$FeCl_3$-Catalyzed Propargylation–Cycloisomerization Tandem Reaction: A Facile One-Pot Synthesis of Substituted Furans

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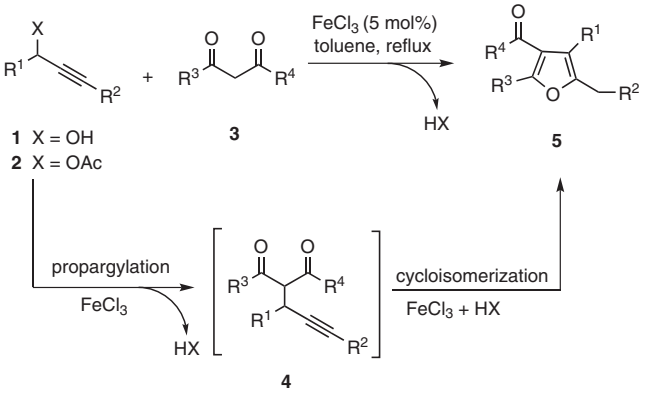
Abstract: An efficient $FeCl_3$-catalyzed tandem propargylation–cycloisomerization reaction of propargylic alcohols or acetates with 1,3-dicarbonyl compounds, leading to the synthesis of substituted furans, has been developed.

Key words: furans, iron(III) chloride, propargylic acetates, propargylic alcohols, tandem reaction

Nucleophilic substitution and cyclization are two major reactions in organic chemistry.[1,2] More powerful and useful transformations are possible when these two classes of reactions are combined in a one-pot procedure. Propargylic substitution followed by cycloisomerization recently developed in our group is a good example of such transformation.[3]

To extend the scope of the $FeCl_3$-catalyzed propargylic substitution reaction,[3a,c] we sought to explore the coupling of propargylic alcohols or acetates with 1,3-dicarbonyl compounds and subsequent cycloisomerization for the synthesis of tetrasubstituted furans. Recently, the efficient propargylation–cycloisomerization sequential reactions of propargylic alcohols with ketones or 1,3-dicarbonyl compounds in the presence of [Cp*RuCl(μ_2-SMe)$_2$-RuCp*Cl]–$PtCl_2$,[4] CF_3CO_2H–Ru(II)[5] or TsOH–K_2CO_3,[6] which lead to the synthesis of substituted furans, have been reported. However, these methods are only applicable to a relatively narrow range of substrates, and two different catalysts are needed. More recently, Tan[7] described an efficient method to synthesize tetrasubstituted furans via In-catalyzed propargylation–cyclization process, but the reaction was performed under N_2 atmosphere and required a rather long time for completion. Herein, we describe an efficient $FeCl_3$-catalyzed propargylation–cycloisomerization tandem reaction (Scheme 1).[8] $FeCl_3$ acts as a bifunctional catalyst and effectively catalyzes two reaction processes in a single reaction vessel under the same conditions. A range of secondary propargylic alcohols or acetates could be employed and a number of functionalities, such as chloro, bromo, ester, and methoxy, are tolerated under the reaction conditions.

Reaction of propargylic alcohol **1a** (**1**: X = OH; R^1 = Ph; R^2 = TMS) with ethyl acetoacetate (**3a**; R^3 = Me; R^4 = OEt) under the reaction conditions (5 mol% $FeCl_3$, toluene, r.t.), produced the coupling product **4a** (R^1 = Ph; R^2 = TMS; R^3 = Me; R^4 = OEt) in low yield, and no cycloisomerization product **5aa** (R^1 = Ph; R^2 = H; R^3 = Me; R^4 = OEt) was obtained. Gratifyingly, the tandem propargylic substitution–cycloisomerization proceeded well at reflux temperature for 0.8 hour, affording a 35% isolated yield of **5aa** and a 47% isolated yield of **4a** which could be completely converted into **5aa** in 82% total yield by extending the reaction time from 0.8 to 2 hours.



Scheme 1 Synthesis of furans from propargylic alcohols or acetates and 1,3-dicarbonyl compounds

With these conditions in hand, we examined the propargylation–cycloisomerization tandem reaction of a range of propargylic alcohols with various 1,3-dicarbonyl compounds (Table 1). The secondary propargylic alcohols **1a** and **1b** participated well in the tandem reaction, producing the propargylation–cycloisomerization products in high to excellent yields with complete regioselectivity (Table 1, entries 1–5 and 7–11). The reaction proceeded smoothly under mild conditions and air was tolerated. These were in contrast to the ruthenium-catalyzed processes[4,5] where the reactions had to be performed under a N_2 atmosphere. However, the trimethylsilyl group was not tolerated under the acidic condition and got removed during workup. Propargylic alcohol **1c** possessing an electron-donating group at the aryl ring reacted smoothly with 1,3-dicarbonyl compounds to afford the furans **5ca** and **5cc** in high yields (Table 1, entries 12 and 13). Moreover, substrates **1d** and **1e** possessing electron-withdrawing group (bromo and ester functionalities) at the aryl ring were also successfully employed in the tandem reaction to give the furans **5da**–**5ec** in moderate yields (Table 1, entries 14–17). Obviously, electron-rich propargylic alcohols provided propargy-

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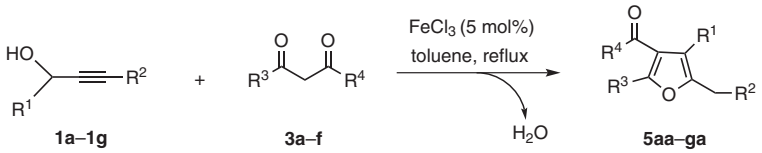
lation–cycloisomerization products in higher yields than electron-poor propargylic alcohols. It should also be noted that functional groups such as bromo, ester, and methoxy in the propargylic alcohols, were readily carried through the propargylation–cycloisomerization tandem reaction, allowing for the subsequent elaboration of the products (Table 1, entries 12–17). Unfortunately, attempted propargylation–cycloisomerization of terminal propargylic alcohol **1f** and internal propargylic alcohol **1g** did not lead to the expected furans, but to a γ-alkynyl ketone intermediate (Table 1, entries 18 and 19). The results suggested that the presence of trimethylsilyl group was vital to the $FeCl_3$-catalyzed cyclization of γ-alkynyl ketones.[9] Among the 1,3-dicarbonyl compounds that were examined, β-diketones **3d** and **3c** gave the most desirable results (Table 1, entries 3, 4, 9, 10, 13, 15 and 17), and β-keto esters **3a** and **3b** also gave the propargylation–cycloisomerization products in moderate to good yields except for entries 18 and 19 (Table 1, entries 1, 2, 7, 8, 12, 14 and 16). However, by using diethyl malonate (**3f**), no furan formation was observed (Table 1, entry 6). In all cases, the results showed that the reactivity of various 1,3-dicarbonyl compounds followed the general trend **3d** >**3c** >**3a**, **3b** >**3f**. Nevertheless, compared with β-keto esters **3a** and **3b**, 1,3-cyclohexanedione (**3e**) reacted more sluggishly to give the propargylation–cycloisomerization products in lower yields (Table 1, entries 5 and 11), possibly due to the steric bulkiness of **3e**. Unfortunately, the reaction of propargylic alcohol **1a** with 1,3-cyclopentadione afforded a complex mixture.

Table 1 Synthesis of Furans from Propargylic Alcohols **1a**–**1g** and 1,3-Dicarbonyl Compounds **3**[a]



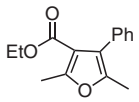
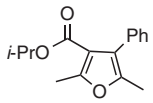
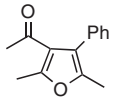
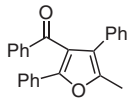
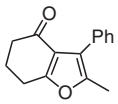
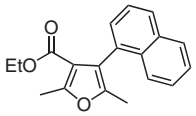
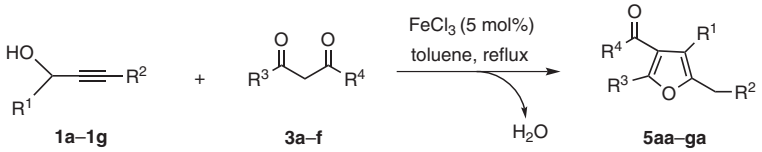
Entry	Propargylic alcohol	1,3-Dicarbonyl compound	Product	Time (h)	Isolated yield (%)
1	**1a**: R^1 = Ph; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	 **5aa**	2	82
2		**3b**: R^3 = Me; R^4 = O*i*-Pr	 **5ab**	2	81
3		**3c**: R^3 = R^4 = Me	 **5ac**	0.7	86
4		**3d**: R^3 = R^4 = Ph	 **5ad**	0.7	90
5		**3e**: R^3 = R^4 = $(CH_2)_3$	 **5ae**	3	72
6		**3f**: R^3 = OEt; R^4 = OEt	–[b]	24	0[b]
7	**1b**: R^1 = 1-naphthyl; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	 **5ba**	2	84

Table 1 Synthesis of Furans from Propargylic Alcohols **1a–1g** and 1,3-Dicarbonyl Compounds **3**[a] (continued)



1a–1g **3a–f** **5aa–ga**

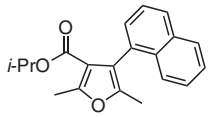
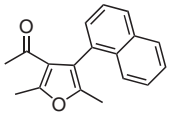
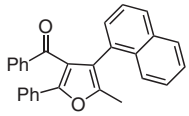
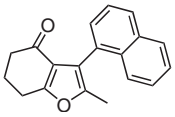
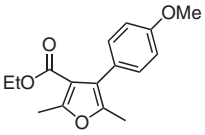
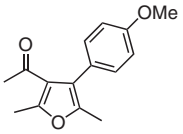
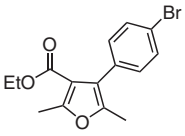
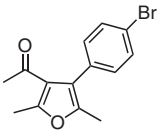
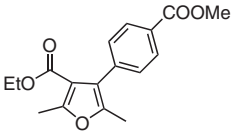
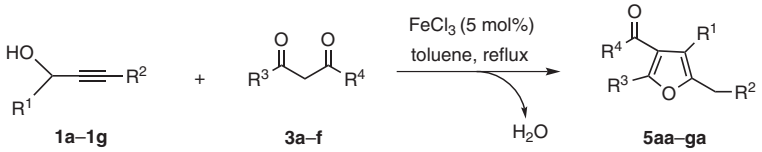
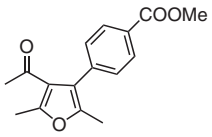
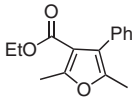
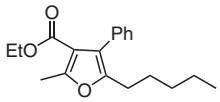
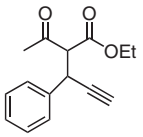
Entry	Propargylic alcohol	1,3-Dicarbonyl compound	Product	Time (h)	Isolated yield (%)
8		**3b**: R^3 = Me; R^4 = O*i*-Pr	 **5bb**	2	82
9		**3c**: R^3 = R^4 = Me	 **5bc**	0.7	87
10		**3d**: R^3 = R^4 = Ph	 **5bd**	0.7	92
11		**3e**: R^3 = R^4 = $(CH_2)_3$	 **5be**	3	73
12	**1c**: R^1 = PMP; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	 **5ca**	1.5	84
13		**3c**: R^3 = R^4 = Me	 **5cc**	0.5	88
14	**1d**: R^1 = 4-BrC_6H_4; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	 **5da**	4	62
15		**3c**: R^3 = R^4 = Me	 **5dc**	3	67
16	**1e**: R^1 = 4-$MeO_2CC_6H_4$; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	 **5ea**	4.5	47

Table 1 Synthesis of Furans from Propargylic Alcohols **1a–1g** and 1,3-Dicarbonyl Compounds **3**[a] (continued)

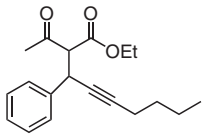


Entry	Propargylic alcohol	1,3-Dicarbonyl compound	Product	Time (h)	Isolated yield (%)
17		**3c**: $R^3 = R^4 = Me$	 **5ec**	3.5	55
18	**1f**: $R^1 = Ph$; $R^2 = H$	**3a**: $R^3 = Me$; $R^4 = OEt$	 **5aa**	24	0[c]
19	**1g**: $R^1 = Ph$; $R^2 = n$-Bu	**3a**: $R^3 = Me$; $R^4 = OEt$	 **5ga**	24	0[c]

[a] Conditions: propargylic alcohols **1** (0.5 mmol), 1,3-dicarbonyl compounds **3** (2.0 mmol), $FeCl_3$ (0.025 mmol), toluene (2.0 mL), reflux.
[b] A complex mixture was obtained.
[c] The propargylic alcohols were completely consumed and γ-alkynyl ketones **4f** and **4g** were obtained in 75 and 81% yield, respectively.



4f

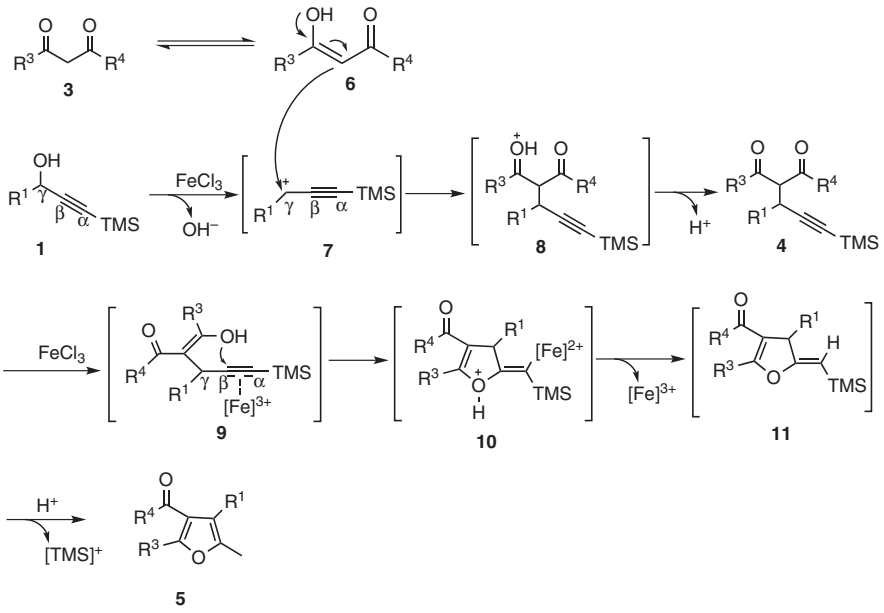


4g

We propose the sequence outlined in Scheme 2 as the likely mechanism for the propargylation–cycloisomerization tandem reaction. Firstly, the ionization of propargylic alcohol **1** would lead to a propargylic cation **7** and the subsequent nucleophilic attack of the enol **6** would give a γ-alkynyl ketone **4**. Coordination of iron(III) to the alkyne would form the π-alkyne iron complex **9** and would enhance the electrophilicity of alkyne. Subsequent 5-*exo-dig* nucleophilic attack of the hydroxyl group on β-carbon of Fe(III)–alkyne complex **9** would generate the alkenyl-iron derivative **10**. Protonolysis of **10** would afford a dihydrofuran **11**, which would then undergo isomerization and desilylation to give furan **5**.

In the proposed mechanism, the formation of propargylic cation **7** and the intramolecular nucleophilic addition of the π-alkyne iron complex **9** are the two critical steps, and the γ-effect and β-effect of the silicon atom play important roles here.[10] The γ-effect of silicon atom stabilizes positive charges in the γ-carbon of propargylic cation **7** and favors the propargylic substitution. On the other hand, the β-effect of silicon atom polarizes the acetylenic bond of complex **9**, and leads to a decrease in the electronic densities on β-carbon, so β-carbon undergoes readily intramolecular nucleophilic attack with the hydroxyl group. Thus, it is anticipated that the propargylic alcohols possessing trimethylsilyl group at R^2 would exhibit unique reactivity. In addition, the proposed mechanism is also in accordance with the observation that the reactivity of 1,3-dicarbonyl compounds follows the trend **3d >3c >3a**, **3b >3f**.[11]

As shown in Table 1, some cases gave the desired furans in somewhat low yields, or even could not afford cyclization products. We reasoned that one equivalent of water produced in the propargylic substitution would suppress the cycloisomerization reaction. Accordingly, we began searching for an appropriate leaving group, which we thought would readily allow for the propargylation–cycloisomerization tandem reaction. We were pleased to find that replacement of the propargylic alcohols with the corresponding propargylic acetates gave the substituted furans in desired yields, and acetic acid produced in the propargylic substitution has no effect on the catalyst activity of $FeCl_3$. To assess the synthetic utility of propargylic acetates versus propargylic alcohols, comparative experiments were performed. Obviously, significantly increased yields of the desired products were obtained for all cases when propargylic acetates were used as substrates, compared to propargylic alcohols. The typical results are depicted in Table 2. For example, treatment of propargylic acetate **2e** with ethyl acetoacetate (**3a**) greatly increased the yield of the tetrasubstituted furan **5ea** from 47% to

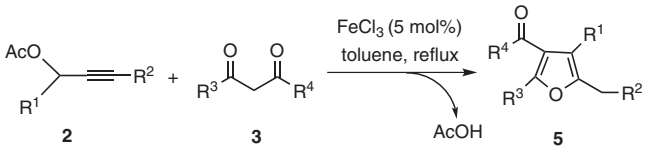


Scheme 2 Proposed mechanism for the propargylation–cycloisomerization tandem reaction

63% whilst reducing the reaction time from 4.5 to 3 hours (Table 2, entry 3). Most notably, terminal propargylic acetate **2f** and internal propargylic acetates **2g**–**2i** possessing a *n*-Bu group at R^2 were successfully employed in the propargylation–cycloisomerization tandem reaction to give the desired furans, albeit in somewhat low yields (Table 2, entries 5–10).

To verify the effects of water and acetic acid on the cycloisomerization reaction, the $FeCl_3$-catalyzed cycloisomerizations of γ-alkynyl ketones **4f** and **4g** were studied as model reactions. The results are summarized in Table 3. γ-Alkynyl ketones **4f** and **4g** underwent the intramolecular cycloisomerization in the presence of 5 mol% $FeCl_3$ to give the corresponding furans in 45% and 42% yields, re-

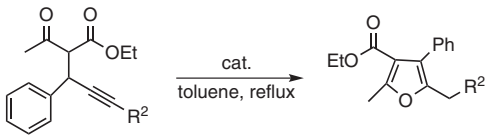
Table 2 Synthesis of Furans from Propargylic Acetates **2d**–**2i** and 1,3-Dicarbonyl Compounds **3**[a]



Entry	**2**	**3**	**5**	Time (h)	Isolated yield (%)
1	**2d**: R^1 = 4-BrC_6H_4; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	**5da**	3 (4)[b]	73 (62)[c]
2		**3c**: R^3 = R^4 = Me	**5dc**	2.5 (3)[b]	77 (67)[c]
3	**2e**: R^1 = 4-$MeO_2CC_6H_4$; R^2 = TMS	**3a**: R^3 = Me; R^4 = OEt	**5ea**	3 (4.5)[b]	63 (47)[c]
4		**3c**: R^3 = R^4 = Me	**5ec**	3 (3.5)[b]	70 (55)[c]
5	**2f**: R^1 = Ph; R^2 = H	**3a**: R^3 = Me; R^4 = OEt	**5aa**	4 (24)[b]	33 (0)[c]
6		**3c**: R^3 = R^4 = Me	**5ac**	3 (24)[d]	45 (0)[e]
7	**2g**: R^1 = Ph; R^2 = *n*-Bu	**3a**: R^3 = Me; R^4 = OEt	**5ga**	4.5 (24)[b]	36 (0)[c]
8		**3c**: R^3 = R^4 = Me	**5gc**	3.5 (24)[d]	48 (0)[e]
9	**2h**: R^1 = 2-$MeOC_6H_4$; R^2 = *n*-Bu	**3c**: R^3 = R^4 = Me	**5hc**	3 (24)[d]	54 (0)[e]
10	**2i**: R^1 = 4-ClC_6H_4; R^2 = *n*-Bu	**3c**: R^3 = R^4 = Me	**5ic**	3.5 (24)[d]	37 (0)[e]

[a] Conditions: propargylic acetates **2** (0.5 mmol), 1,3-dicarbonyl compounds **3** (2.0 mmol), $FeCl_3$ (0.025 mmol), toluene (2.0 mL), reflux.
[b] Values in parentheses are the reaction times when the corresponding propargylic alcohols are used as substrates. See Table 1.
[c] Values in parentheses are the yields when the corresponding propargylic alcohols are used as substrates. See Table 1.
[d] Values in parentheses are the reaction times when the corresponding propargylic alcohols are used as substrates.
[e] Values in parentheses are the yields when the corresponding propargylic alcohols are used as substrates.

Table 3 $FeCl_3$-Catalyzed Cycloisomerization of **4f** and **4g**[a]



4f R^2 = H
4g R^2 = *n*-Bu

5aa R^2 = H
5ga R^2 = *n*-Bu

Entry	**4**	Catalyst	Time (h)	Isolated yield (%)
1	**4f**: R^2 = H	$FeCl_3$ (5 mol%)	3	45
2		$FeCl_3$ (5 mol%)–AcOH (1 equiv)	2.5	44
3		$FeCl_3$ (5 mol%)–H_2O (1 equiv)	24	n.r.[b]
4		AcOH (1 equiv)	24	n.r.[b]
5	**4g**: R^2 = *n*-Bu	$FeCl_3$ (5 mol%)	3.5	42
6		$FeCl_3$ (5 mol%)–AcOH (1 equiv)	3	40
7		$FeCl_3$ (5 mol%)–H_2O (1 equiv)	24	n.r.[b]
8		AcOH (1 equiv)	24	n.r.[b]

[a] The cycloisomerization reactions of **4f** and **4g** (0.5 mmol) were carried out in the presence of catalyst in toluene (2.0 mL) at reflux.
[b] n.r. = no reaction.

spectively (Table 3, entries 1 and 5). Addition of one equivalent of acetic acid accelerated the intramolecular cycloisomerization while retaining the moderate yields (Table 3, entries 2 and 6). In contrast, in the presence of one equivalent of H_2O, no formation of the desired furans was observed (Table 3, entries 3 and 7). The results suggested that water completely inhibited the $FeCl_3$-catalyzed intramolecular cycloisomerization of the γ-alkynyl ketones **4f** and **4g**, whereas acetic acid had essentially no effect. The propargylation of 1,3-dicarbonyl compounds with propargylic acetates provided one equivalent of AcOH, while the reaction with propargylic alcohols provided one equivalent of H_2O. Therefore, it is anticipated that the propargylic acetates have higher reactivity than propargylic alcohols in the propargylation–cycloisomerization tandem reaction catalyzed by $FeCl_3$.

In summary, we have developed an efficient method for the synthesis of the substituted furans using $FeCl_3$ as catalyst. Iron(III) chloride operating as a bifunctional catalyst, catalyzes two mechanistically distinct processes in a single pot under the same reaction conditions; namely, propargylation followed by cycloisomerization. This facile methodology allows rapid access to a variety of tetrasubstituted furans. In comparison with the ruthenium complex, $FeCl_3$ as the catalyst offers several relevant advantages including being inexpensive and commercially available and allowing mild reaction conditions. Further development of this methodology is currently underway in our laboratory.

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synlett.

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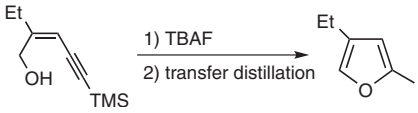
(8) **General Procedure for Synthesis of Tetrasubstituted Furans**: To a 5-mL flask, propargylic alcohols **1** or propargylic acetates **2** (0.5 mmol), 1,3-dicarbonyl compounds **3** (2.0 mmol), toluene (2.0 mL), and $FeCl_3$ (0.025 mmol, 4 mg) were successively added. The reaction mixture was stirred at reflux, and monitored periodically by TLC. Upon completion, toluene was removed under reduced pressure by an aspirator, and then the residue was purified by silica gel column chromatography (EtOAc–hexane) to

afford the corresponding tetrasubstituted furans **5**.

Data of selected compounds: **5ab**: yellow solid; mp 50–51 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.08 (d, 6 H, *J* = 6.0 Hz), 2.18 (s, 3 H), 2.56 (s, 3 H), 5.01 (sept, 1 H, *J* = 6.4 Hz), 7.22–7.25 (m, 2 H), 7.27–7.30 (m, 1 H), 7.32–7.37 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.7, 14.0, 21.7, 67.2, 113.9, 122.5, 126.7, 127.6, 130.1, 133.4, 146.9, 157.2, 163.9. IR (film): 1704 cm^{-1}. MS (ESI): *m/z* (%) = 281 (100) [M + Na$^+$]. Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.39; H, 7.02. Found: C, 74.24; H, 7.19. **5ad**: white solid; mp 117–118 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.46 (s, 3 H), 7.12–7.28 (m, 10 H), 7.35–7.39 (m, 1 H), 7.55–7.58 (m, 2 H), 7.80–7.82 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 12.3, 121.7, 123.5, 126.2, 126.9, 128.1, 128.2, 128.3, 128.4, 129.0, 129.7, 129.8, 132.2, 133.2, 137.4, 148.1, 150.8, 193.8. IR (film): 1669 cm^{-1}. MS (ESI): *m/z* (%) = 361 (100) [M + Na$^+$]. Anal. Calcd for $C_{24}H_{18}O_2$: C, 85.18; H, 5.36. Found: C, 85.31; H, 5.14. **5ae**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.12–2.19 (m, 2 H), 2.30 (s, 3 H), 2.46–2.49 (m, 2 H), 2.87 (t, 2 H, *J* = 6.4 Hz), 7.26–7.31 (m, 1 H), 7.34–7.39 (m, 4 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 12.2, 22.7, 23.9, 38.9, 119.4, 119.9, 127.3, 128.1, 130.0, 131.9, 148.9, 165.9, 194.3. IR (film): 1675 cm^{-1}. MS (ESI): *m/z* (%) = 227 (36) [M + H$^+$], 249 (100) [M + Na$^+$]. Anal. Calcd for $C_{15}H_{14}O_2$: C, 79.62; H, 6.24. Found: C, 79.79; H, 6.09. **5bb**: pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.39 (d, 3 H, *J* = 6.4 Hz), 0.68 (d, 3 H, *J* = 6.4 Hz), 2.11 (s, 3 H), 2.65 (s, 3 H), 4.68 (sept, 1 H, *J* = 6.4 Hz), 7.28–7.48 (m, 4 H), 7.64 (d, 1 H, *J* = 8.4 Hz), 7.81 (d, 1 H, *J* = 8.4 Hz), 7.84 (d, 1 H, *J* = 8.0 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.7, 13.7, 20.7, 21.3, 66.6, 115.3, 119.1, 125.1, 125.5, 125.6, 126.2, 127.4, 127.9, 131.9, 133.3, 133.4, 147.6, 157.6, 163.7. IR (film): 1704 cm^{-1}. HRMS: *m/z* calcd for $C_{20}H_{20}O_3$: 308.1412; found: 308.1413. **5bd**: pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.27 (s, 3 H), 7.03 (dd, app. t, 2 H, *J* = 7.6, 7.6 Hz), 7.17–7.32 (m, 6 H), 7.39–7.41 (m, 2 H), 7.62–7.67 (m, 5 H), 7.73–7.75 (m, 1 H), 7.84–7.86 (m, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 12.5, 121.5, 123.2, 125.1, 125.7, 125.76, 126.1, 126.5, 127.8, 127.9, 128.2, 128.3, 128.4, 128.5, 129.4, 129.7, 129.9, 132.2, 132.7, 133.5, 137.4, 149.2, 151.9, 193.3. IR (film): 1658 cm^{-1}. MS (ESI): *m/z* (%) = 389 (100) [M + H$^+$]. Anal. Calcd for $C_{28}H_{20}O_2$: C, 86.57; H, 5.19. Found: C, 86.39; H, 5.34. **5da**: white solid; mp 96–97 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.15 (t, 3 H, *J* = 7.2 Hz), 2.19 (s, 3 H), 2.57 (s, 3 H), 4.15 (q, 2 H, *J* = 7.2 Hz), 7.14 (d, 2 H, *J* = 8.4 Hz), 7.49 (d, 2 H, *J* = 8.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.7, 14.0, 14.1, 59.9, 113.2, 120.4, 120.9, 130.8, 131.7, 132.3, 147.2, 157.7, 164.1. IR (film): 1701 cm^{-1}. MS (ESI): *m/z* (%) = 345 (100), 347 (90) [M + Na$^+$]. Anal. Calcd for $C_{15}H_{15}BrO_3$: C, 55.75; H, 4.68. Found: C, 55.51; H, 4.82. **5dc**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.00 (s, 3 H), 2.17 (s, 3 H), 2.55 (s, 3 H), 7.14 (d, 2 H, *J* = 8.8 Hz), 7.55 (d, 2 H, *J* = 8.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.6, 14.3, 30.8, 119.8, 121.5, 122.8, 131.5, 131.6, 132.7, 147.2, 156.4, 195.5. IR (film): 1623 cm^{-1}. MS (ESI): *m/z* (%) = 315 (100), 317 (86) [M + Na$^+$]. Anal. Calcd for $C_{14}H_{13}BrO_2$: C, 57.36; H, 4.47. Found: C, 57.47; H, 4.29. **5ea**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.09 (t, 3 H, *J* = 7.2 Hz), 2.20 (s, 3 H), 2.58 (s, 3 H), 3.93 (s, 3 H), 4.12 (q, 2 H, *J* = 7.2 Hz), 7.33 (d, 2 H, *J* = 8.4 Hz), 8.03 (d, 2 H, *J* = 8.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.8, 13.9, 14.1, 52.1, 59.9, 113.3, 120.6, 128.4, 128.9, 130.0, 138.4, 147.5, 157.9, 164.1, 167.1. IR (film): 1723 cm^{-1}. HRMS: *m/z* calcd for $C_{17}H_{19}O_5H^+$: 303.1236; found: 303.1227. **5ec**: yellow solid; mp 100–101 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.97 (s, 3 H), 2.18 (s, 3 H), 2.54 (s, 3 H), 3.94 (s, 3 H), 7.33 (d, 2 H, *J* = 8.4 Hz), 8.08 (d, 2 H, *J* = 8.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 11.6, 14.2, 30.7, 52.2, 120.1, 122.8, 129.0, 129.6, 129.8, 138.7, 147.3, 156.4, 166.8, 195.4. IR (film): 1725, 1671 cm^{-1}. MS (ESI): *m/z* (%) = 273 (18) [M + H$^+$], 295 (100) [M + Na$^+$]. Anal. Calcd for $C_{16}H_{16}O_4$: C, 70.57; H, 5.92. Found: C, 70.85; H, 5.81. **5ga**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.84 (t, 3 H, *J* = 6.8 Hz), 1.07 (t, 3 H, *J* = 7.2 Hz), 1.20–1.27 (m, 4 H), 1.54–1.62 (m, 2 H), 2.49 (t, 2 H, *J* = 7.6 Hz), 2.58 (s, 3 H), 4.09 (q, 2 H, *J* = 7.2 Hz), 7.22–7.24 (m, 2 H), 7.27–7.30 (m, 1 H), 7.31–7.36 (m, 2 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 13.8, 13.9, 14.1, 22.3, 25.8, 28.2, 31.2, 59.7, 113.5, 121.2, 126.7, 127.5, 130.0, 133.4, 151.3, 157.4, 164.4. IR (film): 1712 cm^{-1}. MS (ESI): *m/z* (%) = 323 (100) [M + Na$^+$]. Anal. Calcd for $C_{19}H_{24}O_3$: C, 75.97; H, 8.05. Found: C, 75.80; H, 8.23. **5hc**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.84 (t, 3 H, *J* = 6.8 Hz), 1.18–1.28 (m, 4 H), 1.53–1.61 (m, 2 H), 1.90 (s, 3 H), 2.43 (t, 2 H, *J* = 8.0 Hz), 2.54 (s, 3 H), 3.75 (s, 3 H), 6.93 (d, 1 H, *J* = 8.4 Hz), 6.90–7.02 (m, 1 H), 7.16 (dd, 1 H, *J* = 7.6, 1.6 Hz), 7.32–7.36 (m, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 13.9, 14.3, 22.3, 25.9, 28.1, 29.3, 31.2, 55.2, 110.6, 116.6, 120.6, 122.7, 123.2, 129.2, 131.4, 151.1, 155.8, 157.3, 196.2. IR (film): 1673 cm^{-1}. HRMS: *m/z* [M + H$^+$] calcd for $C_{19}H_{25}O_3$: 301.1806; found: 301.1798. **5ic**: yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.77 (t, 3 H, *J* = 7.2 Hz), 1.09–1.22 (m, 4 H), 1.44–1.52 (m, 2 H), 1.88 (s, 3 H), 2.36 (t, 2 H, *J* = 7.6 Hz), 2.46 (s, 3 H), 7.09 (d, 2 H, *J* = 8.4 Hz), 7.29 (d, 2 H, *J* = 8.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 13.9, 14.4, 22.2, 25.7, 28.1, 30.8, 31.1, 119.5, 122.7, 128.6, 131.2, 132.3, 133.3, 151.3, 156.5, 195.5. IR (film): 1675 cm^{-1}. MS (ESI): *m/z* (%) = 305 (24) [M + H$^+$], 327 (100) [M + Na$^+$]. Anal. Calcd for $C_{18}H_{21}ClO_2$: C, 70.93; H, 6.94. Found: C, 70.81; H, 7.09.

(9) Gabriele has also reported that 4-ethyl-2-methylfuran could be obtained directly by treatment of (*Z*)-2-ethyl-5-trimethylsilylpent-2-en-4-yn-1-ol with TBAF without added solvent followed by transfer distillation; however, PdI_2 as the catalyst is needed in the absence of trimethylsilyl group (Scheme 3). See: Gabriele, B.; Salerno, G.; Lauria, E. *J. Org. Chem.* **1999**, *64*, 7687.



Scheme 3

(10) For synthetic applications of the γ-effect and β-effect of silicon, see: (a) Sakurai, H.; Imai, T.; Hosomi, A. *Tetrahedron Lett.* **1977**, *18*, 4045. (b) Hatanaka, Y.; Kuwajima, I. *Tetrahedron Lett.* **1986**, *27*, 719. (c) Antras, F.; Ahmar, M.; Cazes, B. *Tetrahedron Lett.* **2001**, *42*, 8157.

(11) The percentages of the enol content of 1,3-dicarbonyl compounds in CCl_4 follow the order: dibenzoylmethane (**3d**; 96%) > acetylacetone (**3c**; 80%) > ethyl acetoacetate (**3a**; 7.5%) > diethyl malonate (**3f**; 0.007%). See: Burdett, J. L.; Rogers, M. T. *J. Am. Chem. Soc.* **1964**, *86*, 2105.