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Visible-Light-Induced Photocatalytic Oxidative Decarboxylation of Cinnamic Acids to 1,2-Diketones

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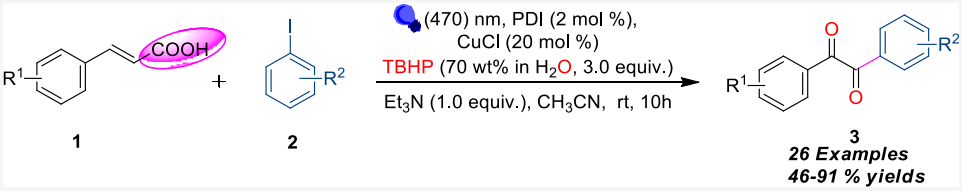


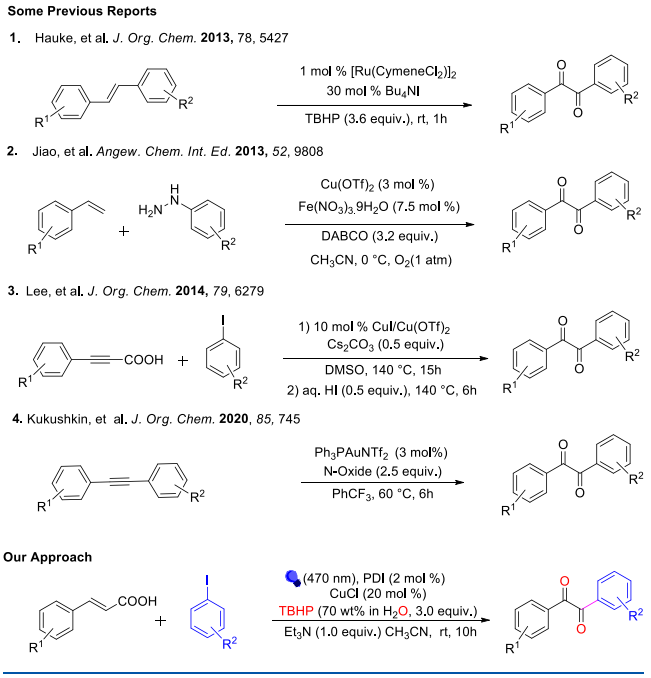
ABSTRACT: A concerted metallophotoredox catalysis has been realized for the efficient decarboxylative functionalization of *α,β*-unsaturated carboxylic acids with aryl iodides in the presence of perylene bisimide dye to afford 1,2-diketones.

INTRODUCTION

1,2-Diketones constitute an important class of privileged structures with key applications in the synthesis of bioactive molecules and natural products.[1,2] Such motifs manifest in vital molecules with antitumor activities[3] and photochemical properties.[4] Besides their uses as ligands[5] and versatile building blocks to medicinal molecules,[6] the 1,2-diketones have also been exploited as pioneers to accomplish *N*-heterocyclic carbenes.[7] Thus, the synthesis of 1,2-diketones has garnered a great deal of interest, and different strategies for their preparation have emerged (Scheme 1). The existing strategies to synthesize 1,2-diketones are mainly comprised of the oxidation of different substrates, such as olefins,[8] *α*-hydroxy ketones,[9] methylene ketones,[10] alkynes,[11] and aryl propiolic acids as a terminal alkyne surrogate,[12] among which the use of an alkyne appears to be the most practical. Different transition metals, such as Pd,[13] Ru,[14] Au,[15a,d] Hg,[15e] and Cu,[16] are prominent amid the consortium of catalysts employed in the synthesis of 1,2-diketones with oxidants such as DMSO, oxone, $K_2S_2O_8$, TBHP, and Ph_2SO. Despite many advantages, the availability and prior synthesis of the reactants in the aforementioned strategies are incommodious. The use of toxic and rare metal catalysts and reagents and at times higher temperatures further endorse the need for the development of a novel and inclusive synthetic strategy for 1,2-diketones.

Decarboxylative cross-coupling has recently come up as a powerful advancement in the formation of carbon−carbon or carbon−heteroatom bonds in organic synthesis.[17] The carboxylic acids are easily available, stable, nontoxic, easy to store and handle, far less air and moisture sensitive in comparison to typical cross-coupling organometallic reagents, and give CO_2 as the only byproduct. Cinnamic acids are especially important as they are commercially available in a great structural diversity and are readily prepared.[18] As a part of our current research endeavor exploiting the use of cinnamic acids in lieu of alkene and alkyne analogues,[19] the exploration of a proficient decarboxylative strategy involving cinnamic

Scheme 1. Synthesis of 1,2-Diketones



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acids under visible light photoredox catalysis to afford the 1,2-diketones was envisioned. In this context, Lee et al. have reported a decarboxylative cross-coupling of aryl propiolic acids with aryl iodides, followed by oxidation to the title products (cf. Scheme 1).[12a]

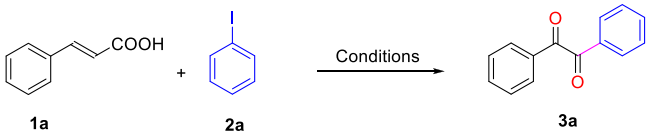
The substrate scope limitation at the propiolic acid end, however, imposed restrictions, and an alternative approach employing the cinnamic acid derivatives was thought to be worthwhile. The last few decades have witnessed a rejuvenation of photoredox catalysis to ensure sustainable synthesis under mild conditions.[20] The activation of traditional inert substrates to reactive intermediates at room temperature upon merely an exposure to visible light has influenced several cross-coupling reactions that otherwise require a high energy influx to overcome the activation barrier. While the approach offers an eco-safe and efficient tool in organic synthesis, it has been largely dependent on expensive ruthenium and iridium complexes for catalysis. Organic dyes present a cost-effective alternative, yet have a restricted range of redox potentials under visible-light irradiation.[21] A recent report by Sun et al. uncovered the synthesis of 1,2-diketones via the visible-light photooxidation of alkynes using eosin-Y as a photocatalyst.[22] Aryl halides act as an efficient aryl source for cross-coupling reactions due to their commercial accessibility.[23] However, the high reduction potential of aryl halides restricts its synthetic appositeness for the photoredox catalysis. Inspired by the Z-scheme of biological photosynthesis, König et al. have disclosed the photocatalytic applicability of *N,N′*-bis(2,6-diisopropylphenyl)-3,4,9,10-perylenetetracarboxylic diimide (PDI) to overcome this limitation by engaging two successive photoexcitations of PDI in a single catalytic cycle.[24]

In view of the above, we herein disclose an efficient visible-light-promoted decarboxylative functionalization of cinnamic acids with aryl iodides in the presence of PDI, CuCl, TBHP, and Et_3N to afford the 1,2-diketones with ample substrate scope and functional group compatibility (cf. Scheme 1, our approach).

RESULTS AND DISCUSSION

To conceive of our idea for the synthesis of 1,2-diketones, an archetypal reaction employing equimolar quantities of cinnamic acid (**1a**) and iodobenzene (**2a**) was meticulously investigated by varying different parameters, such as visible light, the photocatalyst, the catalyst, the base, the oxidant, and the solvent. The findings are given in Table 1. Under the initial reaction stipulations, comprising PDI (2.0 mol %), TBHP (3.0 equiv), and Et_3N (1.0 equiv) in acetonitrile, a trace of the desired product benzil (**3a**) was observed when equimolar amounts (1.0 mmol) of **1a** and **2a** were irradiated using blue LED (470 nm) light at room temperature for 10 h (Table 1, entry 1). Retaining all the parameters of entry 1, some copper salts, viz. CuI, CuBr, CuCl, $CuCl_2{\cdot}2H_2O$, $CuBr_2$, $Cu(OAc)_2$, and $Cu(OAc)_2{\cdot}H_2O$, were then added to envisage the likelihood of metallophotoredox catalysis to effect the chosen transformation (Table 1, entries 2−8, respectively). Out of the different trials, the use of CuCl (20 mol %) gave rise to the best surge in the product yield (86%; Table 1, entry 4). Some other transition metal salts, viz. $FeCl_3$, $CoCl_2{\cdot}6H_2O$, and $NiCl_2{\cdot}6H_2O$, were also examined, but they all proved mediocre (Table 1, entries 9−11, respectively). Notably, when the reaction was carried out in the absence of a base, no product was formed at all (Table 1, entry 12). Bases such as NaOH, K_2CO_3, and KO^{t}Bu were also tested as a part of the optimization progression (Table 1, entries 13−15, respectively), but only NaOH could provide somewhat appreciable product yield (Table 1, entry 13) while the others remained futile (Table 1, entries 14 and 15). However, when DBU or DABCO was employed as base, it led to a substantially higher product yield (Table 1, entries 16 or 17, respectively); however, it did not surpass that of Et_3N. Subsequently, while maintaining other parameters of entry 4 as such, the effect of different solvents was investigated (Table 1, entries 18−23). Whereas DCE and THF provided considerably high product yields (Table 1, entries 18 and 19, respectively), the use of DCM, DMF, DMSO, and toluene led to much lower yields (Table 1, entries 20−23, respectively). Furthermore, some other organic dyes viz. rhodamine B base, eosin-Y, eosin-B, and rose bengal, were also assessed for their redox activity under visible light; however, none of them could match the efficacy of PDI (Table 1, entries 24−27, respectively). Chloro- or bromobenzene, when tried in the place of **2a**, did not work.

Table 1. Optimization of the Reaction Conditions[a]



1a **2a** **3a**

entry	catalyst	photocatalyst	base	solvent	yield (%)[b]
1		PDI	Et_3N	CH_3CN	trace
2	CuI	PDI	Et_3N	CH_3CN	22
3	CuBr	PDI	Et_3N	CH_3CN	36
4	CuCl	PDI	Et_3N	CH_3CN	86
5	$CuCl_2{\cdot}2H_2O$	PDI	Et_3N	CH_3CN	18
6	$CuBr_2$	PDI	Et_3N	CH_3CN	26
7	$Cu(OAc)_2$	PDI	Et_3N	CH_3CN	50
8	$Cu(OAc)_2{\cdot}H_2O$	PDI	Et_3N	CH_3CN	45
9	$FeCl_3$	PDI	Et_3N	CH_3CN	35
10	$CoCl_2{\cdot}6H_2O$	PDI	Et_3N	CH_3CN	20
11	$NiCl_2{\cdot}6H_2O$	PDI	Et_3N	CH_3CN	38
12	CuCl	PDI	-	CH_3CN	0
13	CuCl	PDI	NaOH	CH_3CN	46
14	CuCl	PDI	K_2CO_3	CH_3CN	0
15	CuCl	PDI	KO^{t}Bu	CH_3CN	0
16	CuCl	PDI	DBU	CH_3CN	79
17	CuCl	PDI	DABCO	CH_3CN	75
18	CuCl	PDI	Et_3N	DCE	70
19	CuCl	PDI	Et_3N	THF	75
20	CuCl	PDI	Et_3N	DCM	48
21	CuCl	PDI	Et_3N	DMF	42
22	CuCl	PDI	Et_3N	DMSO	37
23	CuCl	PDI	Et_3N	Toluene	30
24	CuCl	rhodamine B base	Et_3N	CH_3CN	46
25	CuCl	eosin-Y	Et_3N	CH_3CN	70
26	CuCl	eosin-B	Et_3N	CH_3CN	62
27	CuCl	rose bengal	Et_3N	CH_3CN	35

[a]Reaction conditions are as follows: **1a** (1.0 mmol), **2a** (1.0 mmol), photocatalyst (2.0 mol %), catalyst (20 mol %), base (1.0 equiv), oxidant[c] (3.0 equiv), and solvent (2.0 mL) in an open vessel with 470 nm blue LED irradiation at rt for 10 h. [b]Isolated yield after column chromatography. [c]Only TBHP (3.0 equiv., 70 wt % in H_2O) could work out of different oxidants screened, including $K_2S_2O_8$, DTBP, TBHP, and O_2 (balloon).

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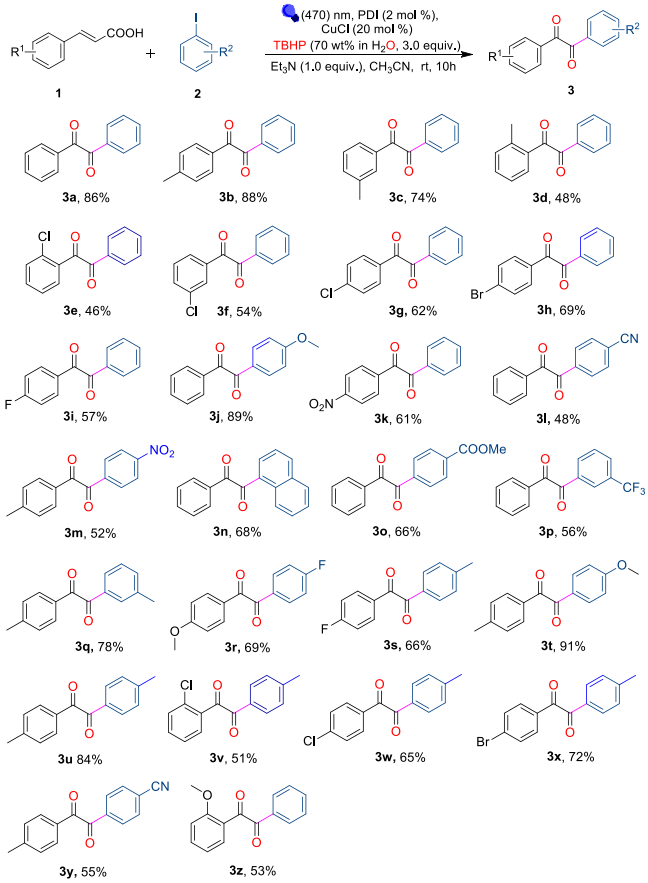
After establishing the optimized conditions, the scope and generality of the approach were explored using different cinnamic acids and iodoarenes (Table 2). A diverse range of

Table 2. Substrate Scope for the Synthesis of 1,2-Diketones[a,b]

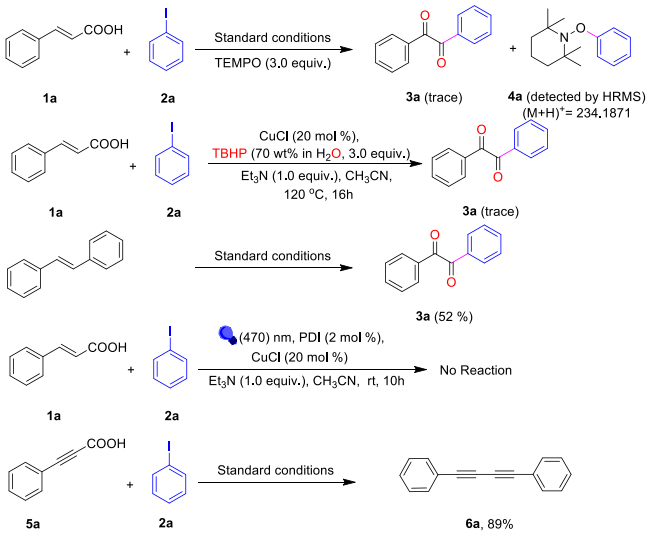


[a]Reaction conditions are as follows: **1** (1.0 mmol), **2** (1.0 mmol), PDI (2.0 mol %), CuCl (20 mol %), Et_3N (1.0 equiv), TBHP (3.0 mmol, 70 wt % in H_2O), and CH_3CN (2.0 mL) in an open vessel irradiated with 470 nm blue LED at rt for 10 h. [b]Isolated yield after column chromatography.

both the reactants with different electron-withdrawing and electron-donating substituents, such as CH_3, Cl, Br, F, OMe, NO_2, CN, CF_3, and COOMe, participated nicely in the reaction to afford the desired products **3a**–**3z** in reasonably high yields. As such, no explicit electronic effect from the substituent was observed, but the steric influence of the *ortho*-substitution somewhat impeded the reaction. An archetypal polycyclic substrate 1-iodonaphthalene also worked well under the established conditions to afford the anticipated product **3n** (68%).

To gain insight into the reaction mechanism, some control experiments were carried out, which are shown in Scheme 2. The presence of radical trapping agents such as TEMPO (2,2,6,6-tetramethylpiperidin-1-yl)oxyl and 2,6-di-*tert*-butyl-4-methylphenol (BHT) under standard conditions suppressed the reaction, thereby implying a radical pathway. The involvement of an aryl radical in the mechanistic pathway was further confirmed by the formation of the adduct 2,2,6,6-tetramethyl-1-phenoxypiperidine **4a**, which was detected by HRMS. The reaction was further carried out under conven-

Scheme 2. Control Experiments



tional heating at 120 °C for 16 h in the absence of a photocatalyst, which could provide only a trace of the desired product **3a**. Control experiments were also executed to observe if stilbene was an intermediate in the reaction pathway. Although the direct oxidation of stilbene under the optimized reaction conditions afforded the desired diketone product, no stilbene was formed when the reaction was carried in the absence of TBHP with the rest of the conditions intact, and cinnamic acid (**1a**) remained unconsumed. Thus, the possibility of a stilbene intermediate in the reaction pathway remains faint. However, the reaction of phenylpropiolic acid **5a** with iodobenzene **2a** under the standard conditions gave rise to the 1,3-dialkyne product (**6a**) rather than the 1,2-diketone product.

Based on control experiments, product isolation, and literature precedent,[24,25] a plausible mechanism involving the metallophotoredox decarboxylative synthesis of 1,2-diketones is outlined in Scheme 3.

The low-valent Cu(I) is initially oxidized by TBHP to Cu(II)−OH. The first excitation of PDI by irradiation undergoes a reductive quenching by triethylamine to form a radical anion $PDI^{\bullet-}$ and an oxidized $Et_3N^{\bullet+}$. Afterward, the further irradiation of $PDI^{\bullet-}$ produces the species $PDI^{\bullet-}$*, which then reduces the iodobenzene **2a** to the radical precursor $PhI^{\bullet-}$, followed by its fragmentation to form a phenyl radical. The phenyl radical next is added to the cinnamate to form the intermediate **A**,[26] which is oxidized by Cu(II)−OH to form the intermediate **B** with the revival of Cu(I) for the next catalytic cycle. The hydroxylation of **B** gives the intermediate **C**, which decarboxylates in the presence of $Et_3N^{\bullet+}$ to form the intermediate **D**[26d] and then affords the intermediate **E** via a radical coupling with *t*-butyl peroxy radical. The Kornblum−DeLaMare rearrangement of **E** affords the *α*-hydroxy ketone **F**, which is eventually oxidized by TBHP to the 1,2-diketone **3a**.

CONCLUSIONS

In conclusion, an oxidative decarboxylative functionalization of cinnamic acids has been realized with aryl iodides using a catalytic combination of copper chloride and *N*,*N*′-bis(2,6-diisopropylphenyl)-3,4,9,10-perylenetetracarboxylic diimide under visible-light irradiation.

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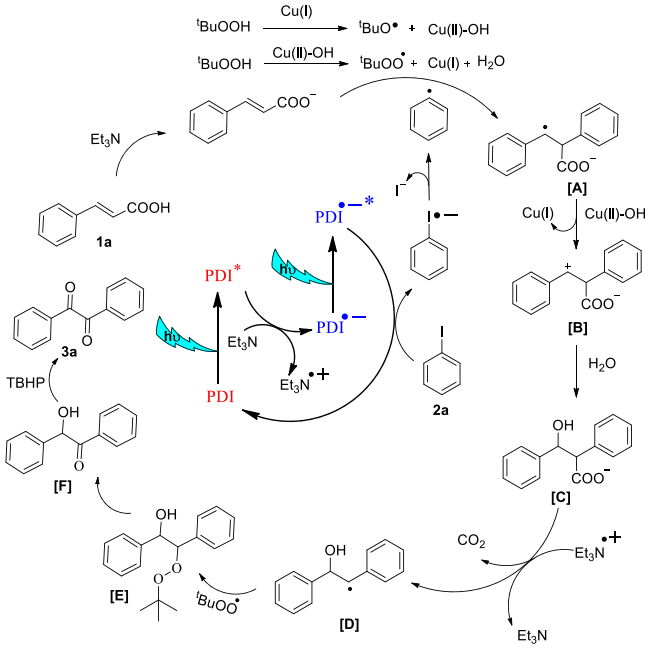
Scheme 3. Plausible Reaction Mechanism



EXPERIMENTAL SECTION

General Information. ^{1}H, $^{13}C\{^{1}H\}$, and ^{19}F spectra were recorded on a JEOL ECZ 500R FT NMR spectrometer (^{1}H NMR at 500 MHz, ^{13}C $\{^{1}H\}$ NMR at 126 MHz, and ^{19}F NMR at 471 MHz). Chemical shifts for the protons are reported in parts per million downfield from tetramethylsilane and are referenced to the residual deuterium in the solvent (^{1}H NMR, $CDCl_3$ at 7.26 ppm), whereas those for the carbons are reported in parts per million downfield from tetramethylsilane and are referenced to the carbon resonance of the solvent peak ($^{13}C\{^{1}H\}$ NMR, $CDCl_3$ at 77.160 ppm). NMR data are represented as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet and m = multiplet), coupling constant (J) (Hz), and integration. Mass spectra were recorded on a Sciex X500R QTOF mass spectrometer. Analytical thin layer chromatography (TLC) was performed on Merck Kieselgel 60 GF254 plates (thickness 0.25 mm). TLC visualization was performed with a 254 nm UV lamp and by staining in an I_2 chamber. Organic solutions were concentrated under reduced pressure using a Büchi rotary evaporator. Purification of the crude products was carried out by column chromatography using silica gel 100−200 mesh. All the reactions were carried out in open vessel using oven-dried glassware. Yield refers to the isolated analytically pure material. Visible-light irradiation was performed using a SP-01-B4 Blue (470 nm) LUXEON Rebel LED on a SinkPAD-II 20 mm Star Base - 70 lm at 700 mA to the reaction mixture contained in a borosilicate glass vessel, and the distance from the light source to the irradiation vessel was 2 cm.

Materials. All the cinnamic acids and iodoarenes were purchased from Sigma-Aldrich, whereas *N*,*N*′-bis(2,6-diisopropylphenyl)-3,4,9,10-perylenetetracarboxylic diimide (PDI) was procured from TCI Chemicals. All other chemicals were used as such without any further purification. Solvents were purified by standard methods.

General Experimental Procedure for the Synthesis of 1,2-Diketones 3. A mixture of cinnamic acid **1** (1.0 mmol), aryl iodide **2** (1.0 mmol), CuCl (20 mol %), Et_3N (1.0 mmol), TBHP (3.0 mmol, 70 wt % in H_2O), PDI (2.0 mol %), and CH_3CN (2.0 mL) contained in a 25 mL borosilicate RB flask was irradiated by Luxeon rebel Blue LED (470 nm) while stirring at room temperature for 24 h. After the completion of the reaction (monitored through TLC), the mixture was quenched using a saturated aqueous solution of sodium bicarbonate (15 mL) and then extracted with ethyl acetate (2 × 15 mL). The combined organic phase was dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The resulting crude product was purified by column chromatography using ethyl acetate/hexane (v/v = 1:50) as the eluent to afford the product **3**.

1,2-Diphenylethane-1,2-dione (**3a**).[15a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (181 mg, 86% yield): mp 92−93 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, J = 7.0 Hz, 4H), 7.67 (t, J = 7.5 Hz, 2H), 7.53 (t, J = 7.5 Hz, 4H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 194.7, 135.0, 133.1, 130.0, 129.2; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{11}O_2$ 211.0754, found 211.0762.

1-Phenyl-2-(p-tolyl)ethane-1,2-dione (**3b**).[13a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (197 mg, 88% yield): mp 91−92 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, J = 8.0 Hz, 2H), 7.88 (d, J = 8.0 Hz, 2H), 7.67 (t, J = 7.5 Hz, 1H), 7.52 (t, J = 8.0 Hz, 2H), 7.32 (d, J = 8.0 Hz, 2H), 2.44 (s, 3H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 194.9, 194.4, 146.4, 134.9, 133.2, 130.7, 130.2, 130.0, 129.9, 129.1, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{13}O_2$ 225.0910, found 225.0913.

1-Phenyl-2-(m-tolyl)ethane-1,2-dione (**3c**).[14c] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (166 mg, 74% yield): mp 88−89 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, J = 7.5 Hz, 2H), 7.78 (d, J = 11.5 Hz, 2H), 7.66 (t, J = 7.0 Hz, 1H), 7.53 (t, J = 7.5 Hz, 2H), 7.48 (d, J = 7.5 Hz, 1H), 7.41 (t, J = 7.5 Hz, 1H), 2.41 (s, 3H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 195.0, 194.9, 139.2, 135.9, 135.0, 133.2, 133.2, 130.4, 130.1, 129.2, 129.1, 127.4, 21.4; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{13}O_2$ 225.0910, found 225.0913.

1-Phenyl-2-(o-tolyl)ethane-1,2-dione (**3d**).[14c] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (108 mg, 48% yield): mp 56−57 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, J = 7.5 Hz, 2H), 7.68−7.64 (m, 2H), 7.54−7.48 (m, 3H), 7.36 (d, J = 7.5 Hz, 1H), 7.28 (d, J = 7.5 Hz, 1H), 2.71 (s, 3H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 196.9, 195.0, 141.5, 134.8, 133.9, 133.3, 133.2, 132.7, 132.0, 130.1, 129.2, 126.2, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{13}O_2$ 225.0910, found 225.0913.

1-(2-Chlorophenyl)-2-phenylethane-1,2-dione (**3e**).[16a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow oil (112 mg, 46% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.00 (d, J = 7.5 Hz, 2H), 7.92 (d, J = 7.5 Hz, 1H), 7.68 (t, J = 7.0 Hz, 1H), 7.55 (t, J = 7.0 Hz, 3H), 7.46 (t, J = 8.0 Hz, 2H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 193.8, 192.2, 134.7, 134.7, 134.2, 134.0, 132.6, 132.3, 130.7, 130.4, 129.0, 127.5; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}ClO_2$ 245.0364, found 245.0367.

1-(3-Chlorophenyl)-2-phenylethane-1,2-dione (**3f**).[27] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (132 mg, 54% yield): mp 91−92 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, J = 7.5 Hz, 3H), 7.85 (d, J = 8.0 Hz, 1H), 7.70 (t, J = 7.5 Hz, 1H), 7.64 (d, J = 8.0 Hz, 1H), 7.55 (t, J = 7.5 Hz, 2H),7.47 (t, J = 8.0 Hz, 1H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 193.8, 193.1, 135.6, 135.3, 134.9, 134.7, 132.8, 130.5, 130.1, 129.7, 129.3, 128.3; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}ClO_2$ 245.0364, found 245.0373.

1-(4-Chlorophenyl)-2-phenylethane-1,2-dione (**3g**).[16a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (151 mg, 62% yield): mp 76−77 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97−7.92 (m, 4H), 7.69−7.66 (m, 1H), 7.54−7.49 (m, 4H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 194.0, 193.2, 141.8, 135.2, 132.9, 131.5, 131.4, 130.1, 129.6, 129.2; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}ClO_2$ 245.0364, found 245.0370.

1-(4-Bromophenyl)-2-phenylethane-1,2-dione (**3h**).[15a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (199 mg, 69% yield): mp 78−79 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97 (d, J = 8.0 Hz, 2H), 7.85 (d, J = 8.0 Hz, 2H), 7.67 (d, J = 8.0 Hz, 3H), 7.54 (t, J = 7.5 Hz, 2H); $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 194.0, 193.4, 135.2, 132.9, 132.6, 131.9, 131.4, 130.7, 130.1, 129.2; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}BrO_2$ 288.9859, found 288.9869.

1-(4-Fluorophenyl)-2-phenylethane-1,2-dione (**3i**).[15a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (130 mg, 57% yield): mp 61−62 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.03−8.00 (m, 2H), 7.98 (d, J = 7.5 Hz, 2H), 7.68 (t,

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J = 7.0 Hz, 1H), 7.53 (t, J = 8.0 Hz, 2H), 7.20 (t, J = 8.5 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 194.2, 192.9, 167.9 (C−F, $^1J_{C-F}$ = 258.9 Hz), 135.1, 133.0, 132.9 (C−F, $^3J_{C-F}$ = 9.9 Hz), 130.1, 129.7 (C−F, $^4J_{C-F}$ = 8.9 Hz), 129.2, 116.6 (C−F, $^2J_{C-F}$ = 22.7 Hz); ^{19}F NMR (471 MHz, $CDCl_3$) δ −101.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}FO_2$ 229.0659, found 229.0659.

*1-(4-Methoxyphenyl)-2-phenylethane-1,2-dione (**3j**).*[13a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow oil (213 mg, 89% yield); ^1H NMR (500 MHz, $CDCl_3$) δ 7.98−7.94 (m, 4H), 7.66 (t, J = 7.0 Hz, 1H), 7.51 (t, J = 7.5 Hz, 2H), 6.99 (d, J = 9.0 Hz, 2H), 3.89 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 194.7, 193.1, 164.9, 134.6, 133.1, 132.3, 129.8, 128.8, 126.0, 114.3, 55.5; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{13}O_3$ 241.0859, found 241.0862.

*1-(4-Nitrophenyl)-2-phenylethane-1,2-dione (**3k**).*[15a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (156 mg, 61% yield): mp 126−127 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.36 (d, J = 9.0 Hz, 2H), 8.18 (d, J = 9.0 Hz, 2H), 7.99 (d, J = 7.0 Hz, 2H), 7.72 (t, J = 7.5 Hz, 1H), 7.56 (t, J = 8.0 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.0, 192.2, 151.3, 137.4, 135.6, 132.5, 131.1, 130.2, 129.4, 124.3; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{14}H_{10}NO_4$ 256.0604, found 256.0610.

*4-(2-Oxo-2-phenylacetyl)benzonitrile (**3l**).*[16a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (113 mg, 48% yield): mp 111−112 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.10 (d, J = 8.0 Hz, 2H), 7.98 (d, J = 7.0 Hz, 2H), 7.83 (d, J = 8.5 Hz, 2H), 7.72 (t, J = 7.5 Hz, 1H), 7.56 (t, J = 7.5 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.1, 192.5, 136.0, 135.5, 132.9, 132.6, 130.3, 130.2, 129.3, 118.0, 117.7; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{10}NO_2$ 236.0706, found 236.0715.

*1-(4-Nitrophenyl)-2-(p-tolyl)ethane-1,2-dione (**3m**).*[11e] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (140 mg, 52% yield): mp 145−146 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.35 (d, J = 8.5 Hz, 2H), 8.16 (d, J = 8.5 Hz, 2H), 7.88 (d, J = 7.5 Hz, 2H), 7.35 (d, J = 8.0 Hz, 2H), 2.46 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 192.7, 192.4, 151.3, 147.1, 137.6, 131.1, 130.3, 130.1, 124.2, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}NO_4$ 270.0761, found 270.0767.

*1-(Naphthalen-1-yl)-2-phenylethane-1,2-dione (**3n**).*[13a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (177 mg, 68% yield): mp 100−101 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 9.31 (d, J = 8.5 Hz, 1H), 8.14 (d, J = 8.5 Hz, 1H), 8.04 (d, J = 7.0 Hz, 2H), 7.96−7.91 (m, 2H), 7.77 (t, J = 7.5 Hz, 1H), 7.68−7.62 (m, 2H), 7.54−7.48 (m, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 197.3, 194.7, 136.1, 135.2, 134.9, 134.2, 133.5, 131.1, 130.2, 129.6, 129.2, 128.9, 128.8, 127.3, 126.1, 124.6; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{18}H_{13}O_2$ 261.0910, found 261.0921.

*Methyl 4-(2-Oxo-2phenylacetyl)benzoate (**3o**).*[27] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (177 mg, 66% yield): mp 71−72 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.17 (d, J = 8.0 Hz, 2H), 8.05 (d, J = 8.0 Hz, 2H), 7.99 (d, J = 7.5 Hz, 2H), 7.70 (t, J = 7.0 Hz, 1H), 7.56 (t, J = 7.5 Hz, 2H), 3.96 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.9, 193.8, 166.0, 136.2, 135.5, 135.3, 132.9, 130.2, 130.1, 129.9, 129.3, 52.8; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{13}O_4$ 269.0808, found 269.0805.

*1-Phenyl-2-(3-(trifluoromethyl)phenyl)ethane-1,2-dione (**3p**).*[14c] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (156 mg, 56% yield): mp 69−70 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.28 (s, 1H), 8.16 (d, J = 8.0 Hz, 1H), 8.00 (d, J = 8.0 Hz, 2H), 7.92 (d, J = 7.5 Hz, 1H), 7.71−7.65 (m, 2 H), 7.58 (t, J = 8.0 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.5, 192.8, 135.4, 133.7, 133.3, 132.8, 132.4 (C−F, $^1J_{C-F}$ = 124.8 Hz), 131.3 (C−F, $^3J_{C-F}$ = 9.9 Hz), 130.2, 129.9, 129.3, 126.6, (C−F, $^2J_{C-F}$ = 12.2 Hz); ^{19}F NMR (471 MHz, $CDCl_3$) δ −62.8; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{10}F_3O_2$ 279.0627, found 279.0630.

*1-(m-Tolyl)-2-(p-tolyl)ethane-1,2-dione (**3q**).*[13a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (186 mg, 78% yield): mp 61−62 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, J = 8.0 Hz, 2H), 7.77 (d, J = 10.0 Hz, 2H), 7.47 (d, J = 7.5 Hz, 1H), 7.40 (t, J = 7.5 Hz, 1H), 7.32 (d, J = 7.5 Hz, 2H), 2.44 (s, 3H), 2.40 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 195.2, 194.6, 146.3, 139.1, 135.8, 133.3, 130.8, 130.4, 130.2, 129.9, 129.0, 127.4, 22.1, 21.4; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{15}O_2$ 239.1067, found 239.1068.

*1-(4-Fluorophenyl)-2-(4-methoxyphenyl)ethane-1,2-dione (**3r**).*[11a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (178 mg, 69% yield): mp 63−64 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.03−8.00 (m, 2H), 7.95 (d, J = 9.0 Hz, 2H), 7.19 (t, J = 8.5 Hz, 2H), 6.99 (d, J = 9.0 Hz, 2H), 3.89 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.2, 192.8, 167.9, 165.8 (C−F, $^1J_{C-F}$ = 267.5 Hz), 132.9 (C−F, $^3J_{C-F}$ = 37.2 Hz), 132.6, 129.9 (C−F, $^4J_{C-F}$ = 8.0 Hz), 126.1, 116.5 (C−F, $^2J_{C-F}$ = 84.3 Hz), 114.6, 55.8; ^{19}F NMR (471 MHz, $CDCl_3$) δ −101.6; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}FO_3$ 259.0765, found 259.0764.

*1-(4-Fluorophenyl)-2-(p-tolyl)ethane-1,2-dione (**3s**).*[13a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (160 mg, 66% yield): mp 78−79 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.03−8.00 (m, 2H), 7.87 (d, J = 8.0 Hz, 2H), 7.32 (d, J = 8.0 Hz, 2H), 7.20 (t, J = 8.0 Hz, 2H), 2.44 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 194.0, 193.1, 167.9 (C−F, $^1J_{C-F}$ = 258.2 Hz), 146.5, 132.9 (C−F, $^4J_{C-F}$ = 9.8 Hz), 130.6, 130.2 (C−F, $^3J_{C-F}$ = 34.8 Hz), 129.8, 116.6 (C−F, $^2J_{C-F}$ = 18.6 Hz), 22.1; ^{19}F NMR (471 MHz, $CDCl_3$): δ −101.5; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}FO_2$ 243.0816, found 243.0826.

*1-(4-Methoxyphenyl)-2-(p-tolyl)ethane-1,2-dione (**3t**).*[27] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (231 mg, 91% yield): mp 106−107 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.95 (d, J = 8.5 Hz, 2H), 7.87 (d, J = 8.0 Hz, 2H), 7.31 (d, J = 8.0 Hz, 2H), 6.98 (d, J = 9.0 Hz, 2H), 3.88 (s, 3H), 2.43 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 194.7, 193.5, 165.1, 146.1, 132.5, 131.8, 130.9, 130.2, 129.8, 114.5, 55.8, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{15}O_3$ 255.1016, found 270.1026.

*1,2-Di-p-tolylethane-1,2-dione (**3u**).*[27] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (200 mg, 84% yield): mp 103−104 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, J = 8.5 Hz, 4H), 7.31 (d, J = 8.0 Hz, 4H), 2.43 (s, 6H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 194.7, 146.2, 130.9, 130.2, 129.9, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{15}O_2$ 239.1067, found 239.1059.

*1-(2-Chlorophenyl)-2-(p-tolyl)ethane-1,2-dione (**3v**).*[28] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (131 mg, 51% yield): mp 66−67 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.94 (d, J = 8.0 Hz, 2H), 7.91 (d, J = 7.5 Hz, 1H), 7.55 (t, J = 7.0 Hz, 1H), 7.45 (t, J = 7.0 Hz, 2H), 7.34 (d, J = 7.5 Hz, 2H), 2.46 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.9, 192.0, 145.9, 134.6, 134.1, 132.3, 130.7, 130.5, 130.2, 129.8, 127.5, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}ClO_2$ 259.0520, found 259.0522.

*1-(4-Chlorophenyl)-2-(p-tolyl)ethane-1,2-dione (**3w**).*[16a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (168 mg, 65% yield): mp 116−117 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.92 (d, J = 8.0 Hz, 2H), 7.86 (d, J = 7.5 Hz, 2H), 7.49 (d, J = 8.0 Hz, 2H), 7.32 (d, J = 7.5 Hz, 2H), 2.44 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.7, 193.4, 146.6, 141.6, 131.6, 131.3, 130.5, 130.2, 129.9, 129.5, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}ClO_2$ 259.0520, found 259.0528.

*1-(4-Bromophenyl)-2-(p-tolyl)ethane-1,2-dione (**3x**).*[29] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (217 mg, 72% yield): mp 93−94 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.86 (d, J = 8.5 Hz, 2H), 7.84 (d, J = 8.5 Hz, 2H), 7.65 (d, J = 8.5 Hz, 2H), 7.32 (d, J = 8.0 Hz, 2H), 2.44 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 193.7, 193.6, 146.6, 132.5, 132.0, 131.4,130.5, 130.2, 129.9, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{12}BrO_2$ 303.0015, found 303.0022.

*4-(2-Oxo-2-(p-tolyl)acetyl)benzonitrile (**3y**).* Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow solid (137 mg, 55% yield): mp 154−156 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 8.09 (d, J = 8.5 Hz, 2H), 7.87 (d, J = 8.0 Hz, 2H), 7.82 (d, J = 8.5 Hz, 2H), 7.34 (d, J = 8.0 Hz, 2H), 2.46 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 192.9, 192.7, 147.1, 136.2, 132.9, 130.3, 130.3, 130.2,

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130.1, 117.9, 117.8, 22.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{12}NO_2$ 250.0863, found 250.0871.

*1-(2-Methoxyphenyl)-2-phenylethane-1,2-dione (**3z**).*[15a] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). Yellow oil (127 mg, 53% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.04 (d, J = 7.0 Hz, 1H), 7.94 (d, J = 7.5 Hz, 2H), 7.63 (q, J = 7.5 Hz, 2H), 7.51 (t, J = 7.5 Hz, 2H), 7.15 (t, J = 7.5 Hz, 1H), 6.95 (d, J = 8.5 Hz, 1H), 3.57 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 194.7, 193.6, 160.5, 136.5, 133.9, 133.0, 130.7, 129.4, 128.8, 124.0, 121.7, 112.4, 55.7; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{15}H_{13}O_3$ 241.0859, found 241.0867.

*1,4-Diphenylbuta-1,3-diyne (**6a**).*[30] Purification by column chromatography (ethyl acetate/hexane, v/v = 1:50). White solid (180 mg, 89%): mp 86−87 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.54 (d, J = 7.5 Hz, 4H), 7.39−7.33 (m, 6H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 132.6, 129.4, 128.6, 121.9, 81.7, 74.1; HRMS (ESI) m/z $[M + H]^+$ Calcd for $C_{16}H_{11}$ 203.0855, found 203.0859.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.1c00322.

copies of ^{1}H, ^{13}C{^{1}H}, and ^{19}F NMR spectra for all compounds (PDF)

FAIR data, including the primary NMR FID files, for compounds **3a**−**3z** and **6a** (ZIP)

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Notes

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