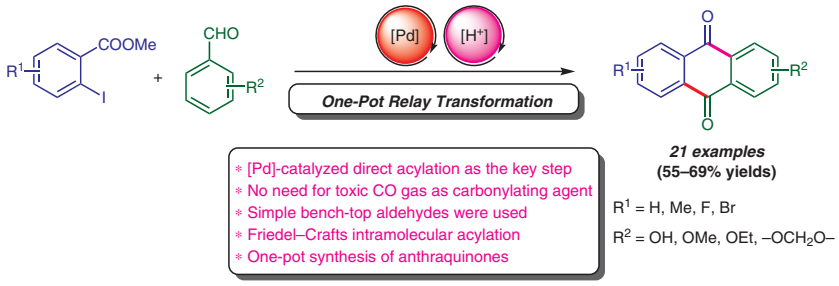

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Abstract A bis-acylation strategy to access functionalized anthraquinones via one-pot relay process, is presented. The first acylation was feasible under [Pd]-catalyzed intermolecular direct acylation reaction, while, the second acylation was accomplished by using intramolecular Friedel–Crafts acylation. Notably, benchtop aldehydes have been utilized as non-toxic acylation agents in the key [Pd]-catalyzed acylation.

Key words anthraquinone, catalysis, acylation, one-pot, Friedel–Crafts acylation

Anthraquinones are essential chemical compounds and are prominent in pharmaceutical and materials chemistry.[1] A wide range of natural products constitute anthraquinone structural motif, manifesting interesting biological features.[2] These anthraquinone-based natural products are significant constituents in lichens, bacteria, fungi, enzymes, and higher plants. Also, anthraquinones are present in vitamins, pigments, etc.[3] They exhibit anticancer, antitumor, antineoplastic, antibacterial, anti-HIV, and antitrypanosomal activities.[4] For example, mitoxantrone (**5**), ametantrone (**6**), and doxorubicin (**7**) exhibit potent antitumor activities and have been utilized in medical care as powerful anticancer agents for the treatment of various leukemia and lymphomas (Figure 1).[5] Moreover, anthraquinone derivatives are industrially utilized as versatile dyeing agents for coloring synthetic and natural fibers, such as wool, silk, cotton, polyester, and polyamide.[6] In addition, these compounds have outstanding photo-oxidant properties, enabling them to absorb UV-A radiation. Further, anthraquinones are capable of cleaving protein molecules upon photoirradiation.[7] Anthraquinone derivatives also serve as useful precursors for the synthesis of organic semiconductors and electronic devices.[8]

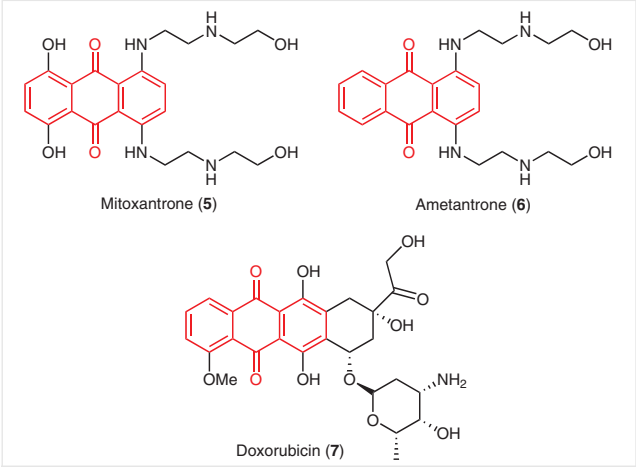


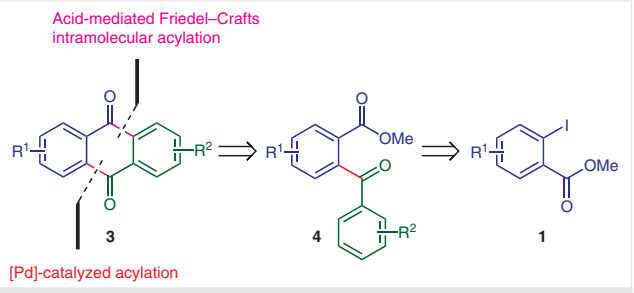
Figure 1 Representative examples of bioactive anthraquinones

The anthraquinones have been the target of synthetic chemists to accomplish various chemical strategies.[9,10] As a result, numerous synthetic routes as well as their industrial applications have been exclusively examined. Anthraquinones are extensively synthesized on the industrial level as dye reagents. The diverse scope for anthraquinone derivatives includes Friedel–Crafts acylation reaction of phthalic anhydride with various substituted arenes,[9a] oxidation of anthracenes or hydroxyanthracenes,[9h] reaction of isobenzofuran and chromium carbenes,[9e] Lewis acid catalyzed or thermal Diels–Alder reactions and aromatization sequences,[9b,g,i] Diels–Alder reaction catalyzed by zinc iodide followed by Friedel–Crafts reaction,[9j] cyclization reactions of polyketides,[9c,d] and copper-catalyzed intramolecular enyne cyclization.[9f] The cyclization reaction between reduced 1,4-naphthoquinone and *ortho*-phthalaldehyde,[10b] and intramolecular dehydro Diels–Alder approach[10a] also belong to further routes towards anthraquinones. Apart from these

advantages, most of these synthetic routes display a number of limitations, such as multiple reaction steps and the use of expensive catalysts.

Therefore, still, there is a room to develop simple, mild, and efficient strategies, which enable the synthesis of a range of anthraquinone derivatives. In this regard, we felt that sequential one-pot transformation would serve as an ideal protocol. Sequential one-pot methods render the construction of more than one bond and yield the products with reasonable complexity. Also, in comparison to stepwise methods, such protocols could contribute to some extent in saving time and reducing the amount of waste generated. Furthermore, these processes cut down the mundane task of isolating and purifying the intermediate product(s). In particular, transition-metal-catalyzed coupling reactions are very significant in the construction of carbon–carbon and carbon–heteroatom bonds.[11] Therefore, we presumed that the synthesis of anthraquinones can be executed by means of a one-pot method, through transition-metal-catalyzed acylation and intramolecular Friedel–Crafts acylation. In this context, we have established direct acylation using benchtop aldehydes as non-toxic acylating agents, under palladium catalysis.[12] Unlike earlier reports, the present protocol deals with [Pd]-catalyzed direct coupling (acylation) of iodoarenes with unactivated aldehydes.[13a,e] Based on this concept of direct acylation, recently, we have demonstrated one-pot formation of indenones, lactams, and phthalzines.[13] Inspired by these results, herein, we describe an efficient sequential one-pot protocol, for the synthesis of various anthraquinones starting from commercially available *ortho*-iodobenzoates and aldehydes.

We intended that anthraquinones **3** could be achieved from *ortho*-keto esters **4** by employing intramolecular Friedel–Crafts acylation. The required *ortho*-keto esters **4** would be accomplished from *ortho*-iodomethylbenzoates **1** via [Pd]-catalyzed acylations as shown in Scheme 1.



Scheme 1 Anticipated retrosynthetic route of anthraquinones **3**

In order to evaluate our protocol for the preparation of anthraquinones, we initiated the synthetic investigations by choosing methyl 2-iodobenzoate (**1a**) and aldehyde **2a** as the model substrates. It has already been established that TBHP (*tert*-butyl hydroperoxide) in decane is as effective as TBHP in H_2O for carrying out acylation reaction in the presence of [Pd]-catalyst.[13a] Therefore, it was anticipated that the desired second reaction step (intramolecular Friedel–Crafts acylation) may be feasible in decane as inert solvent and would avoid the aid of any other solvent. Thus, the acylation reaction was carried out by subjecting *ortho*-iodoester **1a** with aldehyde **2a** using our previously reported conditions [i.e., $Pd(OAc)_2$ (5 mol%), Ag_2O (1.2 equiv), TBHP in decane (5 equiv), 120 °C, 14 h].[13a] After confirming the formation of acylation product **4aa** by TLC, the subsequent acid-mediated Friedel–Crafts type cyclization was explored under various conditions (Table 1). Thus, the reaction mixture containing **4aa** was reacted with concentrated H_2SO_4 (10.0 equiv) at room temperature for 3 hours. Unfortunately, no progress was observed and only the acylated product **4aa** was isolated in 67% yield (Table 1, entry 1). Addition of DCE as second solvent along with the acid to the reaction mixture of **4aa** did not show any progress (entry 2). Even $AlCl_3$ and TfOH could not promote the reaction, respectively (entries 3, 4). On the other hand, acylation reaction was performed in TBHP/H_2O and subsequently, the acylated product **4aa**, was treated with concentrated H_2SO_4 at room temperature for 5 hours (entry 5). This attempt was also futile to furnish the product **3aa**. Gratifyingly, trace amounts of anthraquinone **3aa** and more amounts of transesterification products were observed when the cyclization was conducted in EtOH as solvent at 65 °C for 10 hours (entry 6). Formation of transesterification product could be attributed to the nucleophilic nature of EtOH. This preliminary progress encouraged us to search for more efficient conditions for this transformation. With the increased amount of acid and at slightly elevated temperature (75 °C) for 12 hours, the product **3aa** was formed in 10% yield (entry 7). Replacing EtOH with non-nucleophilic and inert solvent (DCE) and with increased amount of concentrated H_2SO_4 (0.5 mL) at 60 °C for 3 hours, afforded the desired anthraquinone product **3aa** in 55% yield (entry 8). Interestingly, further increasing the amount of acid, from 0.5 mL to 1.0 mL, increased the overall yield of the product **3aa** to 62% (entry 9). However, no progress was observed when the reaction was conducted at room temperature (entry 10), while further increasing the amount of acid decreased the product **3aa** yield to 46% (entry 11). This might be due to decomposition of product **3aa** with excess amount of strong acid. Acylation in TBHP/decane and subsequent acid-mediated cyclization without additional solvent at 60 °C for 2 hours, gave **3aa** in 42% yield (entry 12). On the other hand, by the addition of solvent DCE for the cyclization step, the product **3aa** was accomplished in 50% yield (entry 13).

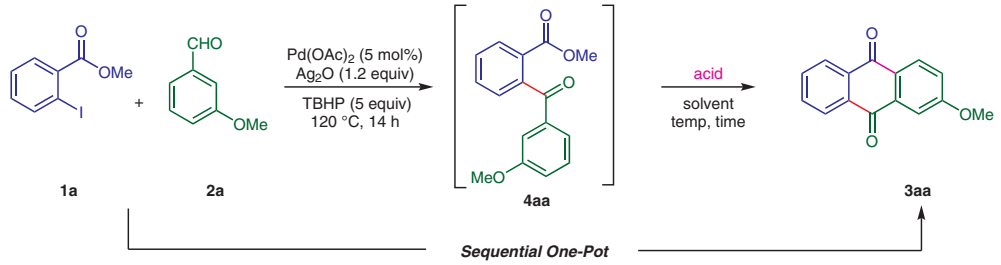
With the above optimized conditions (Table 1, entry 9), next, it was sought to investigate the scope of the method by exploring the reaction between methyl 2-iodobenzoate (**1a**) and other benzaldehydes **2**. Gratifyingly, the process was feasible and furnished the desired anthraquinone products **3aa–ak** (Scheme 2). The reaction was smooth with

electron-releasing substituents on the aromatic ring of benzaldehydes **2a–d**, **2j**, and **2k** (OMe, OEt, and -OCH_2O-). Remarkably, the protocol was also compatible with benzaldehydes **2f–i** possessing free hydroxyl group (Scheme 2, **3af–ai**). Significantly, the efficiency of the reaction was not impeded by *ortho*-substituents on the benzaldehyde moiety **2h** (**3ah**). Notably, the reaction was also competent with highly electron-rich benzaldehyde **2k** (i.e., trimethoxybenzaldehyde **3ak**). However, it is worth noticing that in the case of *para*-methoxybenzaldehyde (**2l**), the expected product **3al** was not formed. No progress of the desired cyclized product formation was observed even after 10 hours, however, with excess amount of concentrated H_2SO_4 (3.0 mL), complete decomposition of the reaction mixture took place. This may be attributed to the fact that the electron-releasing methoxy group is in *meta* relation to the reacting carbon of that aromatic ring and hence, could not promote the second acylation step. Notably, this observation is in good agreement to that of earlier report published by Hilt et al.[9j]

Furthermore, to demonstrate the applicability of the present protocol, next, we turned our attention to check the scope of the method by means of iodoester precursors **1**. Therefore, the reaction was performed between various methyl 2-iodobenzoates **1b–d** and benzaldehydes **2a–j**. Gratifyingly, the reaction was also found suitable and furnished the products **3ba–da** (Scheme 3). As anticipated, the reaction was successful with methyl substituted *ortho*-iodoester **1b** with benzaldehydes **2a–j** (Scheme 3, **3ba–bj**). To our delight, this protocol was also found smooth to methyl 2-iodobenzoates **1c** and **1d** bearing electron-deactivating F and Br functional groups (Scheme 3, **3ca–da**). Notably, anthraquinones **3ca–ci** with bromo-substituent are of particular importance, as they can be further derivatized by means transition-metal-catalyzed coupling reactions.

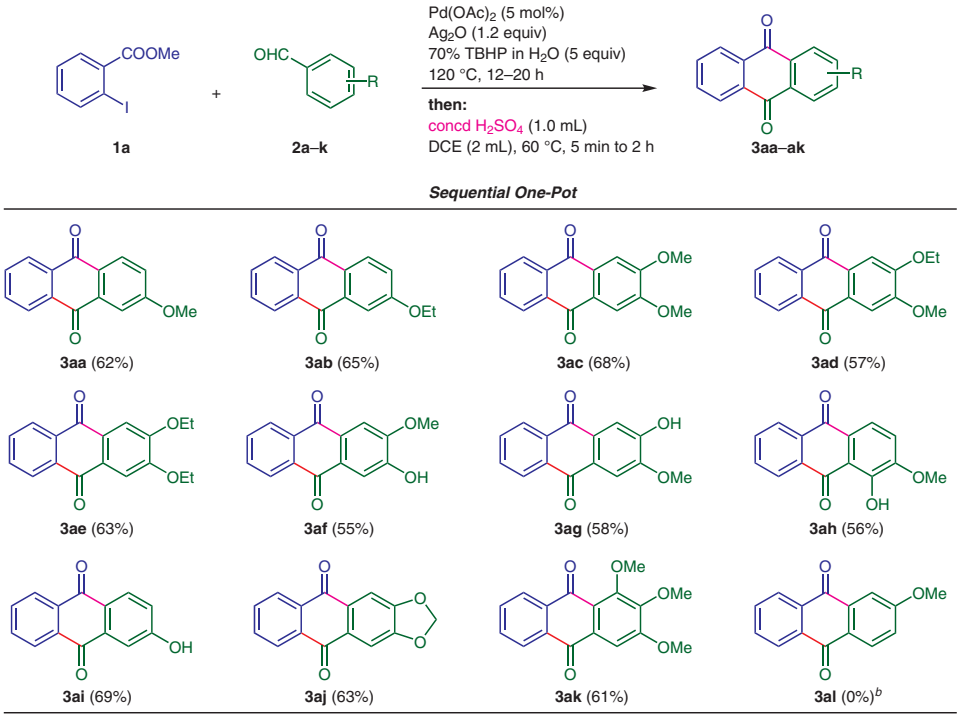
In conclusion, a sequential one-pot relay process has been developed for the synthesis of diverse anthraquinones. The overall process involves a sequential dual acylation via [Pd]-catalyzed intermolecular acylation and acid mediated intramolecular Friedel–Crafts acylation. The key

Table 1 Screening Conditions for One-Pot Synthesis of Anthraquinone **3aa** via the Keto Ester **4aa**[a]

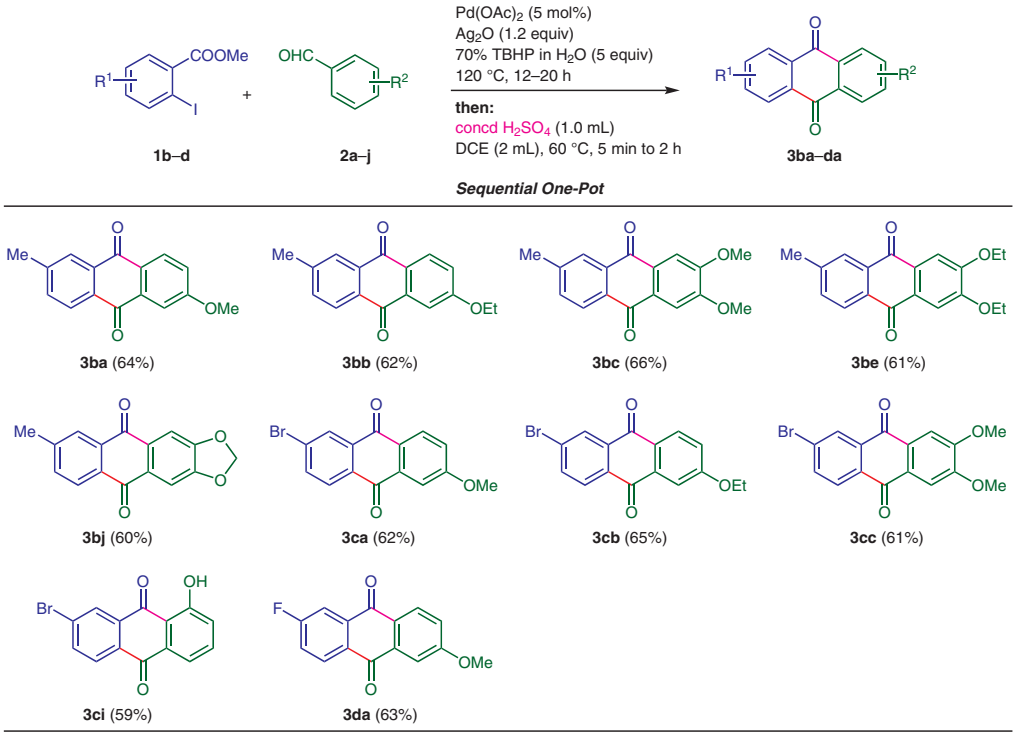


Entry	TBHP (5 equiv)	Acid (equiv or mL)	Solvent (2.0 mL)	Temp (°C)	Time (h)	Yield (%)[b] **3aa**	Yield (%)[b] **4aa**
1	TBHP/decane	H_2SO_4 (10.0)	–[c]	r.t.	3	–[d]	67
2	TBHP/decane	H_2SO_4 (10.0)	DCE	r.t.	3	–[d]	65
3	TBHP/decane	$AlCl_3$ (5.0)	DCE	r.t.	5	–[d]	62
4	TBHP/decane	TfOH (10.0)	DCE	r.t.	3	–[d]	60
5	TBHP/H_2O	H_2SO_4 (10.0)		r.t.	5	–[d]	65
6	TBHP/H_2O	H_2SO_4 (10.0)	EtOH	65	6	trace (**3aa**) + transesterification	–[e]
7	TBHP/H_2O	H_2SO_4 (0.5 mL)	EtOH	75	12	10% (**3aa**) + transesterification	–[e]
8	TBHP/H_2O	H_2SO_4 (0.5 mL)	DCE	60	3	55	–[e]
9	**TBHP/H_2O**	**H_2SO_4 (1.0 mL)**	**DCE**	**60**	**2**	**62**	–[e]
10	TBHP/H_2O	H_2SO_4 (1.0 mL)	DCE	r.t.	5	–[d]	55
11	TBHP/H_2O	H_2SO_4 (2.0 mL)	DCE	60	1.5	46	–[e]
12	TBHP/decane	H_2SO_4 (1.0 mL)	–[c]	60	2	42	–[e]
13	TBHP/decane	H_2SO_4 (1.0 mL)	DCE	60	2	50	–[e]

[a] Reaction was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2a** (217.0 mg, 1.6 mmol).
[b] Chromatographically isolated yields of pure compounds.
[c] No second solvent was used.
[d] No **3aa** was formed.
[e] No **4aa** remained.



Scheme 2 Scope of the method for one-pot synthesis of anthraquinone **3aa–ak**. Isolated yields of chromatographically pure products **3aa–ak** are given. Product **3ai** was not formed.



Scheme 3 Scope of one-pot synthesis of anthraquinone **3ba–da**. Isolated yields of chromatographically pure products **3ba–da** are given.

reaction of the coupling was [Pd]-catalyzed direct acylation between *ortho*-iodoesters and aromatic aldehydes. Simple bench-top benzaldehydes served as nontoxic acylating surrogates.

IR spectra were recorded on a FTIR spectrophotometer. ^{1}H NMR spectra were recorded on 400 MHz spectrometer at 295 K in $CDCl_3$; chemical shifts (δ ppm) and coupling constants (Hz) are reported in standard fashion with reference to either internal standard TMS (δ_H = 0.00) or $CHCl_3$ (δ_H = 7.25). ^{13}C NMR spectra were recorded on 100 MHz spectrometer at r.t. in $CDCl_3$; chemical shifts (δ ppm) are reported relative to $CHCl_3$ [δ_C = 77.00 (central line of triplet)]. In the ^{13}C NMR spectra, the nature of carbons (C, CH, CH_2, and CH_3) was determined by recording the DEPT-135 spectra. In the ^{1}H NMR, standard abbreviations were used throughout to denote the multiplicity of the signals. High-resolution mass spectra (HRMS) were recorded on Q-TOF electron spray ionization (ESI) mode and atmospheric pressure chemical ionization (APCI) modes. Melting points were determined on an electrothermal melting point apparatus and are uncorrected.

All small scale reactions were carried out using Schlenk tube. Reactions were monitored by TLC on silica gel using a combination of hexane and EtOAc as eluents. Reactions were generally run under argon or N_2 atmosphere. Solvents were distilled prior to use; petroleum ether (PE) with a boiling range of 60–80 °C was used. Acme's silica gel (60–120 mesh) was used for column chromatography (approximately 20 g per one gram of crude material).

Aldehydes **2a–k** and *ortho*-iodoesters **1a–d** are commercially available.

Anthraquinones 3; General Procedure

This kind of general experimental procedure is based on our already published procedure.[13]

The general procedure (GP) was carried out with *ortho*-iodoester **1a–d** (105.0–136.0 mg, 0.40 mmol) and aldehyde **2a–k** (195.0–313.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) allowing the reaction mixture to stir at 120 °C for 12–20 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a–d** had completely reacted. Then the reaction mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 5 min to 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the products **3** (57.0–86.0 mg, 55–69%). The products **3aa**, **3ac**, **3ai**, **3aj**, **3ak**, **3ba**, **3bc**, **3be**, and **3bj** are reported in the literature.[9]

2-Methoxyanthracene-9,10-dione (3aa)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2a** (217.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol %), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the reaction mixture was removed from the oil bath and allowed to reach r.t.. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3aa**; yield: 59.0 mg (62%); yellow solid, m.p. 194–196 °C; R_f (**1a**) = 1.0, R_f (**3aa**) = 0.30 (PE/EtOAc 95:05), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ =8.32–8.20 (m, 3 H, ArH), 7.84–7.72 (m, 2 H, ArH), 7.69 (d, *J* = 2.4 Hz, 1 H, ArH), 7.24 (dd, *J* = 8.8, 2.4 Hz, 1 H, ArH), 3.97 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ =183.2 (s, C=O), 182.1 (s, C=O), 164.3 (s, ArC), 135.6 (s, ArC), 134.1 (d, ArCH), 133.6 (s, ArC), 133.6 (d, ArCH), 133.5 (s, ArC), 129.7 (d, ArCH), 127.0 (s, ArC), 127.1 (d, 2 C, ArCH), 121.1 (d, ArCH), 109.9 (d, ArCH), 55.9 (q, CH_3).

2-Ethoxyanthracene-9,10-dione (3ab)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2b** (240.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 12 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the reaction mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 1.5 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ab**; yield: 66.0 mg (65%); orange viscous liquid; R_f (**1a**) = 1.0, R_f (**3ab**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3071, 2941, 1712, 1683, 1611, 1465, 1287, 1099, 1006, 926, 705 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.26–8.22 (m, 3 H, ArH), 8.20 (d, *J* = 8.8 Hz, 1 H, ArH), 7.75–7.22 (m, 2 H, ArH), 7.20 (dd, *J* = 8.5, 2.6 Hz, 1 H, ArH), 4.18 (q, *J* = 6.8 Hz, 2 H), 1.46 (t, *J* = 6.8 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ =183.2 (s, C=O), 182.1 (s, C=O), 163.7 (s, ArC), 135.5 (s, ArC), 134.1 (d, ArCH), 133.6 (s, ArC), 133.6 (d, ArCH), 133.5 (s, ArC), 129.7 (d, ArCH), 127.0 (d, 2 C, ArCH), 126.8 (s, ArC), 121.4 (d, ArCH), 110.4 (d, ArCH), 64.3 (t, CH_2), 14.6 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{16}H_{13}O_3]^+$: 253.0859; found: 253.0859.

2,3-Dimethoxyanthracene-9,10-dione (3ac)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2c** (265.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered.

Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ac**; yield: 73.0 mg (68%); orange solid, m.p. 230–233 °; R_f (**1a**) = 1.0, R_f (**3ac**) = 0.40 (PE/EtOAc 85:15), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.25 (dd, *J* = 5.8, 3.4 Hz, 2 H, ArH), 7.75 (dd, *J* = 5.8, 3.4 Hz, 2 H, ArH), 7.79 (s, 2 H, ArH), 4.05 (s, 6 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.5 (s, 2 C, C=O), 153.8 (s, 2 C, ArC), 133.7 (d, 2 C, ArCH), 133.5 (s, 2 C, ArC), 128.4 (s, 2 C, ArC), 127.0 (d, 2 C, ArCH), 108.3 (d, 2 C, ArCH), 56.5 (q, 2 C, CH_3).

2-Ethoxy-3-methoxyanthracene-9,10-dione (3ad)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2d** (288.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 18 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ad**; yield: 64.0 mg (57%); yellow solid, m.p. 242–245 °C; R_f (**1a**) = 1.0, R_f (**3ad**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3074, 1704, 1680, 1635, 1620, 1590, 1570, 1504, 1475, 1363, 1301, 1257, 1160, 963, 843 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.27–8.24 (m, 2 H, ArH), 7.74 (dd, *J* = 5.8, 3.4 Hz, 2 H, ArH), 7.70 (d, *J* = 5.8 Hz, 2 H, ArH), 4.30 (q, *J* = 7.0 Hz, 2 H), 4.05 (s, 3 H), 1.54 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.6 (s, C=O), 182.5 (s, C=O), 154.0 (s, ArC), 153.3 (s, ArC), 133.7 (d, 2 C, ArCH), 133.6 (s, 2 C, ArC), 128.4 (s, ArC), 128.2 (s, ArC), 127.0 (d, 2 C, ArCH), 109.1 (d, ArCH), 108.5 (d, ArCH), 65.0 (t, CH_2), 56.5 (q, CH_3) 14.5 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{17}H_{15}O_4]^+$: 283.0965; found: 283.0964.

2,3-Diethoxyanthracene-9,10-dione (3ae)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2e** (310.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ae**; yield: 75.0 mg (63%); yellow solid, m.p. 247–248 °C; R_f (**1a**) = 1.0, R_f (**3ae**) = 0.30 (PE/EtOAc 85:15), UV detection.

IR (MIR-ATR): 3062, 1710, 1682, 1639, 1622, 1591, 1582, 1500, 1471, 1367, 1311, 1253, 1170, 903, 743 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.24 (dd, *J* = 5.8, 3.4 Hz, 2 H, ArH), 7.73 (dd, *J* = 5.8, 3.4 Hz, 2 H, ArH), 7.70 (s, 2 H, ArH), 4.29 (q, *J* = 6.8 Hz, 4 H), 1.53 (t, *J* = 6.8 Hz, 6 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.6 (s, 2 C, C=O), 153.4 (s, 2 C, ArC), 133.7 (d, 2 C, ArCH), 133.6 (d, 2 C, ArCH), 128.2 (s, 2 C, ArC), 126.9 (d, 2 C, ArCH), 109.3 (d, 2 C, ArCH), 65.0 (t, 2 C, CH_2), 14.5 (q, 2 C, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{18}H_{17}O_4]^+$: 297.1121; found: 297.1125.

2-Hydroxy-3-methoxyanthracene-9,10-dione (3af)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2f** (243.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 20 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 5 min. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3af**; yield: 56.0 mg (55%); red solid, m.p. 252–254 °C; R_f (**1a**) = 1.0, R_f (**3af**) = 0.30 (PE/EtOAc 80:20), UV detection.

IR (MIR-ATR): 3065, 1710, 1682, 1631, 1627, 1587, 1560, 1501, 1476, 1392, 1343, 1311, 1282, 1236, 1152, 943, 812 cm^{-1}.

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 10.76 (s, 1 H, Ar–O*H*), 8.15–8.10 (m, 2 H, ArH), 7.86–7.84 (m, 2 H, ArH), 7.59 (s, 1 H, ArH), 7.52 (s, 1 H, ArH), 3.96 (s, 3 H).

^{13}C NMR (DMSO-d_6, 100 MHz): δ = 181.8 (s, C=O), 181.4 (s, C=O), 152.8 (s, ArC), 152.5 (s, ArC), 134.1 (d, ArCH), 134.0 (d, ArCH), 133.1 (s, ArC), 133.0 (s, ArC), 128.0 (s, ArC), 126.5 (s, ArC), 126.5 (d, ArCH), 126.4 (d, ArCH), 112.4 (d, ArCH), 108.8 (d, ArCH), 56.0 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{11}O_4]^+$: 255.0652; found: 255.0648.

2-Hydroxy-3-methoxyanthracene-9,10-dione (3ag)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2g** (243.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 19 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 10 min. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ag**; yield: 59.0 mg (58%); red solid, m.p. 252–254 °C; R_f (**1a**) = 1.0, R_f (**3ag**) = 0.30 (PE/EtOAc 80:20), UV detection.

This product is identical with the product **3af** obtained from **1a** and **2f**.

IR (MIR-ATR): 3070, 1701, 1688, 1642, 1619, 1583, 15750, 1507, 1415, 1358, 1311, 1248, 1205, 918, 803 cm^{-1}.

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 10.76 (s, 1 H, Ar–O*H*), 8.15–8.10 (m, 2 H, ArH), 7.86–7.84 (m, 2 H, ArH), 7.59 (s, 1 H, ArH), 7.52 (s, 1 H, ArH), 3.96 (s, 3 H).

^{13}C NMR (DMSO-d_6, 100 MHz): δ = 181.8 (s, C=O), 181,4 (s, C=O), 152.8 (s, ArC), 152.5 (s, ArC), 134.1 (d, ArCH), 134.0 (d, ArCH), 133.1 (s, ArC), 133.0 (s, ArC), 128.0 (s, ArC), 126.5 (s, ArC), 126.5 (d, ArCH), 126.4 (d, ArCH), 112.4 (d, ArCH), 108.8 (d, ArCH), 56.0 (q, CH_3).

HR-MS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{11}O_4]^+$: 255.0652; found: 255.0648.

1-Hydroxy-2-methoxyanthracene-9,10-dione (3ah)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2h** (243.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 18 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 20 min. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ah**; yield: 57.0 mg (56%); red solid, m.p. 238–242 °C; R_f (**1a**) = 1.0, R_f (**3ah**) = 0.60 (PE/EtOAc 80:20), UV detection.

IR (MIR-ATR): 3070, 1701, 1688, 1642, 1619, 1583, 15750, 1507, 1415, 1358, 1311, 1248, 1205, 918, 803 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 13.03 (s, 1 H, Ar–O*H*), 8.31–8.26 (m, 2 H, ArH), 7.86 (d, *J* = 8.8 Hz, 1 H, ArH), 7.80–7.77 (m, 2 H, ArH), 7.17 (d, *J* = 8.3 Hz, 1 H, ArH), 4.01 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 189.2 (s, C=O), 181.5 (s, C=O), 154.0 (s, ArC), 152.8 (s, ArC), 134.8 (d, ArCH), 134.1 (s, ArC), 133.8 (d, ArCH), 133.3 (s, ArC), 127.4 (d, ArCH), 126.9 (d, ArCH), 125.3 (s, ArC), 121.1 (d, ArCH), 116.1 (s, ArC), 115.8 (d, ArCH), 56.4 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{11}O_4]^+$: 255.0652; found: 255.0639.

2-Hydroxyanthracene-9,10-dione (3ai)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2i** (195.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ai**; yield: 62.0 mg (69%); red solid, m.p. 306–308 °C; R_f (**1a**) = 1.0, R_f (**3ai**) = 0.30 (PE/EtOAc 75:25), UV detection.

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 11.03 (br s, 1 H, Ar–O*H*), 8.17–8.14 (m, 2 H, ArH), 8.08 (d, *J* = 8.8 Hz, 1 H, ArH), 7.90–7.86 (m, 2 H, ArH), 7.49 (d, *J* = 2.9 Hz, 1 H, ArH), 7.24 (dd, *J* = 8.8, 2.9 Hz, 1 H, ArH).

^{13}C NMR (DMSO-d_6, 100 MHz): δ = 182.7 (s, C=O), 181.2 (s, C=O), 163.1 (s, ArC), 135.2 (s, ArC), 134.6 (d, ArCH), 134.0 (d, ArCH), 133.2 (s, ArC), 133.1 (s, ArC), 129.9 (d, ArCH), 126.7 (d, ArCH), 126.6 (d, ArCH), 125.2 (s, ArC), 121.6 (d, ArCH), 112.2 (d, ArCH).

Anthra[2,3-*d*][1,3]dioxole-5,10-dione (3aj)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2j** (240.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 17 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 1.5 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3aj**; yield: 64.0 mg (63%); yellow viscous liquid; R_f (**1a**) = 1.0, R_f (**3aj**) = 0.30 (PE/EtOAc 90:10), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.32–8.20 (m, 2 H, ArH), 7.80–7.50 (m, 2 H, Ar–H), 7.66 (s, 2 H, ArH), 6.15 (s, 2 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.0 (s, 2 C, C=O), 152.6 (s, 2 C, ArC), 133.8 (d, 2 C, ArCH), 133.3 (s, 2 C, ArC), 130.8 (s, 2 C, ArC), 127.1 (d, 2 C, ArCH), 106.4 (d, 2 C, ArCH), 102.6 (t, CH_2).

1,2,3-Trimethoxyanthracene-9,10-dione (3ak)

GP was carried out with *ortho*-iodoester **1a** (105.0 mg, 0.40 mmol) and aldehyde **2k** (313.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ak**; yield: 73.0 mg (61%); red solid, m.p. 165–167 °C; R_f (**1a**) = 1.0, R_f (**3ak**) = 0.30 (PE/EtOAc 70:30), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.25 (dd, *J* = 7.8, 1.7 Hz, 1 H, ArH), 8.22 (dd, *J* = 7.8, 2.4 Hz, 1 H, ArH), 7.77 (ddd, *J* = 7.8, 7.8, 2.4 Hz, 1 H, ArH), 7.73 (ddd, *J* = 7.8, 7.8, 1.7 Hz, 1 H, ArH), 7.67 (s, 1 H, ArH), 4.03 (s, 3 H), 3.99 (s, 3 H), 3.98 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.7 (s, C=O), 181.5 (s, C=O), 157.5 (s, ArC), 154.8 (s, ArC), 148.4 (s, ArC), 134.9 (s, ArC), 134.1 (d, ArCH), 133.1 (d, ArCH), 132.5 (s, ArC), 130.8 (s, ArC), 127.0 (d, ArCH), 126.6 (d, ArCH), 121.3 (s, ArC), 106.4 (d, ArCH), 61.6 (q, CH_3), 61.3 (q, CH_3), 56.4 (q, CH_3).

2-Methoxy-6-methylanthracene-9,10-dione (3ba)

GP was carried out with *ortho*-iodoester **1b** (110.0 mg, 0.40 mmol) and aldehyde **2a** (217.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h.

Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ba**; yield: 65.0 mg (64%); yellow solid, m.p. 192–194 °C; R_f (**1a**) = 1.0, R_f (**3ba**) = 0.30 (PE/EtOAc 95:05), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.15 (d, *J* = 8.3 Hz, 1 H, ArH), 8.09 (d, *J* = 7.8 Hz, 1 H, ArH), 7.99 (s, 1 H, ArH), 7.63 (d, *J* = 2.4 Hz, 1 H, ArH), 7.49 (dd, *J* = 7.8, 1.2 Hz, 1 H, ArH), 7.18 (dd, *J* = 8.3, 2.4 Hz, 1 H, ArH), 3.93 (s, 3 H), 2.47 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.9 (s, C=O), 182.2 (s, C=O), 164.2 (s, ArC), 145.2 (s, ArC), 135.5 (s, ArC), 134.3 (d, ArCH), 133.4 (s, ArC), 131.2 (s, ArC), 129.5 (d, ArCH), 127.3 (d, ArCH), 127.2 (d, ArCH), 127.0 (s, ArC), 120.8 (d, ArCH), 109.8 (d, ArCH), 55.6 (q, CH_3), 21.8 (q, CH_3).

2-Ethoxy-6-methylanthracene-9,10-dione (3bb)

GP was carried out with *ortho*-iodoester **1b** (110.0 mg, 0.40 mmol) and aldehyde **2b** (240.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1b** had completely reacted. Then the reaction mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3bb**; yield: 66.0 mg (62%); red solid, m.p. 210–213 °C; R_f (**1b**) = 1.0, R_f (**3bb**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3080, 1705, 1690, 1639, 1621, 1580, 15751, 1517, 1408, 1361, 1310, 1249, 1215, 908, 813 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.17 (d, *J* = 8.8 Hz, 1 H, ArH), 8.11 (d, *J* = 7.8 Hz, 1 H, ArH), 8.03 (s, 1 H, ArH), 7.63 (d, *J* = 2.9 Hz, 1 H, ArH), 7.50 (dd, *J* = 7.8, 0.9 Hz, 1 H, ArH), 7.18 (dd, *J* = 8.8, 2.6 Hz, 1 H, ArH), 4.18 (q, *J* = 7.0 Hz, 2 H), 2.49 (s, 3 H), 1.46 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 183.0 (s, C=O), 182.3 (s, C=O), 163.6 (s, ArC), 145.2 (s, ArC), 135.6 (s, ArC), 134.3 (d, ArCH), 133.5 (s, ArC), 131.3 (s, ArC), 129.6 (d, ArCH), 127.4 (d, ArCH), 127.3 (d, ArCH), 126.9 (s, ArC), 121.2 (d, ArCH), 110.3 (d, ArCH), 64.3 (t, CH_2), 21.9 (q, CH_3), 14.6 (q, CH_3).

HR-MS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{17}H_{15}O_3]^+$: 267.1016; found: 267.1017.

2,3-Dimethoxy-6-methylanthracene-9,10-dione (3bc)

GP was carried out with *ortho*-iodoester **1b** (110.0 mg, 0.40 mmol) and aldehyde **2c** (265.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 17 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1b** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 30 min. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3bc**; yield: 75.0 mg (66%); yellow viscous liquid; R_f (**1b**) = 1.0, R_f (**3bc**) = 0.30 (PE/EtOAc 85:15), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.11 (d, *J* = 7.8 Hz, 1 H, ArH), 8.01 (s, 1 H, ArH), 7.65 (s, 1 H, ArH), 7.64 (s, 1 H, ArH), 7.51 (dd, *J* = 7.8, 0.9 Hz, 1 H, ArH), 4.03 (s, 6 H), 2.49 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.7 (s, C=O), 182.3 (s, C=O), 153.7 (s, ArC), 153.6 (s, ArC), 144.7 (s, ArC), 134.4 (d, ArCH), 133.4 (s, ArC), 131.3 (s, ArC), 128.5 (s, ArC), 128.4 (s, ArC), 127.8 (d, ArCH), 127.2 (d, ArCH), 108.3 (d, ArCH), 108.2 (d, ArCH), 56.5 (q, 2 C, CH_3), 21.8 (q, CH_3).

2,3-Diethoxy-6-methylanthracene-9,10-dione (3be)

GP was carried out with *ortho*-iodoester **1b** (110.0 mg, 0.40 mmol) and aldehyde **2e** (310.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol %), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 18 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1b** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 30 min. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3be**; yield: 76.0 mg (61%); yellow viscous liquid; R_f (**1b**) = 1.0, R_f (**3be**) = 0.30 (PE/EtOAc 95:05), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.13 (d, *J* = 7.8 Hz, 1 H, ArH), 8.03 (s, 1 H, ArH), 7.67 (s, 2 H, ArH), 7.52 (dd, *J* = 7.8, 1.9 Hz, 1 H, ArH), 4.28 (q, *J* = 7.0 Hz, 2 × 2 H), 2.50 (s, 3 H), 1.52 (t, *J* = 7.0 Hz, 2 × 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.9 (s, C=O), 182.5 (s, C=O), 153.3 (s, ArC), 153.2 (s, ArC), 144.7 (s, ArC), 134.4 (d, ArCH), 133.5 (s, ArC), 131.4 (s, ArC), 128.3 (s, ArC), 128.2 (s, ArC), 127.3 (d, ArCH), 127.1 (d, ArCH), 109.3 (d, ArCH), 109.2 (d, ArCH), 64.9 (t, 2 C, 2 × CH_2), 21.8 (q, CH_3), 14.5 (q, 2 C, 2 × CH_3).

7-Methylanthra[2,3-*d*][1,3]dioxole-5,10-dione (3bj)

GP was carried out with *ortho*-iodoester **1b** (110.0 mg, 0.40 mmol) and aldehyde **2j** (240.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 17 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1a** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 1 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of

the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3bj**; yield: 64.0 mg (60%); redish viscous liquid; R_f (**1b**) = 1.0, R_f (**3bj**) = 0.30 (PE/EtOAc 90:10), UV detection.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.14 (d, *J* = 7.8 Hz, 1 H, ArH), 8.04 (s, 1 H, ArH), 7.65 (s, 2 H, ArH), 7.54 (d, *J* = 7.8 Hz, 1 H, ArH), 6.15 (s, 2 H, ArH), 2.50 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.3 (s, C=O), 181.9 (s, C=O), 152.6 (s, ArC), 152.5 (s, ArC), 144.9 (s, ArC), 134.6 (d, ArCH), 133.2 (s, ArC), 131.1 (s, ArC), 130.9 (s, ArC), 130.8 (s, ArC), 127.4 (d, ArCH), 127.3 (d, ArCH), 106.3 (d, 2 C, ArCH), 102.6 (t, CH_2), 21.9 (q, CH_3).

2-Bromo-6-methoxyanthracene-9,10-dione (3ca)

GP was carried out with *ortho*-iodoester **1c** (136.0 mg, 0.40 mmol) and aldehyde **2a** (217.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 17 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1c** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ca**; yield: 79.0 mg (62%); yellow solid, m.p. 212–215 °C; R_f (**1c**) = 1.0, R_f (**3ca**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3056, 2938, 1710, 1687, 1612, 1460, 1280, 1081, 914, 705 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.40 (d, *J* = 1.9 Hz, 1 H, ArH), 8.23 (d, *J* = 8.8 Hz, 1 H, ArH), 8.12 (d, *J* = 8.3 Hz, 1 H, ArH), 8.86 (dd, *J* = 8.3, 2.4 Hz, 1 H, ArH), 7.70 (d, *J* = 2.4 Hz, 1 H, ArH), 7.28–7.26 (m, 1 H, ArH), 3.98 (s, 3 H, OCH_3).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.5 (s, C=O), 180.9 (s, C=O), 164.6 (s, ArC), 136.7 (d, ArCH), 135.4 (s, ArC), 134.7 (s, ArC), 132.1 (s, ArC), 130.2 (d, ArCH), 129.9 (d, ArCH), 129.8 (s, ArC), 128.9 (d, ArCH), 126.7 (s, ArC), 121.3 (d, ArCH), 110.1 (d, ArCH), 56.0 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{10}{}^{79}BrO_3]^+$: 316.9808; found: 316.9806; *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{10}{}^{81}BrO_3]^+$: 318.9789; found: 318.9789.

2-Bromo-6-ethoxyanthracene-9,10-dione (3cb)

GP was carried out with *ortho*-iodoester **1c** (136.0 mg, 0.40 mmol) and aldehyde **2b** (240.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1c** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3cb**; yield: 86.0 mg (65%); red solid, m.p. 202–203 °C; R_f (**1c**) = 1.0, R_f (**3cb**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3070, 1709, 1691, 1645, 1599, 1580, 15751, 1506, 1410, 1357, 1310, 1245, 1215, 940, 813 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.40 (d, *J* = 1.9 Hz, 1 H, ArH), 8.22 (d, *J* = 8.3 Hz, 1 H, ArH), 8.12 (d, *J* = 8.3 Hz, 1 H, ArH), 8.86 (dd, *J* = 8.0, 2.2 Hz, 1 H, ArH), 7.67 (d, *J* = 2.9 Hz, 1 H, ArH), 7.26–7.23 (m, 1 H, ArH), 4.21 (q, *J* = 7.0 Hz, 2 H), 1.48 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 182.5 (s, C=O), 180.9 (s, C=O), 164.0 (s, ArC), 136.6 (d, ArCH), 135.4 (s, ArC), 134.8 (s, ArC), 132.2 (s, ArC), 130.2 (d, ArCH), 129.9 (d, ArCH), 129.7 (s, ArC), 128.9 (d, ArCH), 126.5 (s, ArC), 121.6 (d, ArCH), 110.6 (d, ArCH), 64.5 (t, CH_2), 14.6 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{16}H_{12}{}^{79}BrO_3]^+$: 330.9964; found: 330.9988; *m*/*z* [M + H]$^+$ calcd for $[C_{16}H_{12}{}^{81}BrO_3]^+$: 332.9946; found: 332.9958.

6-Bromo-2,3-dimethoxyanthracene-9,10-dione (3cc)

GP was carried out with *ortho*-iodoester **1c** (136.0 mg, 0.40 mmol) and aldehyde **2c** (265.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1c** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3cc**; yield: 85.0 mg (61%); yellow viscous liquid; R_f (**1c**) = 1.0, R_f (**3cc**) = 0.30 (PE/EtOAc 80:20), UV detection.

IR (MIR-ATR): 3074, 1709, 1691, 1640, 1620, 1576, 15751, 1517, 1416, 1363, 1313, 1244, 1213, 928, 834 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.36 (d, *J* = 2.4 Hz, 1 H, ArH), 8.09 (d, *J* = 8.3 Hz, 1 H, ArH), 7.84 (dd, *J* = 8.3, 1.9 Hz, 1 H, ArH), 7.67 (s, 1 H, ArH), 7.66 (s, 1 H, ArH), 4.05 (s, 6 H, OCH_3).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 181.7 (s, C=O), 181.2 (s, C=O), 154.1 (s, ArC), 154.0 (s, ArC), 136.7 (d, ArCH), 134.6 (s, ArC), 132.1 (s, ArC), 129.9 (d, ArCH), 129.2 (s, ArC), 128.7 (d, ArCH), 128.2 (s, ArC), 128.1 (s, ArC), 108.4 (d, 2 × CH, ArCH), 56.6 (q, 2 C, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{16}H_{12}{}^{79}BrO_4]^+$: 346.9913; found: 346.9900; *m*/*z* [M + H]$^+$ calcd for $[C_{16}H_{12}{}^{81}BrO_4]^+$: 348.9895; found: 348.9891.

7-Bromo-1-hydroxyanthracene-9,10-dione (3ci)

GP was carried out with *ortho*-iodoester **1c** (136.0 mg, 0.40 mmol) and aldehyde **2i** (195.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowing the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1c** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of

the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3ci**; yield: 71.0 mg (59%); red solid, m.p. 227–230 °C; R_f (**1c**) = 1.0, R_f (**3ci**) = 0.30 (PE/EtOAc 80:20), UV detection.

IR (MIR-ATR): 3061, 2937, 1711, 1692, 1618, 1469, 1285, 1181, 911, 715 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ =12.41 (s, 1 H, Ar–O*H*), 8.41 (d, *J* = 1.9 Hz, 1 H, ArH), 8.14 (d, *J* = 8.3 Hz, 1 H, ArH), 7.91 (dd, *J* = 8.3, 1.9 Hz, 1 H, ArH), 7.81 (dd, *J* = 7.5, 1.2 Hz, 1 H, ArH), 7.69 (dd, *J* = 8.3, 8.3 Hz, 1 H, ArH), 7.31 (dd, *J* = 8.3, 0.9 Hz, 1 H, ArH).

^{13}C NMR ($CDCl_3$, 100 MHz): δ =187.4 (s, C=O), 181.6 (s, C=O), 162.6 (s, ArC), 137.7 (d, ArCH), 137.1 (d, ArCH), 134.3 (s, ArC), 133.2 (s, ArC), 132.2 (s, ArC), 129.9 (d, ArCH), 129.8 (s, ArC), 129.1 (d, ArCH), 124.6 (d, ArCH), 119.8 (d, ArCH), 115.9 (s, ArC).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{14}H_8{}^{79}BrO_3]^+$: 302.9651; found: 302.9662; [M + H]$^+$ calcd for $[C_{14}H_8{}^{81}BrO_3]^+$: 304.9632; found: 304.9648.

2-Fluoro-6-methoxyanthracene-9,10-dione (3da)

GP was carried out with *ortho*-iodoester **1d** (112.0 mg, 0.40 mmol) and aldehyde **2a** (217.0 mg, 1.6 mmol) in the presence of $Pd(OAc)_2$ (5.0 mg, 5 mol%), Ag_2O (111.3 mg, 0.48 mmol), and TBHP (257.1 mg, 2.0 mmol) by allowinng the reaction mixture to stir at 120 °C for 14 h. Progress of the reaction was monitored by TLC until the *ortho*-iodoester **1d** had completely reacted. Then the mixture was removed from the oil bath and allowed to reach r.t. DCE (2 mL) and concd H_2SO_4 (1.0 mL) were added and the mixture was stirred at 60 °C for 2 h. Progress of the product formation was monitored by TLC until the reaction was complete. The mixture was quenched by the addition of aq $NaHCO_3$ and then extracted with CH_2Cl_2 (3 × 15 mL). The combined organic layers were washed with brine, dried (Na_2SO_4), and filtered. Evaporation of the solvent under reduced pressure and purification of the crude material by silica gel column chromatography (PE/EtOAc) furnished the product **3da**; yield: 65.0 mg (63%); yellow viscous liquid; R_f (**1d**) = 1.0, R_f (**3da**) = 0.30 (PE/EtOAc 95:05), UV detection.

IR (MIR-ATR): 3071, 2928, 1711, 1689, 1622, 1462, 1285, 1181, 914, 705 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.30 (dd, *J* = 8.5, 5.1 Hz, 1 H, ArH), 8.22 (d, *J* = 8.8 Hz, 1 H, ArH), 7.90 (dd, *J* = 8.8, 2.4 Hz, 1 H, ArH), 7.70 (d, *J* = 2.4 Hz, 1 H, ArH), 7.43–7.38 (m, 1 H, ArH), 7.26–7.23 (m, 1 H, ArH), 3.97 (s, 3 H, OCH_3).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 181.9 (s, C=O), 180.9 (s, C=O), 166.4 (s, ArC_F, $J_{C,F}$ = 260 Hz), 164.6 (s, ArC), 136.5 (s, ArC, $J_{C,F}$ = 8.7 Hz), 135.5 (s, ArC), 130.5 (d, $J_{C,F}$ = 8.8 Hz, ArCH), 130.2 (s, $J_{C,F}$ = 2.9 Hz, ArC), 129.9 (d, ArCH), 127.0 (s, ArC), 121.1 (d, ArCH), 120.9 (d, $J_{C,F}$ = 22.9 Hz, ArCH), 113.8 (d, $J_{C,F}$ = 22.7 Hz, ArCH), 110.2 (d, ArCH), 56.0 (q, CH_3).

HRMS (ESI$^+$): *m*/*z* [M + H]$^+$ calcd for $[C_{15}H_{10}FO_3]^+$: 257.0608; found: 257.0606.

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Supporting Information

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