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Copper-Catalyzed Coupling of 2-Siloxy-1-alkenes and Diazocarbonyl Compounds: Approach to Multisubstituted Furans, Pyrroles, and Thiophenes

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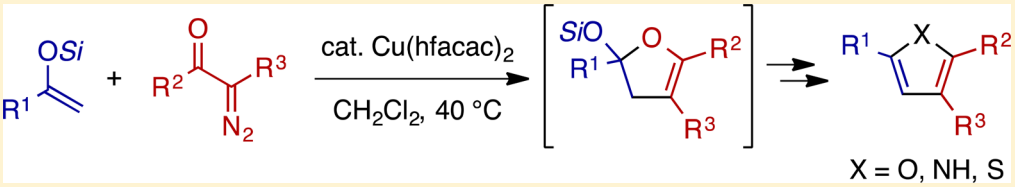
Supporting Information



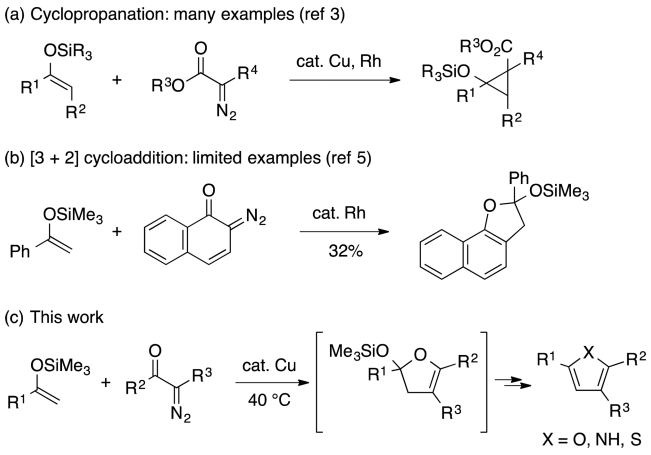
ABSTRACT: We report herein copper(II)-catalyzed cyclization reactions of silyl enol ethers derived from methyl ketones with α-diazo-β-ketoesters or α-diazoketones to afford 2-siloxy-2,3-dihydrofuran derivatives or 2,3,5-trisubstituted furans, respectively, under mild conditions. The former cyclization products serve as versatile 1,4-diketone surrogates, allowing facile preparation of 2,3,5-trisubstituted furans, pyrroles, and thiophenes.

INTRODUCTION

Transition-metal carbenoids generated through the decomposition of diazocarbonyl compounds have been extensively utilized as electrophilic reactive intermediates for a diverse set of catalytic transformations.[1] Olefins represent the most frequently employed nucleophilic reaction partners to electrophilic carbenoids, which typically take part in cyclopropanation.[2] In this context, the reactivity of silyl enol ethers, typical electron-rich olefins utilized in numerous organic reactions, has been extensively studied. Their reactions with common α-diazoesters under copper or rhodium catalysis lead to donor/acceptor-substituted cyclopropane derivatives (Scheme 1a),[3] which have proved to serve as useful intermediates for natural product synthesis.[4] On the other hand, Kitamura and coworkers recently reported a rhodium-catalyzed reaction of enol silyl ether and diazonaphthoquinone to afford a dihydronaphthofuran derivative (Scheme 1b).[5] As Kitamura's study was specifically focused on the reaction of ketene silyl acetal and diazonaphthoquinone, this [3 + 2] mode of cycloaddition remains largely unexplored with respect to both enol silyl ethers and diazocarbonyl compounds regardless of its potential utility for the synthesis of furans and other five-membered heterocycles.[6]

Recently, we developed a copper-catalyzed condensation reaction of ketimines and α-diazo-β-ketoesters to afford multisubstituted pyrroles.[7] The reaction is considered to involve a copper carbenoid stabilized by two adjacent carbonyl groups, which serves as an electrophile toward the nitrogen atom of ketimine to generate an azomethine ylide.[7,8] In this connection as well as in light of the aforementioned background on the reaction of enol silyl ethers, we became interested in the reactivity of the same or similar copper carbenoids toward silyl enol ethers. We report here that a simple copper(II) salt, $Cu(hfacac)_2$ (hfacac = hexafluoroacetylacetonate), is capable of promoting a coupling reaction of silyl enol ethers derived from methyl ketones with a variety of α-diazo-β-ketoesters (R^3 = ester) and α-diazoketones (R^3 = aryl) (Scheme 1c). The former diazo compounds afford 2-siloxy-2,3-dihydrofurans that serve as 1,4-diketone surrogates for facile preparation of multisubstituted furan, pyrrole, and thiophene derivatives, while the latter directly furnish trisubstituted furans.

Scheme 1. Transition-Metal-Catalyzed Reaction of Silyl Enol Ether and Diazocarbonyl Compound



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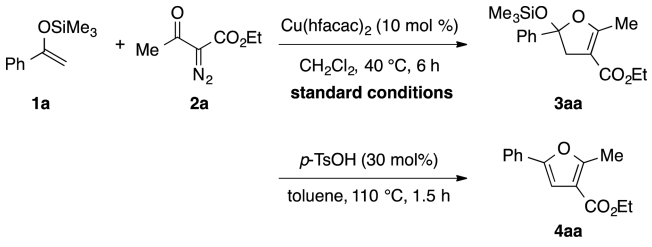
RESULTS AND DISCUSSION

The present study commenced with screening of reaction conditions for the condensation of acetophenone-derived silyl enol ether **1a** and ethyl acetoacetate-derived diazo compound **2a** (1.2 equiv). Treatment of these starting materials with a catalytic amount of $Cu(hfacac)_2$ (10 mol %) in CH_2Cl_2 at 40 °C resulted in a smooth denitrogenative coupling reaction to afford a 2-siloxy-2,3-dihydrofuran derivative **3aa** in 84% isolated yield (Table 1, entry 1). The same reaction could also be

Table 1. Coupling of Silyl Enol Ether 1a and α-Diazo-β-ketoester 2a[a]



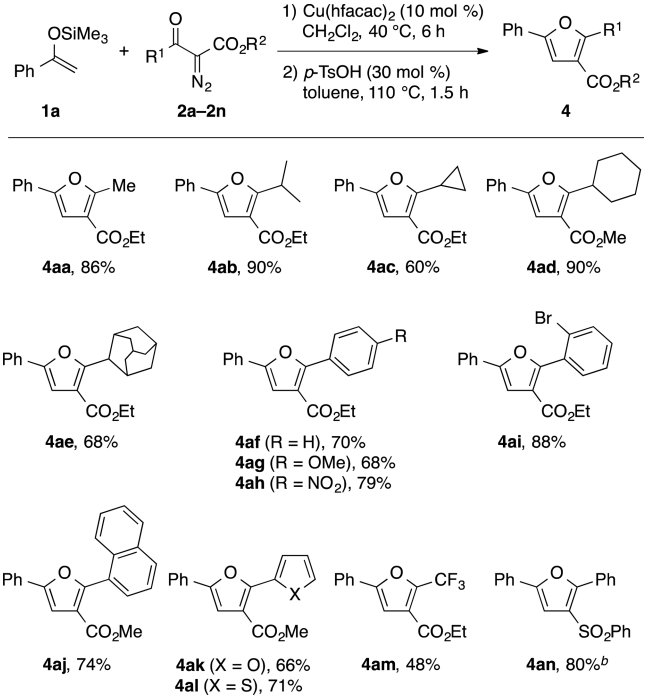
entry	deviation from standard conditions	yield (%)[b]
1	none	84[c] (86)[d]
2	$Cu(tfacac)_2$ instead of $Cu(hfacac)_2$	0
3	$Cu(acac)_2$ instead of $Cu(hfacac)_2$	0
4	$Cu(OAc)_2$ instead of $Cu(hfacac)_2$	0
5	$Rh_2(OAc)_4$ instead of $Cu(tfacac)_2$	12
6	5 mol % of $Cu(hfacac)_2$	65
7	none	(72)[d,e]

[a]The reaction was performed using 0.2 mmol of **1a** and 0.24 mmol of **2a**. [b]Determined by GC or ^1H NMR. [c]Isolated yield. [d]Isolated yield of furan **4aa** obtained by direct treatment of crude **3aa** with *p*-TsOH. [e]α-(*tert*-Butyldimethylsiloxy)styrene was used instead of **1a**.

followed by direct treatment of crude **3aa** with *p*-TsOH, which furnished a trisubstituted furan **4aa** in 86% overall yield. In sharp contrast, less Lewis acidic $Cu(tfacac)_2$ (tfacac = trifluoroacetylacetonate) completely failed to promote the reaction (entry 2), although it was the optimum catalyst for our previously developed pyrrole-forming reaction using ketimine as a nucleophilic reaction partner. In this case, the silyl enol ether **1a** was mostly recovered, whereas the diazo compound **2a** underwent complete decomposition to unidentified products. We speculate that the copper carbenoid derived from $Cu(tfacac)_2$ and **2a** was not electrophilic enough toward **1a**. Not unexpectedly, even less Lewis acidic Cu(II) salts such as $Cu(acac)_2$ and $Cu(OAc)_2$ were entirely ineffective as well (entries 3 and 4). The reaction using $Rh_2(OAc)_4$ as a catalyst resulted in a much lower yield (entry 5). An attempt to reduce the loading of $Cu(hfacac)_2$ to 5 mol % resulted in a decreased yield (entry 6). Note that α-(*tert*-butyldimethylsiloxy)styrene, instead of **1a**, could also be converted to the furan product **4aa** under the standard conditions albeit in a slightly lower yield (entry 7).

Having identified $Cu(hfacac)_2$ as an effective catalyst for the coupling of **1a** and **2a**, we explored the scope of the present furan synthesis. First, a series of α-diazo-β-ketoesters and related compounds **2a**–**n** were subjected to the reaction with silyl enol ether **1a** (Table 2). The reaction proved to tolerate a variety of R^1 groups such as primary and secondary alkyl groups (**4aa**–**ae**), aryl and heteroaryl groups with electron-donating or -withdrawing groups (**4af**–**al**), and a trifluoromethyl group

Table 2. Reaction of Silyl Enol Ether 1a with Various α-Diazo-β-ketoesters[a]

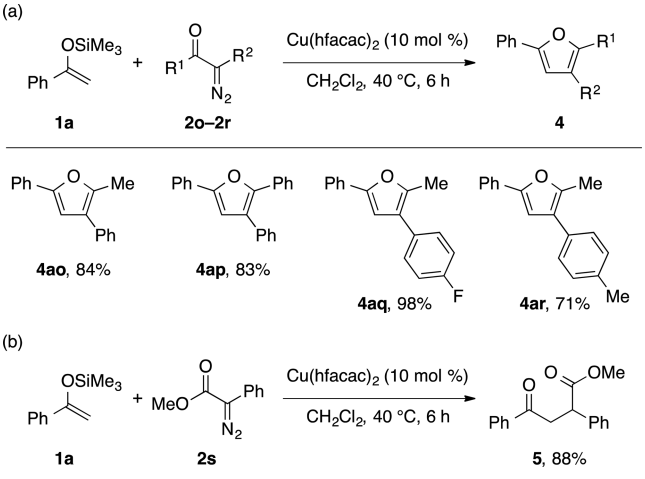


[a]The reaction was performed using 0.2 mmol of silyl enol ether and 0.24 mmol of diazo compound. [b]100 mol % of *p*-TsOH was used.

(**4am**), thus affording the corresponding trisubstituted furans in moderate to good yields. Besides the α-diazo-β-ketoesters, α-diazo-β-ketosulfone also smoothly participated in the reaction with **1a** to afford 3-sulfonylfuran **4an** in a good yield. Unfortunately, the reaction of α-diazo-β-diketone such as the one derived from acetylacetone did not afford a desired furan product but gave an intractable mixture of products.

When α-diazoketones **2o**–**r** were used as reaction partners for **1a**, the Cu-catalyzed reaction directly afforded 2,3,5-trisubstituted furan products **4ao**–**ar** in good yields, without a need for the treatment with *p*-TsOH (Scheme 2a). We

Scheme 2. Reaction of Silyl Enol Ether 1a with α-Diazoketone or α-Diazoester[a]



[a]The reaction was performed using 0.2 mmol of silyl enol ether and 0.24 mmol of diazo compound.

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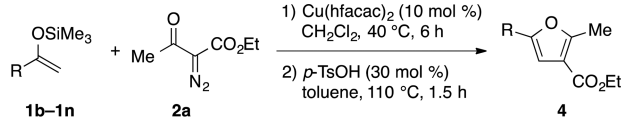
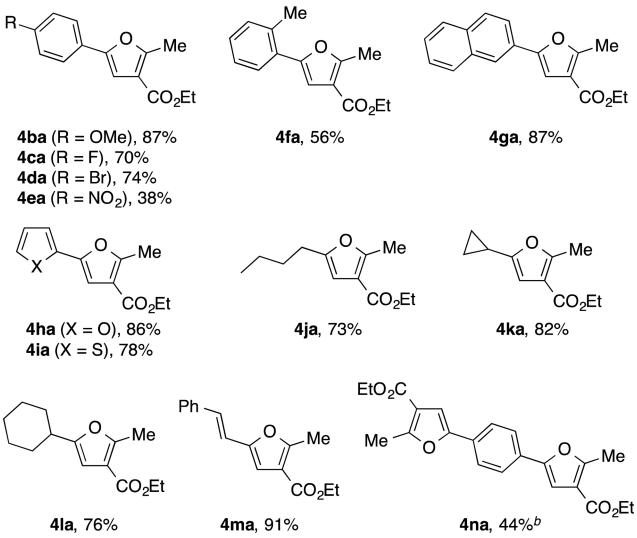
consider that the lack of electron-withdrawing groups on the 4-position of the corresponding 2-siloxy-2,3-dihydrofuran intermediates makes them prone to loss of silanol, which is presumably assisted by the Lewis acidic copper catalyst. Note also that the reaction of **1a** with α-diazoester **2s** directly afforded a 1,4-ketoester derivative **5** in a good yield (Scheme 2b), without a trace of cyclopropane or other cyclic intermediates.

Silyl enol ethers derived from various methyl ketones were amenable to the Cu-catalyzed coupling with α-diazo-β-ketoester **2a**, thus furnishing the desired trisubstituted furans in moderate to good yields (Table 3). Tolerable R groups on

Table 3. Reaction of Various Silyl Enol Ethers with α-Diazo-β-ketoester 2a[a]



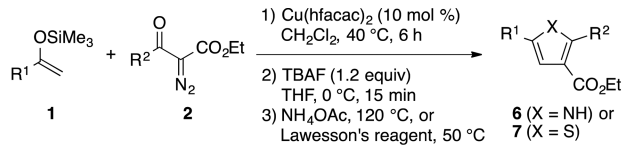


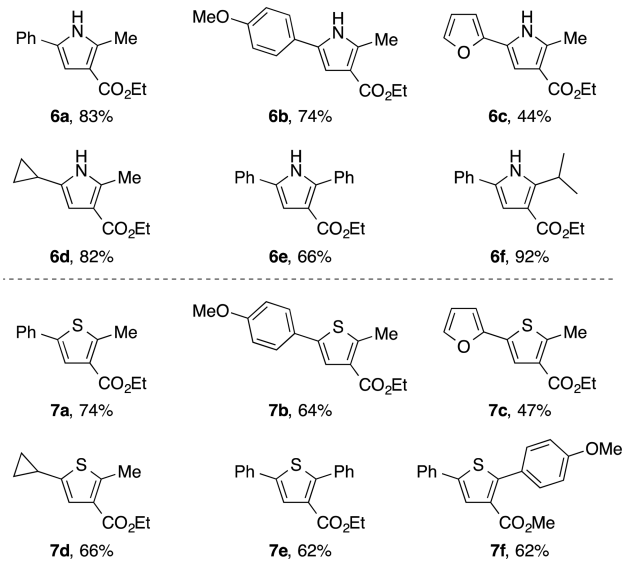
[a]The reaction was performed using 0.2 mmol of silyl enol ether and 0.24 mmol of diazo compound. [b]0.2 mmol of bis-silyl enol ether and 0.48 mmol of diazo compound were used.

silyl enol ether include functionalized aryl (**4ba–ga**), heteroaryl (**4ha** and **4ia**), alkyl (**4ja–la**), and alkenyl (**4ma**) groups. Silyl enol ether derived from 1,4-diacetylbenzene underwent 2-fold coupling with **2a** to afford a teraryl product **4na** in a modest yield. Unfortunately, reactions of trisubstituted silyl enol ethers, such as those derived from propiophenone, tetralone, and cyclohexanone, with **2a** under the present conditions resulted in full recovery of the silyl enol ethers and complete decomposition of **2a**. Note also that the reaction of ketene silyl acetal was rather sluggish. For example, the Cu-catalyzed coupling of phenyl acetate derived ketene silyl acetal with **2a** afforded the corresponding 2-siloxy-2,3-dihydrofuran in only 16% yield (data not shown).

2-Siloxy-2,3-dihydrofuran serves as a 1,4-diketone surrogate for the preparation of five-membered heteroarenes other than furan (Table 4). Thus, fluoride-mediated desilylation of the crude coupling product **3aa** was followed by treatment with ammonium acetate in acetic acid under heating conditions, affording a N–H pyrrole derivative **6a** in 83% overall yield. This protocol was effective for a series of silyl enol ether/α-

Table 4. Preparation of Multisubstituted Pyrroles and Thiophenes[a]



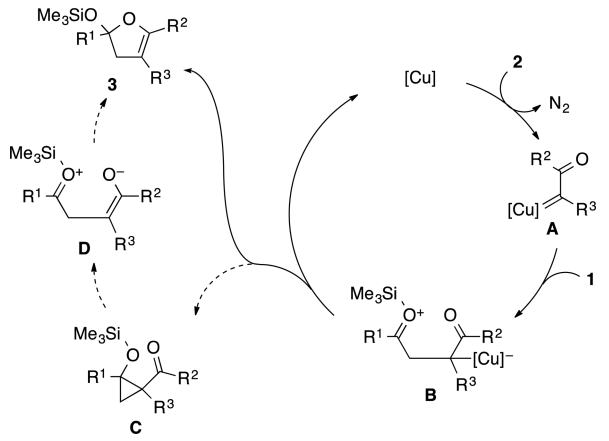


[a]The reaction was performed using 0.2 mmol of silyl enol ether and 0.24 mmol of diazo compound.

diazo-β-ketoester coupling products, thus enabling facile preparation of trisubstituted N–H pyrroles **6b–f** in moderate to good yields. Likewise, the use of Lawesson's reagent instead of ammonium acetate in the above procedure allowed preparation of trisubstituted thiophenes **7a–f** in moderate to good yields.

Scheme 3 shows plausible reaction pathways for the present copper-catalyzed reaction. Decomposition of the diazocarbonyl

Scheme 3. Plausible Reaction Pathways



compound with the copper catalyst generates an electrophilic copper carbenoid **A**. The silyl enol ether then undergoes nucleophilic attack on the carbenoid carbon to give an intermediate **B** bearing oxonium and enolate moieties. Intramolecular attack of the enolate oxygen to the oxonium carbon would directly afford 2-siloxy-2,3-dihydrofuran **3** while

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liberating the copper catalyst. An alternative pathway involving a siloxycyclopropane intermediate **C**, its ring-opening, and recyclization may not be fully excluded, however. When the R^3 substituent of **3** is not electron-withdrawing, loss of the siloxy group would be facilitated by the copper catalyst, thus leading to direct formation of the furan product **4**.

CONCLUSION

In summary, we have demonstrated that 2-siloxy-1-alkenes serve as excellent nucleophiles toward copper carbenoids generated from α-diazo-β-ketoesters or α-diazoketones, affording 2-siloxy-2,3-dihydrofuran derivatives or 2,3,5-trisubstituted furans, respectively. By simple follow-up operations, the former products can be transformed into 2,3,5-trisubstituted furans, pyrroles, and thiophenes. While the same type of multisubstituted furans may be directly prepared by transition-metal-catalyzed coupling of α-diazo-β-ketoesters and terminal alkynes[8c,d,9] or by other means,[10,11] the accessibility to analogous pyrroles[12] and thiophenes would make the present approach useful alternative to existing synthetic methods for five-membered heteroarenes.[13]

EXPERIMENTAL SECTION

General Information. All reactions dealing with air- and moisture-sensitive compounds were carried out in oven-dried reaction vessels under a nitrogen atmosphere using standard Schlenk techniques. All commercial materials were used without further purification. Silyl enol ethers[14] and diazocarbonyl compounds[7] were prepared according to the literature procesures. Analytical thin-layer chromatography (TLC) was performed on Merck 60 F254 silica gel plates. Standard flash chromatography was performed on silica gel 60 (300−400 mesh). Melting points (°C) were determined using a capillary melting point apparatus and are uncorrected. ^{1}H and ^{13}C NMR spectra were recorded on 400 MHz NMR spectrometers. Chemical shifts are reported in ppm relative to an internal standard, tetramethylsilane (0.00 ppm), or residual protiated solvent. Data are presented as follows: chemical shift (ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, sept = septet, m = multiplet), coupling constant *J* (Hz), and integration. High-resolution mass spectra (HRMS) were obtained by ESI method using a Q-Tof Premier LC HR mass spectrometer.

General Procedure for Furan Synthesis from Silyl Enol Ethers and α-Diazo-β-ketoesters (Tables 2 and 3). A 10 mL Schlenk tube equipped with a stirrer bar was charged with silyl enol ether (0.20 mmol), $Cu(hfacac)_2$ (9.6 mg, 0.020 mmol, 10 mol %), and diazocarbonyl compound (0.24 mmol), followed by the addition of dichloromethane (1.0 mL). The resulting mixture was stirred at 40 °C for 6 h. Upon cooling to room temperature, *p*-toluenesulfonic acid monohydrate (11.4 mg, 0.030 mmol, 30 mol %) was added, followed by the addition of toluene (1.0 mL). The resulting mixture was stirred at 110 °C for 1.5 h and then cooled to room temperature. The reaction mixture was diluted with ethyl acetate (5 mL), passed through a pad of silica gel, and concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel to afford the furan product.

Ethyl 2-methyl-5-phenyl-5-((trimethylsilyl)oxy)-4,5-dihydrofuran-3-carboxylate (***3aa***): synthesized without the treatment with *p*-toluenesulfonic acid monohydrate; colorless oil (54 mg, 84% yield, eluent = hexane/EtOAc (98:2)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 7.3 Hz, 2H), 7.42−7.32 (m, 3H), 4.20 (q, *J* = 7.1 Hz, 2H), 3.18 (dd, *J* = 15.9, 1.1 Hz, 1H), 3.09 (dd, *J* = 15.9, 1.7 Hz, 1H), 2.38 (s, 3H), 1.30 (t, *J* = 7.1 Hz, 3H), 0.09 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.8, 165.0, 144.2, 128.1, 128.1, 124.8, 109.5, 102.0, 59.6, 47.2, 14.4, 14.3, 1.3; HRMS (ESI) calcd for $C_{17}H_{25}O_4Si$ $[M + H]^+$ 321.1522, found 321.1524.

Ethyl 2-methyl-5-phenylfuran-3-carboxylate[10b] (***4aa***): colorless oil (40 mg, 86% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65−7.63 (m, 2H), 7.38 (t, *J* = 7.7 Hz, 2H), 7.34−7.21 (m, 1H), 6.88 (s, 1H), 4.31 (q, *J* = 7.1 Hz, 2H), 2.65 (s, 3H), 1.37 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.1, 158.6, 151.7, 130.1, 128.7, 127.6, 123.6, 115.4, 105.5, 60.2, 14.4, 13.9; HRMS (ESI) calcd for $C_{14}H_{15}O_3$ $[M + H]^+$ 231.1021, found 231.1025.

Ethyl 2-isopropyl-5-phenylfuran-3-carboxylate[10b] (***4ab***): yellow oil (46 mg, 90% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58−7.51 (m, 2H), 7.29 (t, *J* = 7.7 Hz, 2H), 7.19−7.15 (m, 1H), 6.79 (s, 1H), 4.22 (q, *J* = 7.1 Hz, 2H), 3.72 (hept, *J* = 7.0 Hz, 1H), 1.28 (t, *J* = 7.1 Hz, 3H), 1.26 (d, *J* = 4.0 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.8, 164.1, 151.5, 130.5, 128.9, 127.8, 123.8, 113.7, 105.7, 60.3, 27.6, 21.1, 14.6; HRMS (ESI) calcd for $C_{16}H_{19}O_3$ $[M + H]^+$ 259.1334, found 259.1340.

Ethyl 2-cyclopropyl-5-phenylfuran-3-carboxylate (***4ac***): colorless oil (31 mg, 60% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59−7.53 (m, 2H), 7.36 (t, *J* = 7.7 Hz, 2H), 7.24 (t, *J* = 6.4 Hz, 1H), 6.87 (s, 1H), 4.33 (q, *J* = 7.1 Hz, 2H), 2.83 (tt, *J* = 8.4, 5.2 Hz, 1H), 1.38 (t, *J* = 7.1 Hz, 3H), 1.19−1.13 (m, 1H), 1.13−1.06 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.6, 162.9, 150.5, 130.3, 128.9, 127.7, 123.7, 115.2, 106.1, 60.4, 14.7, 9.6, 9.2; HRMS (ESI) calcd for $C_{16}H_{17}O_3$ $[M + H]^+$ 257.1178, found 257.1170.

Methyl 2-cyclohexyl-5-phenylfuran-3-carboxylate (***4ad***): yellow oil (51 mg, 90% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65−7.62 (m, 2H), 7.37 (t, *J* = 7.7 Hz, 2H), 7.33−7.16 (m, 1H), 6.86 (s, 1H), 3.84 (s, 3H), 3.47 (tt, *J* = 11.9, 3.5 Hz, 1H), 1.97−1.78 (m, 4H), 1.79−1.62 (m, 3H), 1.53−1.19 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.7, 164.6, 151.6, 130.4, 128.9, 127.8, 123.8, 113.4, 105.5, 51.5, 37.2, 31.2, 26.4, 26.1; HRMS (ESI) calcd for $C_{18}H_{21}O_3$ $[M + H]^+$ 285.1491, found 285.1501.

Ethyl 2-(adamantan-2-yl)-5-phenylfuran-3-carboxylate (***4ae***): white solid (48 mg, 68% yield, eluent = hexane/EtOAc (97:3)); mp = 135−137 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64−7.62 (m, 2H), 7.37 (t, *J* = 7.7 Hz, 2H), 7.28−7.11 (m, 1H), 6.93 (s, 1H), 4.31 (q, *J* = 7.1 Hz, 2H), 2.25 (d, *J* = 2.6 Hz, 6H), 2.09 (s, 3H), 1.89−1.74 (m, 6H), 1.39 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.9, 164.0, 149.9, 130.5, 128.9, 127.7, 123.8, 114.4, 107.7, 60.5, 39.2, 37.3, 36.9, 28.7, 14.7; HRMS (ESI) calcd for $C_{23}H_{27}O_3$ $[M + H]^+$ 351.1960, found 351.1956.

Ethyl 2,5-diphenylfuran-3-carboxylate[9b] (***4af***): colorless solid (41 mg, 70% yield, eluent = hexane/EtOAc (97:3)); mp = 80−82 °C (lit.[15] mp 79−80 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09−8.06 (m, 2H), 7.80−7.68 (m, 2H), 7.53−7.35 (m, 5H), 7.35−7.25 (m, 1H), 7.08 (s, 1H), 4.33 (q, *J* = 7.1 Hz, 2H), 1.36 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 156.7, 152.6, 130.0, 129.6, 129.0, 128.6, 128.34, 128.28, 124.2, 116.0, 108.1, 60.9, 14.5; HRMS (ESI) calcd for $C_{19}H_{17}O_3$ $[M + H]^+$ 293.1178, found 293.1180.

Ethyl 2-(4-methoxyphenyl)-5-phenylfuran-3-carboxylate (***4ag***): white solid (44 mg, 68% yield, eluent = hexane/EtOAc (97:3)); mp = 95−97 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 (d, *J* = 8.9 Hz, 2H), 7.78−7.65 (m, 2H), 7.41 (t, *J* = 7.7 Hz, 2H), 7.29 (t, *J* = 7.4 Hz, 1H), 7.06 (s, 1H), 6.98 (d, *J* = 8.9 Hz, 2H), 4.33 (q, *J* = 7.1 Hz, 2H), 3.86 (s, 3H), 1.37 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.9, 160.7, 157.1, 151.9, 130.20, 130.15, 129.0, 128.1, 124.1, 122.7, 114.7, 113.8, 108.1, 60.7, 55.6, 14.6; HRMS (ESI) calcd for $C_{20}H_{19}O_4$ $[M + H]^+$ 323.1283, found 323.1296.

Ethyl 2-(4-nitrophenyl)-5-phenylfuran-3-carboxylate[16] (***4ah***): yellow solid (53 mg, 79% yield, eluent = hexane/EtOAc (92:8)); mp = 126−128 °C (lit.[16] mp 128−129 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.33 (d, *J* = 9.2 Hz, 2H), 8.28 (d, *J* = 9.2 Hz, 2H), 7.85−7.67 (m, 2H), 7.47−7.43 (m, 2H), 7.40−7.33 (m, 1H), 7.13 (s, 1H), 4.37 (q, *J* = 7.1 Hz, 2H), 1.40 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 154.1, 153.3, 147.7, 135.6, 129.3, 129.2, 129.0, 128.8, 124.5, 123.7, 118.9, 108.9, 61.4, 14.5; HRMS (ESI) calcd for $C_{19}H_{16}NO_5$ $[M + H]^+$ 338.1028, found 338.1025.

Ethyl 2-(2-bromophenyl)-5-phenylfuran-3-carboxylate (***4ai***): yellow oil (65 mg, 88% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75−7.70 (m, 2H), 7.68 (dd, *J* = 8.0, 1.1 Hz, 1H), 7.54 (dd, *J* = 7.6, 1.7 Hz, 1H), 7.42−7.37 (m, 3H), 7.34−7.27 (m, 2H), 7.09 (s, 1H), 4.21 (q, *J* = 7.1 Hz, 2H), 1.18 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.2, 155.7, 153.8, 133.1,

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132.7, 132.0, 131.1, 130.0, 129.0, 128.4, 127.0, 124.3, 124.2, 118.4, 106.3, 60.7, 14.2; HRMS (ESI) calcd for $C_{19}H_{16}BrO_3$ $[M + H]^+$ 371.0283, found 371.0283.

*Methyl 2-(naphthalen-1-yl)-5-phenylfuran-3-carboxylate (**4aj**):* white solid (49 mg, 74% yield, eluent = hexane/EtOAc (97:3)); Mp = 145−147 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, J = 8.2 Hz, 1H), 7.93−7.89 (m, 1H), 7.87 (d, J = 7.6 Hz, 1H), 7.76−7.72 (m, 3H), 7.60−7.54 (m, 1H), 7.53−7.46 (m, 2H), 7.40 (t, J = 7.6 Hz, 2H), 7.31 (t, J = 7.4 Hz, 1H), 7.19 (s, 1H), 3.66 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.9, 156.9, 153.8, 133.8, 132.2, 130.5, 130.1, 129.7, 129.1, 128.6, 128.4, 127.8, 126.9, 126.3, 125.8, 125.1, 124.3, 118.1, 106.8, 51.7; HRMS (ESI) calcd for $C_{22}H_{17}O_3$ $[M + H]^+$ 329.1178, found 329.1184.

*Methyl 5-phenyl-[2,2′-bifuran]-3-carboxylate (**4ak**):* colorless solid (35 mg, 66% yield, eluent = hexane/EtOAc (97:3)); mp = 93−95 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.74 (d, J = 7.3 Hz, 2H), 7.57 (dd, J = 7.0, 2.3 Hz, 2H), 7.41 (t, J = 7.6 Hz, 2H), 7.31 (t, J = 7.4 Hz, 1H), 7.03 (s, 1H), 6.57 (dd, J = 3.5, 1.8 Hz, 1H), 3.89 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.5, 152.6, 148.4, 144.8, 143.7, 129.8, 129.0, 128.4, 124.3, 114.3, 113.7, 112.3, 107.3, 51.9; HRMS (ESI) calcd for $C_{16}H_{13}O_4$ $[M + H]^+$ 269.0814, found 269.0820.

*Methyl 5-phenyl-2-(thiophene-2-yl)furan-3-carboxylate (**4al**):* white solid (40 mg, 71% yield, eluent = hexane/EtOAc (97:3)); mp = 71−73 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12 (dd, J = 3.8, 1.0 Hz, 1H), 7.74−7.68 (m, 2H), 7.46−7.37 (m, 3H), 7.31 (t, J = 7.4 Hz, 1H), 7.13 (dd, J = 5.0, 3.9 Hz, 1H), 7.02 (s, 1H), 3.90 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 152.4, 152.0, 131.8, 129.7, 129.0, 128.4, 128.2, 127.8, 124.2, 114.0, 107.6, 51.9; HRMS (ESI) calcd for $C_{16}H_{13}O_3S$ $[M + H]^+$ 285.0585, found 285.0582.

*Ethyl 5-phenyl-2-(trifluoromethyl)furan-3-carboxylate[17] (**4am**):* colorless solid (27 mg, 48% yield, eluent = hexane/EtOAc (95:5)); mp = 38−41 °C (lit.[17] mp 37−39 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77−7.69 (m, 2H), 7.52−7.37 (m, 3H), 7.08 (d, J = 0.9 Hz, 1H), 4.40 (q, J = 7.1 Hz, 2H), 1.41 (t, J = 7.1 Hz, 3H).; ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.9, 154.9, 142.2 (q, J_{C-F} = 42 Hz), 129.3, 128.9, 128.4, 121.4, 118.7 (q, J_{C-F} = 267 Hz), 106.9, 61.5, 13.9; HRMS (ESI) calcd for $C_{14}H_{12}F_3O_3$ $[M + H]^+$ 285.0739, found 285.0747.

*2,5-Diphenyl-3-(phenylsulfonyl)furan (**4an**).* Synthesized by a modified procedure using 100 mol % of *p*-toluenesulfonic acid monohydrate: white solid (58 mg, 80% yield, eluent = hexane/EtOAc (95:5)); mp = 148−150 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (dd, J = 6.7, 2.9 Hz, 2H), 7.86 (d, J = 8.1 Hz, 2H), 7.76−7.70 (m, 2H), 7.56−7.52 (m, 1H), 7.50−7.40 (m, 7H), 7.36 (t, J = 7.3 Hz, 1H), 7.12 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.1, 152.8, 141.8, 133.3, 130.1, 129.0, 128.9, 128.72, 128.67, 128.4, 127.1, 125.7, 124.2, 107.3; HRMS (ESI) calcd for $C_{22}H_{17}O_3S$ $[M + H]^+$ 361.0898, found 361.0895.

*Ethyl 5-(4-methoxyphenyl)-2-methylfuran-3-carboxylate[10b] (**4ba**):* colorless solid (45 mg, 87% yield, eluent = hexane/EtOAc (97:3)); mp = 62−64 °C (lit.[9a] mp 54−56 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, J = 8.9 Hz, 2H), 6.91 (d, J = 8.9 Hz, 2H), 6.73 (s, 1H), 4.30 (q, J = 7.1 Hz, 2H), 3.82 (s, 3H), 2.63 (s, 3H), 1.36 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.4, 159.5, 158.2, 152.0, 125.3, 123.4, 115.5, 114.4, 104.0, 60.3, 55.5, 14.6, 14.1; HRMS (ESI) calcd for $C_{15}H_{17}O_4$ $[M + H]^+$ 261.1127, found 261.1134.

*Ethyl 5-(4-fluorophenyl)-2-methylfuran-3-carboxylate[10b] (**4ca**):* white solid (35 mg, 70% yield, eluent = hexane/EtOAc (98:2)); mp = 63−65 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.82−7.40 (m, 2H), 7.07 (t, J = 8.8 Hz, 2H), 6.81 (s, 1H), 4.31 (q, J = 7.1 Hz, 2H), 2.63 (s, 3H), 1.37 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.2, 162.5 (d, J_{C-F} = 246 Hz), 158.8, 151.1, 126.7 (d, J_{C-F} = 4 Hz), 125.7 (d, J_{C-F} = 8 Hz), 116.0 (d, J_{C-F} = 22 Hz), 115.7, 105.4, 60.5, 14.6, 14.1; HRMS (ESI) calcd for $C_{14}H_{14}FO_3$ $[M + H]^+$ 249.0927, found 249.0935.

*Ethyl 5-(4-bromophenyl)-2-methylfuran-3-carboxylate[10b] (**4da**):* white solid (46 mg, 74% yield, eluent = hexane/EtOAc (97:3)); mp = 75−77 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 (s, 4H), 6.87 (s, 1H), 4.31 (q, J = 7.1 Hz, 2H), 2.63 (s, 3H), 1.37 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 158.9, 150.7, 131.9, 129.0, 125.1, 121.4, 115.6, 106.1, 60.3, 14.4, 13.9; HRMS (ESI) calcd for $C_{14}H_{14}BrO_3$ $[M + H]^+$ 309.0126, found 309.0131.

*Ethyl 2-methyl-5-(4-nitrophenyl)furan-3-carboxylate (**4ea**):* yellow solid (21 mg, 38% yield, eluent = hexane/EtOAc (92:8)); mp = 131−133 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.25 (d, J = 9.0 Hz, 2H), 7.77 (d, J = 9.0 Hz, 2H), 7.12 (s, 1H), 4.34 (q, J = 7.1 Hz, 2H), 2.69 (s, 3H), 1.39 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 160.6, 149.4, 146.6, 135.7, 124.4, 123.8, 116.3, 109.6, 60.5, 14.4, 14.0; HRMS (ESI) calcd for $C_{14}H_{14}NO_5$ $[M + H]^+$ 276.0872, found 276.0876.

*Ethyl 2-methyl-5-(o-tolyl)furan-3-carboxylate[18] (**4fa**):* colorless oil (27 mg, 56% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$): 7.87−7.62 (m, 1H), 7.36−7.17 (m, 3H), 6.77 (s, 1H), 4.32 (q, J = 7.1 Hz, 2H), 2.65 (s, 3H), 2.49 (s, 3H), 1.37 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.2, 158.2, 151.2, 134.6, 131.2, 129.4, 127.7, 126.8, 126.0, 115.2, 109.1, 60.2, 21.9, 14.4, 13.9; HRMS (ESI) calcd for $C_{15}H_{17}O_3$ $[M + H]^+$ 245.1178, found 245.1169.

*Ethyl 2-methyl-5-(naphthalen-2-yl)furan-3-carboxylate[18] (**4ga**):* white solid (49 mg, 87% yield, eluent = hexane/EtOAc (97:3)); mp = 91−93 °C (lit.[18] 96 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.08 (s, 1H), 7.80 (dd, J = 17.4, 8.4 Hz, 3H), 7.69 (dd, J = 8.5, 1.6 Hz, 1H), 7.52−7.38 (m, 2H), 6.98 (s, 1H), 4.32 (q, J = 7.1 Hz, 2H), 2.67 (s, 3H), 1.37 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.2, 159.1, 152.0, 133.7, 133.0, 128.7, 128.4, 128.0, 127.6, 126.8, 126.3, 122.3, 122.2, 115.8, 106.3, 60.4, 14.6, 14.2; HRMS (ESI) calcd for $C_{18}H_{17}O_3$ $[M + H]^+$ 281.1178, found 281.1183.

*Ethyl 5-methyl-[2,2′-bifuran]-4-carboxylate[19] (**4ha**):* brown oil (38 mg, 86% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 (dd, J = 1.7, 0.7 Hz, 1H), 6.77 (s, 1H), 6.54 (d, J = 3.3 Hz, 1H), 6.45 (dd, J = 3.4, 1.8 Hz, 1H), 4.30 (q, J = 7.1 Hz, 2H), 2.63 (s, 3H), 1.36 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 158.4, 145.7, 144.3, 142.1, 115.1, 111.3, 105.5, 60.3, 14.3, 13.8; HRMS (ESI) calcd for $C_{12}H_{13}O_4$ $[M + H]^+$ 221.0814, found 221.0821.

*Ethyl 2-methyl-5-(thiophene-2-yl)furan-3-carboxylate[10b] (**4ia**):* colorless oil (37 mg, 78% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26−7.25 (m, 2H), 7.05 (dd, J = 5.0, 3.7 Hz, 1H), 6.75 (s, 1H), 4.33 (q, J = 7.1 Hz, 2H), 2.65 (s, 3H), 1.39 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.9, 158.3, 147.3, 132.8, 127.6, 124.4, 122.9, 115.4, 105.4, 60.3, 14.4, 13.8; HRMS (ESI) calcd for $C_{12}H_{13}O_3S$ $[M + H]^+$ 237.0585, found 237.0596.

*Ethyl 5-butyl-2-methylfuran-3-carboxylate[10a] (**4ja**):* colorless oil (31 mg, 73% yield, eluent = hexane/EtOAc (98:2)); ^{1}H NMR (400 MHz, $CDCl_3$): 6.24 (s, 1H), 4.29 (q, J = 7.1 Hz, 2H), 2.67−2.43 (m, 5H), 1.70−1.58 (m, 2H), 1.42−1.34 (m, 5H), 0.95 (t, J = 7.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.4, 157.5, 154.4, 113.8, 105.4, 59.9, 29.9, 27.3, 22.2, 14.4, 13.8, 13.7; HRMS (ESI) calcd for $C_{12}H_{19}O_3$ $[M + H]^+$ 211.1334, found 211.1324.

*Ethyl 5-cyclopropyl-2-methylfuran-3-carboxylate (**4ka**):* colorless oil (32 mg, 82% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.17 (s, 1H), 4.26 (q, J = 7.1 Hz, 2H), 2.51 (s, 3H), 1.90−1.71 (m, 1H), 1.33 (t, J = 7.1 Hz, 3H), 0.95−0.78 (m, 2H), 0.77−0.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.3, 157.2, 155.3, 113.9, 104.1, 59.9, 14.4, 13.7, 8.3, 6.4; HRMS (ESI) calcd for $C_{11}H_{15}O_3$ $[M + H]^+$ 195.1021, found 195.1024.

*Ethyl 5-cyclohexyl-2-methylfuran-3-carboxylate (**4la**):* colorless oil (36 mg, 76% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.19 (d, J = 0.7 Hz, 1H), 4.26 (q, J = 7.1 Hz, 2H), 2.52 (s, 4H), 2.09−1.96 (m, 2H), 1.89−1.73 (m, 2H), 1.40−1.17 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.5, 158.8, 157.2, 113.6, 103.5, 59.9, 36.9, 31.3, 26.0, 25.8, 14.4, 13.7; HRMS (ESI) calcd for $C_{14}H_{21}O_3$ $[M + H]^+$ 237.1491, found 237.1488.

*(E)-Ethyl 2-methyl-5-styrylfuran-3-carboxylate (**4ma**):* yellow oil (47 mg, 91% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$): 7.44 (d, J = 7.4 Hz, 2H), 7.33 (t, J = 7.6 Hz, 2H), 7.24 (dd, J = 8.6, 6.0 Hz, 1H), 7.00 (d, J = 16.3 Hz, 1H), 6.78 (d, J = 16.3 Hz, 1H), 6.56 (s, 1H), 4.29 (q, J = 7.1 Hz, 2H), 2.62 (s, 3H), 1.35 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.1, 159.1, 151.2, 137.0, 128.2, 128.0, 127.7, 126.6, 116.0, 115.6, 109.1, 60.4, 14.6, 14.2; HRMS (ESI) calcd for $C_{16}H_{17}O_3$ $[M + H]^+$ 257.1178, found 257.1185.

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*Diethyl 5,5′-(1,4-phenylene)bis(2-methylfuran-3-carboxylate) (**4na**):* 2.4 equiv (0.48 mmol) of ethyl 2-diazo-3-oxobutanoate was used; white solid (34 mg, 44% yield, eluent = hexane/EtOAc (97:3)); mp = 149−151 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (s, 4H), 6.92 (s, 2H), 4.34 (q, J = 7.1 Hz, 4H), 2.67 (s, 6H), 1.40 (t, J = 7.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 158.8, 151.3, 129.1, 123.9, 115.6, 105.8, 60.2, 14.4, 13.9; HRMS (ESI) calcd for $C_{22}H_{23}O_6$ $[M + H]^+$ 383.1495, found 383.1499.

General Procedure for Furan Synthesis from Enol Silyl Ethers and Diazoketones (Scheme 2). A 10 mL Schlenk tube equipped with a stirrer bar was charged with silyl enol ether (0.20 mmol), $Cu(hfacac)_2$ (9.6 mg, 0.020 mmol, 10 mol %) followed by the addition of dichloromethane (0.5 mL). A dichloromethane solution (0.5 mL) of diazoketone (0.26 mmol) was added dropwise over 5 min at room temperature. The resulting mixture was then stirred at 40 °C for 6 h. Upon cooling to room temperature, the reaction mixture was diluted with ethyl acetate (5 mL), passed through a pad of silica gel, and concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel to afford the furan product.

2-Methyl-3,5-diphenylfuran[11a] *(**4ao**):* brown oil (39 mg, 84% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (dd, J = 8.3, 1.1 Hz, 2H), 7.36−7.23 (m, 6H), 7.22−7.09 (m, 2H), 6.68 (s, 1H), 2.41 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.9, 147.8, 134.3, 131.1, 128.89, 128.85, 127.7, 127.3, 126.7, 123.7, 123.3, 106.7, 13.4; HRMS (ESI) calcd for $C_{17}H_{15}O$ $[M + H]^+$ 235.1123, found 235.1133.

2,3,5-Triphenylfuran[11a] *(**4ap**):* white solid (49 mg, 83% yield, eluent = hexane/EtOAc (97:3)); Mp = 91−93 °C (lit.[11a] mp 91−92 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85−7.81 (m, 2H), 7.74−7.63 (m, 2H), 7.56−7.52 (m, 2H), 7.50−7.42 (m, 4H), 7.42−7.29 (m, 5H), 6.88 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.8, 148.1, 134.6, 131.3, 130.8, 129.0, 128.94, 128.91, 128.6, 127.8, 127.7, 127.5, 126.4, 124.8, 124.1, 109.7; HRMS (ESI) calcd for $C_{22}H_{17}O$ $[M + H]^+$ 297.1279, found 297.1284.

*3-(4-Fluorophenyl)-2-methyl-5-phenylfuran (**4aq**):* brown oil (49 mg, 98% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75−7.68 (m, 2H), 7.46−7.38 (m, 4H), 7.31−7.27 (m, 1H), 7.19−7.10 (m, 2H), 6.78 (s, 1H), 2.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.7 (d, J_{C-F} = 244 Hz), 151.7, 147.4, 130.7, 130.1 (d, J_{C-F} = 4 Hz), 129.0 (d, J_{C-F} = 8 Hz), 128.7, 127.1, 123.5, 122.2, 115.5 (d, J_{C-F} = 21 Hz), 106.4, 13.1; HRMS (ESI) calcd for $C_{17}H_{14}FO$ $[M + H]^+$ 253.1029, found 253.1034.

2-Methyl-5-phenyl-3-(p-tolyl)furan[11d] *(**4ar**):* brown oil (35 mg, 71% yield, eluent = hexane/EtOAc (97:3)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63−7.54 (m, 2H), 7.32−7.20 (m, 4H), 7.14 (t, J = 7.8 Hz, 3H), 6.68 (s, 1H), 2.42 (s, 3H), 2.29 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 151.5, 147.3, 136.2, 131.2, 131.0, 129.3, 128.7, 127.4, 127.0, 123.4, 123.0, 106.6, 21.2, 13.2; HRMS (ESI) calcd for $C_{18}H_{17}O$ $[M + H]^+$ 249.1279, found 249.1284.

Methyl 4-oxo-2,4-diphenylbutanoate[20] *(**5**):* synthesized employing the general procedure for the reaction of α-diazo-β-ketoester (vide intra) without the treatment with *p*-toluenesulfonic acid monohydrate; colorless solid (47 mg, 88% yield, eluent = hexane/EtOAc (95:5)); mp = 100−102 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, J = 7.8 Hz, 2H), 7.56 (t, J = 7.4 Hz, 1H), 7.45 (t, J = 7.7 Hz, 2H), 7.35 (d, J = 4.1 Hz, 4H), 7.33−7.22 (m, 1H), 4.30 (dd, J = 10.3, 3.9 Hz, 1H), 3.95 (dd, J = 18.0, 10.3 Hz, 1H), 3.69 (s, 3H), 3.27 (dd, J = 18.0, 4.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.6, 173.9, 138.4, 136.4, 133.3, 128.9, 128.6, 128.1, 127.8, 127.6, 52.4, 46.4, 42.8; HRMS (ESI) calcd for $C_{17}H_{17}O_3$ $[M + H]^+$ 269.1178, found 269.1176.

Synthesis of Multisubstituted Pyrroles (Table 4): Method A. The copper-catalyzed reaction of silyl enol ether and α-diazo-β-ketoester was performed in the same manner as described above. The reaction mixture was then cooled to 0 °C, followed by the addition of THF (1.0 mL). A THF solution of tetrabutylammonium fluoride (1 M, 0.24 mL, 0.24 mmol) was added dropwise, and the resulting mixture was stirred at 0 °C for 15 min. The resulting solution was concentrated under reduced pressure using the Schlenk line, followed by the addition of ammonium acetate (123 mg, 1.6 mmol) and acetic acid (1.0 mL). The resulting mixture was stirred at 120 °C for 20 h. The reaction was cooled to room temperature and the solvents were removed under reduced pressure. The residue was purified by flash chromatography on silica gel to afford the pyrrole product.

Synthesis of Multisubstituted Pyrroles (Table 4): Method B. Method A was slightly modified. After desilylation with tetrabutylammonium fluoride, the resulting solution was concentrated under reduced pressure using the Schlenk line, followed by the addition of ammonium acetate (616 mg, 8.0 mmol). The resulting mixture was stirred at 120 °C for 14 h. The reaction was cooled to room temperature and diluted with ethyl acetate (20.0 mL), followed by extraction with water. The organic phase was dried over magnesium sulfate and concentrated under reduced pressure. The residue was purified by flash chromatography on silica gel to afford the pyrrole product.

Ethyl 2-methyl-5-phenyl-1H-pyrrole-3-carboxylate[12a] *(**6a**):* synthesized by method A; brown solid (38 mg, 83% yield, eluent = hexane/EtOAc (90:10)); mp = 114−116 °C (lit.[12a] mp 115−116 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.71 (s, 1H), 7.53−7.45 (m, 2H), 7.42−7.34 (m, 2H), 7.24 (dt, J = 9.0, 4.3 Hz, 1H), 6.87 (d, J = 2.9 Hz, 1H), 4.32 (q, J = 7.1 Hz, 2H), 2.61 (s, 3H), 1.39 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.7, 136.2, 131.9, 130.0, 128.9, 126.6, 123.7, 113.4, 107.4, 59.6, 14.5, 13.4; HRMS (ESI) calcd for $C_{14}H_{16}NO_2$ $[M + H]^+$ 230.1181, found 230.1184.

*Ethyl 5-(4-methoxyphenyl)-2-methyl-1H-pyrrole-3-carboxylate (**6b**):* synthesized by method B; brown solid (38 mg, 74% yield, eluent = hexane/EtOAc (90:10)); mp = 146−148 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.61 (s, 1H), 7.38 (d, J = 8.8 Hz, 2H), 6.89 (d, J = 8.8 Hz, 2H), 6.71 (d, J = 2.9 Hz, 1H), 4.29 (q, J = 7.1 Hz, 2H), 3.80 (s, 3H), 2.56 (s, 3H), 1.35 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.8, 158.5, 135.1, 130.1, 125.2, 124.9, 114.4, 113.1, 106.1, 59.5, 55.3, 14.5, 13.3; HRMS (ESI) calcd for $C_{15}H_{18}NO_3$ $[M + H]^+$ 260.1287, found 260.1300.

*Ethyl 5-(furan-2-yl)-2-methyl-1H-pyrrole-3-carboxylate (**6c**):* synthesized by method B; brown solid (19 mg, 44% yield, eluent = hexane/EtOAc (90:10)); mp = 134−136 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.54 (s, 1H), 7.34 (d, J = 1.7 Hz, 1H), 6.73 (d, J = 2.8 Hz, 1H), 6.42 (dd, J = 3.4, 1.8 Hz, 1H), 6.36 (d, J = 3.3 Hz, 1H), 4.28 (q, J = 7.1 Hz, 2H), 2.57 (s, 3H), 1.35 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.4, 147.3, 140.6, 135.5, 121.9, 113.1, 111.6, 106.6, 102.8, 59.5, 14.5, 13.3; HRMS (ESI) calcd for $C_{12}H_{14}NO_3$ $[M + H]^+$ 220.0974, found 220.0985.

*Ethyl 5-cyclopropyl-2-methyl-1H-pyrrole-3-carboxylate (**6d**):* synthesized by method A; colorless solid (32 mg, 82% yield, eluent = hexane/EtOAc (90:10)); mp = 55−57 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (s, 1H), 6.14 (d, J = 2.8 Hz, 1H), 4.24 (q, J = 7.1 Hz, 2H), 2.47 (s, 3H), 1.79−1.64 (m, 1H), 1.32 (t, J = 7.1 Hz, 3H), 0.84−0.71 (m, 2H), 0.66−0.52 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.9, 134.9, 132.6, 111.2, 105.4, 59.3, 14.5, 13.2, 7.7, 6.4; HRMS (ESI) calcd for $C_{11}H_{16}NO_2$ $[M + H]^+$ 194.1181, found 194.1184.

Ethyl 2,5-diphenyl-1H-pyrrole-3-carboxylate[12b] *(**6e**):* Synthesized by method A; yellow solid (39 mg, 66% yield, eluent = hexane/EtOAc (90:10)); mp = 149−151 °C (lit.[12c] mp 149−151 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.72 (s, 1H), 7.63−7.61 (m, 2H), 7.54−7.49 (m, 2H), 7.43−7.32 (m, 5H), 7.25 (dd, J = 8.8, 5.9 Hz, 1H), 7.00 (d, J = 3.0 Hz, 1H), 4.21 (q, J = 7.1 Hz, 2H), 1.26 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 137.8, 131.9, 131.8, 131.5, 129.04, 129.03, 128.4, 128.2, 127.0, 124.0, 113.8, 109.1, 59.8, 14.3; HRMS (ESI) calcd for $C_{19}H_{18}NO_2$ $[M + H]^+$ 292.1338, found 292.1336.

Ethyl 2-isopropyl-5-phenyl-1H-pyrrole-3-carboxylate[21] *(**6f**):* synthesized by method A; brown solid (47 mg, 92% yield, eluent = hexane/EtOAc (90:10)); mp = 111−113 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.46 (s, 1H), 7.54−7.42 (m, 2H), 7.37 (t, J = 7.8 Hz, 2H), 7.25−7.20 (m, 1H), 6.84 (d, J = 2.9 Hz, 1H), 4.29 (q, J = 7.1 Hz, 2H), 3.86 (hept, J = 7.0 Hz, 1H), 1.38−1.32 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.3, 146.0, 132.0, 129.7, 129.0, 126.6, 123.8, 112.0, 107.7, 59.5, 26.1, 22.0, 14.5; HRMS (ESI) calcd for $C_{16}H_{20}NO_2$ $[M + H]^+$ 258.1494, found 258.1502.

Synthesis of Multisubstituted Thiophenes (Table 4). The copper-catalyzed reaction and the TBAF-mediated desilylation were performed by the same procedure as described for the pyrrole

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synthesis. After desilylation, Lawesson's reagent (194 mg, 0.48 mmol) was added, and the resulting mixture was stirred at 50 °C for 12 h. The reaction was cooled to room temperature and the solvents were removed under reduced pressure. The residue was purified by flash chromatography on silica gel to afford the thiophene product.

*Ethyl 2-methyl-5-phenylthiophene-3-carboxylate (**7a**):* colorless oil (37 mg, 74% yield, eluent = hexane/EtOAc (95:5)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (s, 1H), 7.58−7.53 (m, 2H), 7.37 (t, J = 7.6 Hz, 2H), 7.31−7.25 (m, 1H), 4.33 (q, J = 7.1 Hz, 2H), 2.75 (s, 3H), 1.39 (t, J = 7.1 Hz, 3H).; ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.7, 148.5, 139.3, 133.7, 129.2, 128.9, 127.6, 125.6, 124.6, 60.4, 15.6, 14.4; HRMS (ESI) calcd for $C_{14}H_{15}O_2S$ $[M + H]^+$ 247.0793, found 247.0796.

*Ethyl 5-(4-methoxyphenyl)-2-methylthiophene-3-carboxylate (**7b**):* yellow solid (35 mg, 64% yield, eluent = hexane/EtOAc (95:5)); mp = 84−86 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54−7.45 (m, 3H), 6.92 (d, J = 8.8 Hz, 2H), 4.35 (q, J = 7.1 Hz, 2H), 3.85 (s, 3H), 2.76 (s, 3H), 1.41 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.7, 159.3, 147.6, 139.2, 129.1, 126.9, 126.5, 123.5, 114.3, 60.3, 55.4, 15.6, 14.4; HRMS (ESI) calcd for $C_{15}H_{17}O_3S$ $[M + H]^+$ 277.0898, found 277.0889.

*Ethyl 5-(furan-2-yl)-2-methylthiophene-3-carboxylate (**7c**):* reddish oil (22 mg, 47% yield, eluent = hexane/EtOAc (95:5)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (s, 1H), 7.39 (dd, J = 1.8, 0.7 Hz, 1H), 6.50−6.35 (m, 2H), 4.32 (q, J = 7.1 Hz, 2H), 2.73 (s, 3H), 1.38 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 148.6, 147.9, 141.8, 129.0, 128.8, 124.0, 111.7, 105.1, 60.4, 15.4, 14.4; HRMS (ESI) calcd for $C_{12}H_{13}O_3S$ $[M + H]^+$ 237.0585, found 237.0584.

*Ethyl 5-(4-methoxyphenyl)-2-methylthiophene-3-carboxylate (**7d**):* yellow oil (28 mg, 66% yield, eluent = hexane/EtOAc (95:5)); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.01 (d, J = 0.6 Hz, 1H), 4.28 (q, J = 7.1 Hz, 2H), 2.65 (s, 3H), 2.02−1.86 (m, 1H), 1.35 (t, J = 7.1 Hz, 3H), 0.96−0.91 (m, 2H), 0.70−0.66 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.7, 146.3, 143.4, 127.7, 124.2, 60.1, 15.4, 14.4, 10.6, 9.2; HRMS (ESI) calcd for $C_{11}H_{15}O_2S$ $[M + H]^+$ 211.0793, found 211.0796.

*Ethyl 2,5-diphenylthiophene-3-carboxylate[22] (**7e**):* yellow solid (38 mg, 62% yield, eluent = hexane/EtOAc (95:5)); mp = 44−46 °C (lit.[22] mp 45−46 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (s, 1H), 7.65 (d, J = 7.4 Hz, 2H), 7.58−7.55 (m, 2H), 7.45−7.41 (m, 5H), 7.35 (t, J = 7.4 Hz, 1H), 4.25 (q, J = 7.1 Hz, 2H), 1.23 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 149.7, 142.5, 133.4, 133.5, 129.8, 129.0, 128.6, 128.0, 127.9, 125.7, 125.4, 60.6, 14.0; HRMS (ESI) calcd for $C_{19}H_{17}O_2S$ $[M + H]^+$ 309.0949, found 309.0954.

*Methyl 2-(4-methoxyphenyl)-5-phenylthiophene-3-carboxylate (**7f**):* white solid (40 mg, 62% yield, eluent = hexane/EtOAc (95:5)); mp = 143−145 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (s, 1H), 7.64−7.52 (m, 2H), 7.49 (d, J = 8.7 Hz, 2H), 7.39 (t, J = 7.6 Hz, 2H), 7.30 (t, J = 7.4 Hz, 1H), 6.94 (d, J = 8.7 Hz, 2H), 3.84 (s, 3H), 3.76 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 160.1, 150.4, 141.9, 133.5, 131.1, 129.0, 128.0, 127.8, 125.7, 125.50, 125.45, 113.5, 55.3, 51.6; HRMS (ESI) calcd for $C_{19}H_{17}O_3S$ $[M + H]^+$ 325.0898, found 325.0893.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00904.

^{1}H and ^{13}C NMR spectra of all compounds (PDF)

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Notes

The authors declare no competing financial interest.

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