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Iron-Catalyzed Synthesis of Functionalized 2*H*-Chromenes via Intramolecular Alkyne−Carbonyl Metathesis

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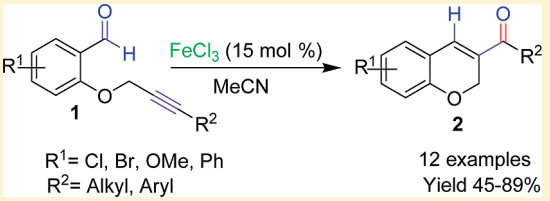
Supporting Information

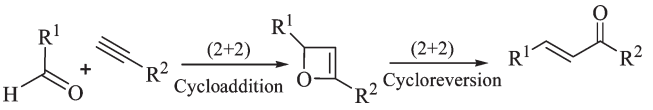
ABSTRACT: An iron-catalyzed intramolecular alkyne−aldehyde metathesis strategy of the alkynyl ether of salicylaldehyde derivatives has been developed which works under mild reaction conditions to produce the functionalized 2*H*-chromene derivatives. This protocol is compatible toward a wide range of functional groups, such as methoxy, fluoro, chloro, bromo, and phenyl groups. This method provides an atom-economical and environmentally friendly approach for the synthesis of a series of substituted 2*H*-chromenes.



Substituted 2*H*-chromenes (2*H*-1-benzopyran derivatives) are an important class of structural motif found in many natural products.[1] These also have very important medicinal qualities as anti-HIV,[2] antitumor,[3] antibacterial/antimicrobial,[4] fungicidal,[5] and insecticidal agents.[6] Moreover, 2*H*-chromene motifs are also present in various health-promoting agents like antioxidants[7] and polyphenols.[8] In addition to their biological applications, they have also been widely used as photochromic materials.[9] Consequently, significant efforts have been made toward the synthesis of substituted 2*H*-chromene motifs.[10] However, many of the reported methods suffer from low yields of the products, nonavailability of the substrates, use of a stoichiometric amount of reagents, and limitations of the specific substitution pattern. Very recently, a few catalytic methods have been developed using transition-metal complexes such as Pt,[11] Pd,[12] Au,[13] and Ru[14] to synthesize 2*H*-chromene derivatives. Among them, Pt- and Au-catalyzed hydroarylation reactions of the terminal alkyne are the most studied protocols; unfortunately, cyclization via a hydroarylation reaction often leads to mixture of products. Very recently, another alternative approach has been described by Aponick et al. involving a Au(I)-catalyzed dehydrative cyclization of salicylaldehyde-derived diols in the presence of AgOTf as a cocatalyst.[15] We noted, however, that many of the above-described approaches are associated with the use of toxic, moisture-sensitive, and expensive transition-metal complexes as catalyst. Considering these, the development of less expensive and environmentally benign C−C bond-forming approaches toward the synthesis of library of functionalized 2*H*-chromenes is therefore highly desirable.

On the other hand, alkyne−carbonyl metathesis is a very useful reaction for the construction of the carbon−carbon double bond as this transformation represents a completely atom-economical alternative to the use of stabilized Wittig reagents in carbonyl olefination reactions. This reaction generally proceeds via a formal [2 + 2] cycloaddition and cycloreversion pathway and produces conjugated carbonyl compounds (Scheme 1).

Scheme 1. Alkyne−Carbonyl Metathesis Reaction



A few Lewis and Brønsted acid catalyzed inter- and intramolecular versions of this reaction have been investigated recently. The intramolecular version of this reaction is very attractive because proper design of the substrates could lead to complex carbo- and heterocyclic compounds.[16] However, few studies toward the synthesis of heterocyclic compounds have achieved to date.[16a,b,g] Therefore, the construction of heterocycles using the alkyne−aldehyde metathesis reaction in the presence of an environmentally friendly and inexpensive catalyst would be of significant importance in organic synthesis.

Iron is one of the most abundant metals on the earth. Recently, it has received much attention as an alternative and promising catalyst for many organic transformations because of its easy availability, low price, sustainability, and environmentally friendly characteristics. As a consequence, a series of novel iron-catalyzed organic transformations including cross-couplings, oxidations, reductions, etc. have been developed.[17] Recently, iron salt has also been employed for the synthesis of 2*H*-chromenes via intramolecular hydroarylation of alkynes;[18] however, this method generally required 2−4 equiv of aniline as additives, and it works at high temperature in DMF solvent. In addition, it also suffers from concomitant formation of benzofuran derivatives. In continuation of our interests in the development of various iron-catalyzed transformations,[19] we would report herein our findings of an iron-catalyzed intramolecular alkyne−aldehyde metathesis reaction for the regioselective synthesis of substituted 2*H*-chromenes

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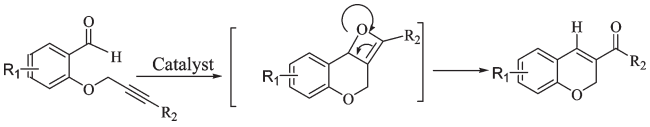
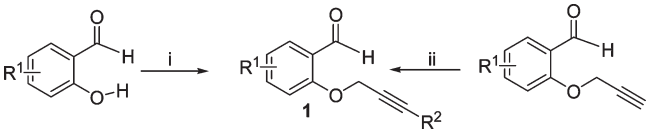
Scheme 2. Design of Intramolecular Alkyne−Aldehyde Metathesis for the Synthesis of 2*H*-Chromenes



Scheme 3. Preparation of the Propargylic Ether of Salicylaldehyde[a]



[a] Reaction conditions: (i) K_2CO_3, propargyl bromide, CH_3CN, reflux; (ii) R^2X, $Pd(PPh_3)_4$, CuI, Et_3N, DMSO.

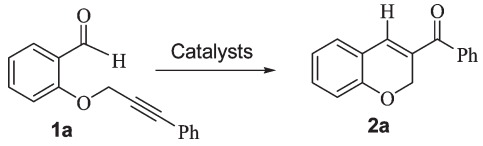
(Scheme 2). This protocol is found to work well for a wide variety of substrates in high yields.

The required starting materials for this transformation could easily be obtained from salicylaldehyde or its derivatives. Salicylaldehyde is readily alkylated with substituted propargylic bromide to obtain propargylic ether derivatives. A majority of substrates have been prepared following this method in high yields (Scheme 3). Aryl-substituted alkynyl ether could also be prepared from easily available unsubstituted propargylic ether derivatives of salicylaldehyde by the Sonogashira coupling reaction.

At first, we screened the various iron salts to determine their catalytic efficiency toward the intramolecular alkyne−aldehyde metathesis reaction. For this purpose, the easily accessible alkynyl ether of salicylaldehyde **1a** was chosen as a model substrate to develop appropriate reaction conditions for this transformation. We were pleased to find that treating **1a** with a catalytic amount of anhydrous $FeCl_3$ (15 mol %) in acetonitrile under refluxing conditions gave the desired cyclization product **2a** exclusively in 70% yield after 4 h (Table 1, entry 6). Further increasing the amount of catalyst loading did not increase the yield, whereas reducing the amount of the catalyst led to a lower yield of the desired product (Table 1, entry 5), even after prolonged heating. It was also observed that anhydrous $FeCl_3$ was a more effective catalyst than hydrated $FeCl_3$ (Table 1, entry 10). Other iron salts such as $FeBr_3$ and $Fe(OTf)_3$ were also found to catalyze the reaction, albeit affording the desired product with lower yields (Table 1, entries 8 and 9). $Fe(acac)_3$ did not have any catalytic activity in this reaction (Table 1, entry 11). The Lewis acidity of the various iron salts may play a crucial role. In order to determine the high catalytic activity of $FeCl_3$, we have also studied the same reaction using other Lewis acid catalysts such as $InCl_3$ and $AlCl_3$. It was found that $InCl_3$ gave 30% yield and $AlCl_3$ gave only a trace amount of the desired product under similar reaction conditions. The reaction was also investigated using various common organic solvents, such as dichloromethane, 1,2-dichloroethane, acetonitrile, toluene, and nitromethane, at different temperatures, and acetonitrile was found to be optimal among them in terms of the yield. In order to avoid any photoisomerization the reaction was studied in the dark.

Under the optimized reaction conditions, we explored the feasibility of the reaction with a variety of substrates. The results

Table 1. Optimization of Fe-Catalyzed Intramolecular Aldehyde−Alkyne Metathesis Reaction[a]



entry	solvent	catalyst	time (h)	*T* (°C])	yield[b] (%)
1	dichloromethane	$FeCl_3$ (10 mol %)	12	r.t	15
2	dichloromethane	$FeCl_3$ (10 mol %)	12	reflux	20
3	dichloroethane	$FeCl_3$ (10 mol %)	5	reflux	35
4	toluene	$FeCl_3$ (10 mol %)	4	reflux	25
5	acetonitrile	$FeCl_3$ (10 mol %)	5	reflux	60
6	**acetonitrile**	**$FeCl_3$ (15 mol %)**	**4**	**reflux**	**70**
7	nitromethane	$FeCl_3$ (10 mol %)	7	reflux	50
8	acetonitrile	$FeBr_3$ (15 mol %)	6	reflux	55
9	acetonitrile	$Fe(OTf)_3$ (15 mol %)	4	reflux	35
10	acetonitrile	$FeCl_3 \cdot 6H_2O$(15 mol %)	9	reflux	50
11	acetonitrile	$Fe(acac)_3$ (10 mol %)	9	reflux	n.r.
12	acetonitrile	$InCl_3$ (15 mol %)	9	reflux	30
13	acetonitrile	$AlCl_3$ (15 mol %)	9	reflux	trace

[a] Reaction conditions: substrate **1a** (0.5 mmol) and solvent (3 mL). [b] Yield after column chromatography.

are summarized in Table 2. The reaction appeared to be quite general with respect to a wide variety of functional groups such as −Cl, −Br, −OMe, and −Ph in salicylaldehyde. In general, good yields were obtained with the substrates having weakly electron-withdrawing halides such as 4-Cl (**1b**), 2,4-Cl(**1c** and **1h**), and 4-Br (**1d**) as substituents of the aromatic ring of the salicylaldehyde. Interestingly, dichloro-substituted salicylaldehyde derivatives **1c** and **1h** produced the desired products **2c** and **2h** in 89% and 74% yields (Table 2, entries 3 and 8), respectively.

Along these lines, it is noteworthy to mention that halide-substituted chromenes are very attractive for further synthetic transformations through various cross-coupling reactions. Similarly, electron-donating groups such −OMe on the salicylaldehyde unit also underwent a smooth intramolecular alkyne−aldehyde metathesis reaction in the presence of catalytic $FeCl_3$ to yield the desired products **2e** and **2g** in 76% and 68% yields, respectively (Table 2, entries 5 and 7). The result was also consistent for naphthalene system **1f**, which gave the desired tricyclic 2*H*-chromene derivative **2f** in 68% yield at 60 °C (Table 2, entry 6). Moreover, biphenyl system **1j** also underwent smooth conversion to the desired chromene derivative **2j** in 68% yield (Table 2, entry 10). Likewise, the variations of substituents on the aromatic ring attached to alkyne were also well-tolerated for this protocol, which provides good yields for electron-donating groups such as 4-OMe **1i** (Table 2, entry 9) and for electron-withdrawing substituents such as 4-F (**2g**) and 4-Br (**2h**) (Table 2, entries 7 and 8). Thus, these results demonstrated the potential usefulness of this process for the synthesis of complex 2*H*-chromene derivatives. The electronic nature of the substituents on the aromatic rings of **1** has little influence in this process, since good yields were obtained with both electron-rich and weakly electron-deficient molecules.

Next, alkyl groups at the alkynyl terminus (Table 2, entries **2k** and **2l**) were also examined to prove the generality of this

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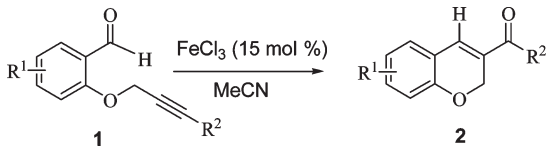
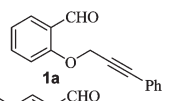
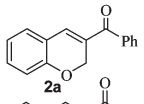
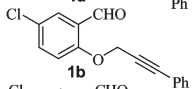
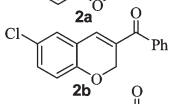
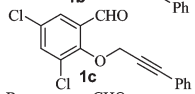
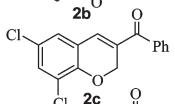
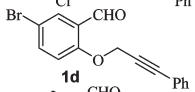
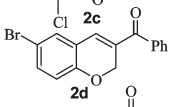
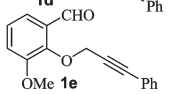
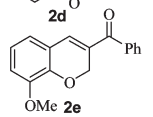
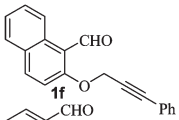
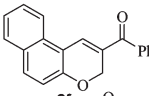
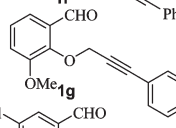
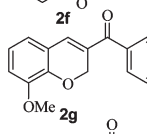
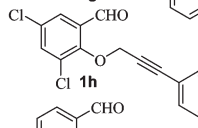
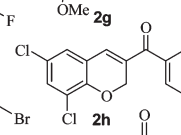
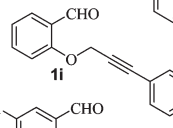
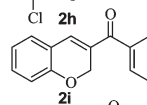
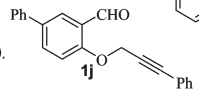
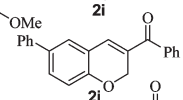
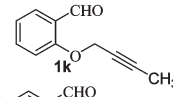
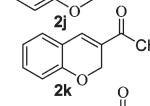
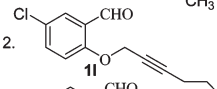
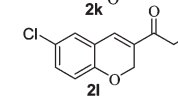
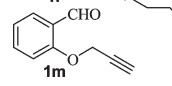
Table 2. $FeCl_3$-Catalyzed Intramolecular Alkyne-Aldehyde Metathesis for the Synthesis of Functionalized 2*H*-Chromenes[a]

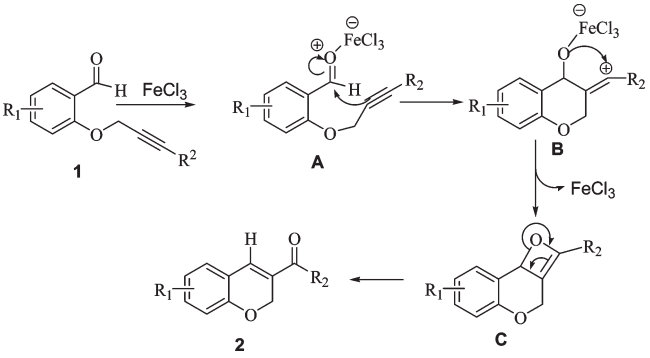


Entry	Substrate **1**	Product **2**	Time(h)	Yield(%)[b]
1.	 **1a**	 **2a**	4	70
2.	 **1b**	 **2b**	6	68
3.	 **1c**	 **2c**	8	89
4.	 **1d**	 **2d**	7	72
5.	 **1e**	 **2e**	8	76
6.	 **1f**	 **2f**	5	68[c]
7.	 **1g**	 **2g**	6	68
8.	 **1h**	 **2h**	7	74
9.	 **1i**	 **2i**	4	64
10.	 **1j**	 **2j**	5	68
11.	 **1k**	 **2k**	11	50[d]
12.	 **1l**	 **2l**	15	45[d]
13	 **1m**	—	6	N.R[e]

[a] Reaction conditions: Substrate **1a** (0.5 mmol), acetonitrile (3 mL) and $FeCl_3$ (15 mol-%). [b] Yield after column chromatography. [c] Reaction was performed in nitromethane (3 mL) at 60 °C. [d] Reaction was performed in 1,2-dichloroethane (3 mL) under refluxing condition. [e] N.R = No Reaction.

transformation. It was also observed that the reaction proceeded to produce the desired products in moderate yields and took a longer time to reach completion compared to the aryl-substituted alkynes. These results indicate the aryl-substituted alkynes to be more effective substrates compared to the alkyl-substituted alkynes. Thus, the iron-catalyzed intramolecular alkyne−aldehyde metathesis reaction has been well accommodated with various

Scheme 4. Proposed Mechanism for the Iron−Salt Catalyzed Intramolecular Alkyne−Aldehyde Metathesis



functional groups which could be useful for further synthetic transformations. Unfortunately, when propargylic ether **1m** without any substituents at the alkyne terminus (Table 2, entry 13) was employed, no reaction occurred.

On the basis of the above results and the known chemistry of the alkyne−carbonyl methathesis reaction, we tentatively propose the mechanism depicted in Scheme 4. The reaction proceeds through a formal [2 + 2] cycloaddition reaction; the exact role of the iron−salt is not known; however the reaction is initiated by the coordination of the carbonyl group with the iron−salt through Lewis acid−base interaction to form a reactive species **A**. Then nucleophilic attack of the alkyne unit to the activated aldehyde group generates a vinylic cation intermediate **B** and subsequent cyclization by intramolecular nucleophilic attack of the carbonyl oxygen at the vinylic carbocation center leads to the formation of an oxetene intermediate **C** regenerating the iron−salt for next catalytic cycle. The oxetene intermediate then undergoes formal (2 + 2) cycloreversion producing the desired 2*H*-chromene derivative with complete regioselectivity. The generation of vinylic carbocation is supported by the fact that terminal alkyne did not produce the product, and aryl-substituted alkynes were more efficient compare to alkyl-substituted alkynes toward this transformation.

In summary, we have developed an $FeCl_3$-catalyzed intramolecular alkyne−aldehyde metathesis process for the library synthesis of functionalized 2*H*-chromene from readily available alkynyl ethers of salicylaldehyde derivatives. A number of functional groups including methoxy, phenyl, chloro, fluoro, and bromo groups are well-tolerated in this reaction conditions. The attractive features of this procedure are the mild reaction conditions, high atom-economy, use of inexpensive starting materials, and environmentally friendly catalyst. Moreover, this protocol can introduce carbonyl functionality in the chromene unit. Thus, the present reaction represents a versatile access to functionalized 2*H*-chromenes and would be a useful tool for the synthesis of biologically and photochemically active molecules.

EXPERIMENTAL SECTION

General Methods. ^1H NMR spectra were recorded in $CDCl_3$ solutions. Chemical shifts are expressed in parts per million (ppm, δ) and are referenced to $CHCl_3$ (δ = 7.26 ppm) as an internal standard. All coupling constants are absolute values and are expressed in hertz. Signal description: s = singlet, d = doublet, t = triplet, m = multiplet, dd = doublet of doublets, brs = broad singlet. ^{13}C NMR spectra were recorded in $CDCl_3$ solutions with complete proton decoupling. Chemical shifts

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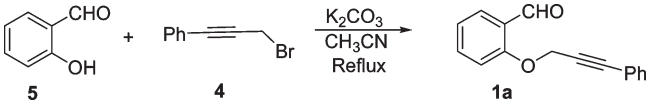
are expressed in parts per million (ppm, δ) and are referenced to $CDCl_3$ (δ = 77.0 ppm) as an internal standard. High-resolution mass spectra (HRMS) were performed in dichloromethane solvent. The molecular fragments are quoted as the relation between mass and charge (m/z). The IR spectra were recorded as thin films with KBr. The routine monitoring of reactions was performed with silica gel coated glass slides and precoated Al plates, which were analyzed with iodine, UV light, and alkaline $KMnO_4$, respectively. All reactions involving moisture-sensitive reactants were executed with oven-dried glassware.

Representative Experimental Procedure for the Preparation of Propargylic Bromide.

At first, propargylic alcohol **3** (1.50 g, 11.4 mmol) was taken in a 50 mL round-bottom flask. PBr_3 (4.60 g, 17.1 mmol) was added dropwise by a pressure equalizer funnel while the mixture was stirred at 0 °C. After 0.5 h of stirring at the same temperature, the reaction mixture was poured into ice−water (150 mL), and the solution was neutralized by addition of solid $NaHCO_3$. After complete neutralization, the aqueous solution was extracted with dichloromethane (2 × 50 mL) followed by washing the organic layer by saturated NaCl solution (50 mL). Finally, the dichloromethane part was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography through a short silica gel (mess 60−120) column to afford compound **4** (1.90 g, 9.7 mmol, 85%) as a yellow oil.

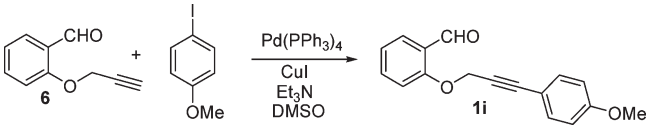
Representative Experimental Procedure for the Synthesis of Propargylic Ether 1a[20].



Salicylaldehyde **5** (626 mg, 5.13 mmol) was dissolved in dry acetonitrile (15 mL) in a 50 mL round-bottom flask. To this solution was added propargylic bromide **4** (1.00 g, 5.13 mmol) followed by anhydrous K_2CO_3 (3.50 g, 25.7 mmol), and the reaction mixture was refluxed under an Ar atmosphere for 4 h. The mixture was cooled to room temperature and filtered through the sintered glass crucible. After that, the solvent acetonitrile was removed under reduced pressure, and the residue was purified by silica gel (mess 60−120) column chromatography to obtain the product **1a** (875 mg, 3.71 mmol, 72%) as a white solid.

Compounds **1b**−**h**,**j**−**m** were also synthesized by similar procedure.

Scheme 5. Representative Experimental Procedure for the Synthesis of Propargyl Ether 1i:[21]



To a mixture of compound **6** (950 mg, 5.0 mmol), 4-iodoanisole (1.17 g, 5 mmol), and triethylamine (0.759 g, 7.5 mmol) in dry DMSO (10 mL) under an Ar atmoshphere were added Pd $(PPh_3)_4$ (58 mg, 0.05 mmol) and CuI (0.029 g, 0.15 mmol) successively. The reaction mixture was stirred at room temperature for 8 h. Then the mixture was dissolved in water and extracted with EtOAc. The compound was purified using silica gel column chromatography to afford the propargylic ether **1i** as a white solid (953 mg, 68%).

The experimental details and spectroscopic data (IR, ^1H, ^{13}C NMR and HRMS for all unknown final compounds **2b**−**l** and only ^1H and ^{13}C NMR spectroscopic data for known final compound **2a** are provided below.

General Procedure for $FeCl_3$-Catalyzed Synthesis of 2H-Chromenes. Representative Experimental Procedure for the Synthesis of (2H-Chromen-3-yl)methanone ***2a*** *(Table 2, Entry 1).* Compound **1a** (118 mg, 0.5 mmol) was taken in a 25 mL round-bottom flask containing 3 mL of dry acetonitrile solvent. Anhydrous $FeCl_3$ (12 mg, 0.08 mmol) was added, and the reaction mixture was heated to reflux for 4 h under an Ar atmosphere in the dark. After complete conversion of the starting material (TLC), acetonitrile was distilled out under reduced pressure and the residue was purified by silica gel (mess 60−120) column chromatography to afford **2a** (83 mg, 0.35 mmol, 70%) as a yellow oil. IR (KBr): 3058, 1626, 1483, 1322, 1294, 1074, 708 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.16 (s, 2 H), 6.89−6.95 (m, 2 H), 7.09−7.12 (m, 2 H), 7.25−7.27 (m, 1 H), 7.49 (t, J = 7.5 Hz, 2 H), 7.58 (t, J = 7.1 Hz, 1 H), 7.71−7.75 (m, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 65.3, 116.4, 121.0, 121.9, 128.5, 129.0, 129.4, 129.9, 132.0, 132.6, 137.1, 137.6, 155.6, 194.1. HRMS: calcd for $C_{16}H_{13}O_2$ [M + 1] 237.0916, found 237.0912.

(6-Chloro-2H-chromen-3-yl)(phenyl)methanone ***2b*** *(Table 2, Entry 2).* Compound **1b** (135 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 6 h to afford **2b** (92 mg, 0.34 mmol, 68%) as a yellow solid. Mp: 88 °C. IR (KBr): 1627, 1339, 1261, 1036, 710 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.15 (s, 2 H), 6.84 (d, J = 8.6 Hz, 1 H), 7.03 (s, 1 H), 7.08 (s, 1 H), 7.18−7.22 (m, 1 H), 7.49 (t, J = 7.2 Hz, 2 H), 7.58 (t, J = 7.3 Hz, 1 H), 7.72 (d, J = 7.1 Hz, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 65.5, 117.7, 122.2, 126.6, 128.5, 129.0, 130.8, 132.0, 132.3, 135.5, 137.2, 154.0, 193.9. HRMS: calcd for $C_{16}H_{12}ClO_2$ [M + 1] 271.0526, found 271.0523.

(6,8-Dichloro-2H-chromen-3-yl)(phenyl)methanone ***2c*** *(Table 2, Entry 3).* Compound **1c** (152 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 8 h to afford **2c** (137 mg, 0.45 mmol, 89%) as a brownish yellow solid. Mp: 130 °C. IR (KBr): 3066, 1629, 1463, 1337, 1212, 714 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.25 (s, 2 H), 7.0 (s, 2 H), 7.30 (brs, 1 H), 7.48−7.52 (m, 2 H), 7.58−7.63 (m, 1 H), 7.72 (d, J = 7.2 Hz, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 66.2, 122.3, 123.0, 126.4, 127.0, 128.5, 128.6, 129.0, 131.3, 131.9, 132.5, 134.4, 136.9, 149.7, 193.5. HRMS: calcd for $C_{16}H_{10}Cl_2O_2Na$ [M + Na] 326.9956, found 326.9955.

(6-Bromo-2H-chromen-3-yl)(phenyl)methanone ***2d*** *(Table 2, Entry 4).* Compound **1d** (158 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 7 h to afford **2d** (114 mg, 0.36 mmol, 72%) as a yellowish white solid. Mp: 120 °C. IR (KBr): 3448, 1646, 1627, 1476, 1338, 818 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.16 (s, 2 H), 6.79 (d, J = 8.6 Hz, 1 H), 7.03 (s, 1 H), 7.23 (d, J = 2.35 Hz, 1 H), 7.35 (dd, J = 8.6, 2.4 Hz, 1 H), 7.47−7.52 (m, 2 H), 7.57−7.62 (m, 1 H), 7.72 (d, J = 7.0 Hz, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 58.7, 107.0, 111.5, 116.0, 121.8, 122.3, 124.0, 124.7, 125.6, 128.1, 128.6, 130.5, 147.7, 187.1. HRMS: calcd for $C_{16}H_{11}BrO_2Na$ [M + Na] 336.9840, found 336.9835.

(8-Methoxy-2H-chromen-3-yl)(phenyl)methanone ***2e*** *(Table 2, Entry 5).* Compound **1e** (133 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 8 h to afford **2e** (96 mg, 0.36 mmol, 76%) as a yellow solid. Mp: 94 °C. IR (KBr): 1622, 1336, 1269, 1097, 775, 709 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 3.91 (s, 3 H), 5.22 (s, 2 H), 6.74 (d, J = 7.0 Hz, 1 H), 6.89 (d, J = 7.7 Hz, 2 H), 7.11 (s, 1 H), 7.48 (t, J = 7.6 Hz, 2 H), 7.56 (d, J = 6.7 Hz, 1 H), 7.72 (d, J = 7.8 Hz, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 56.3, 65.7, 115.1, 121.4, 121.7, 121.8, 128.6, 129.1, 130.0, 132.2, 137.1, 137.6, 144.6, 148.2, 194.2. HRMS: calcd for $C_{17}H_{14}O_3Na$ [M + Na] 289.0841, found 289.0835.

(3H-Benzo[f]chromen-2-yl)(phenyl)methanone ***2f*** *(Table 2, Entry 6).* Compound **1f** (143 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in nitromethane solvent at 60 °C for 5 h to

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afford **2f** (97.4 mg, 0.34 mmol, 68%) as a sticky brown solid. IR (KBr): 3061, 1626, 1562, 133, 817, 750 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.26 (s, 2 H), 7.16 (d, J = 8.9 Hz, 1H), 7.36−7.42 (m, 1 H), 7.47−7.56 (m, 3 H), 7.61(d, J = 7.3 Hz, 1 H), 7.77−7.85 (m, 6 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 65.2, 114.4, 117.7, 121.1, 124.4, 127.5, 127.7, 128.5, 128.9, 129.1, 129.4, 130.0, 130.1, 132.0, 133.4, 137.9,193.9. HRMS: calcd for $C_{20}H_{16}O_2$ [M + 1] 287.1072, found 287.1069.

(4-Fluorophenyl)(8-methoxy-2H-chromen-3-yl)methanone ***2g*** *(Table 2, Entry 7).* Compound **1g** (142 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 6 h to afford **2g** (97 mg, 0.34 mmol, 68%) as a yellow solid. Mp: 82 °C. IR (KBr): 3462, 1624, 1597, 1482, 1345, 1267, 1227 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 3.89 (s, 3 H), 5.18 (s, 2 H), 6.74 (d, J = 6.9 Hz, 1 H), 6.86−6.93 (m, 2 H), 7.08 (s, 1 H), 7.16 (t, J = 8.5 Hz, 2 H), 7.73−7.78 (m, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 56.3, 65.8, 115.2, 115.6, 115.9, 121.4, 121.7, 129.9, 131.6, 131.8, 133.8, 136.9, 144.7, 148.3, 163.6, 167.0 (d, J_{C-F} = 255 Hz), 192.7. HRMS: calcd for $C_{17}H_{14}FO_3$ [M + 1] 285.0927, found 285.0922.

(4-Bromophenyl)(6,8-dichloro-2H-chromen-3-yl)methanone ***2h*** *(Table 2, Entry 8).* Compound **1h** (192 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 7 h to afford **2h** (142.1 mg, 0.37 mmol, 74%) as a yellow solid. Mp: 102 °C. IR (KBr): 3449, 1686, 1627, 1581, 1337, 1213, 826 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.23 (s, 2 H), 7.0 (d, J = 7.5, 2 H), 7.32 (brs, 1 H), 7.62 (dd, J = 8.3, 17.3 Hz, 4 H).[13] ^{13}C NMR (125 MHz, $CDCl_3$): δ = 66.2, 122.6, 123.0, 126.7, 127.2, 127.7, 130.7, 131.3, 132.1, 132.3, 134.6, 135.8, 150.0, 192.5. HRMS: calcd for $C_{16}H_{10}BrCl_2O_2$ [M + 1] 382.9241, found 382.9236.

(2H-Chromen-3-yl)(4-methoxyphenyl)methanone ***2i*** *(Table 2, Entry 9).* Compound **1i** (133 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 4 h to afford **2i** (85 mg, 0.32 mmol, 64%) as a yellow solid. Mp: 85 °C. IR (KBr): 3447, 1616, 1599, 1570, 1256, 1171, 751 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ: 3.80 (s, 3 H), 5.05 (s, 2 H), 6.80−6.85 (m, 1 H), 6.89 (d, J = 5.0 Hz, 2 H), 6.90−7.0 (m, 2 H), 7.68 (dd, J = 6.9, 2.0 Hz, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 55.6, 65.7, 113.9, 116.5, 121.3, 121.9, 129.3, 130.1, 130.2, 131.5, 132.3, 135.8, 155.6, 163.1, 192.9. HRMS: calcd for $C_{17}H_{14}NaO_3$ [M + Na] 289.0841, found 289.0836.

Phenyl(6-phenyl-2H-chromen-3-yl)methanone ***2j*** *(Table 2, Entry 10).* Compound **1j** (156 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in acetonitrile solvent as described for the synthesis of **2a** for 4 h to afford **2j** (106 mg, 0.34 mmol, 68%) as a greenish yellow solid. Mp: 102 °C. IR (KBr): 2360, 1625, 1337, 765, 711 cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ = 5.21 (s, 2 H), 7.0 (d, J = 8.5 Hz, 1 H), 7.19 (s, 1 H), 7.31−7.35 (m, 2 H), 7.40 (t, J = 7.7 Hz, 2 H), 7.49−7.53 (m, 4 H), 7.58−7.61 (m, 2 H), 7.75 (d, J = 8.0 Hz, 2 H). ^{13}C NMR (125 MHz, $CDCl_3$): δ = 65.6, 116.9, 121.3, 126.8, 127.3, 128.0, 128.6, 129.0, 129.1, 129.5, 130.3, 131.3, 132.2, 137.1, 140.1, 155.2, 194.2. HRMS: calcd for $C_{22}H_{17}O_2$ [M + 1] 313.1229, found 313.1224.

1-(2H-Chromen-3-yl)ethanone ***2k*** *(Table 2, Entry 11).* Compound **1k** (87 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in 1,2-dichloroethane solvent as described for the synthesis of **2a** for 11 h to afford **2k** (44 mg, 0.25 mmol, 50%) as a pale yellow solid. Mp: 86 °C. IR (KBr): 3298, 2924, 1654, 1604, 1458 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.34 (s, 3 H), 4.94 (s, 2H), 6.79 (d, J = 8.0 Hz, 1 H), 6.87 (t, J = 7.4 Hz, 1 H) 7.10 (d, J = 7.6 Hz, 1 H), 7.17−7.22 (m, 1 H), 7.24 (brs, 1 H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 24.0, 63.2, 115.3, 119.7, 120.8, 128.1, 129.7, 131.5, 133.0, 154.5, 195.0. HRMS: calcd for $C_{11}H_{11}O_2$ [M + 1] 175.0759, found 175.0761.

1-(2H-Chromen-3-yl)butan-1-one ***2l*** *(Table 2, Entry 12).* Compound **1l** (115 mg, 0.5 mmol) and anhydrous $FeCl_3$ (12 mg, 0.08 mmol) were treated in 1,2-dichloroethane solvent as described for the synthesis of **2a** for 15 h to afford **2l** (52 mg, 0.23 mmol, 45%) as a yellow sticky liquid. IR (KBr): 3286, 2968, 1658, 1632, 1489, 1238 cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ = 0.98 (t, J = 7 Hz, 3 H), 1.66−1.74 (m, 2 H), 2.71 (t, J = 7.5 Hz, 2 H), 5.0 (s, 2 H), 6.79 (d, J = 8.5 Hz, 1 H), 7.14(d, J = 2.5 Hz, 1 H), 7.18−7.22 (m, 1 H), 7.26 (s, 1 H). ^{13}C NMR (125 MHz, $CDCl_3$): δ = 14.0, 18.1, 39.2, 64.8, 117.8, 126.6, 128.5, 131.6, 131.9, 154.2, 198.4. HRMS: calcd for $C_{22}H_{17}O_2$ [M + 1] 237.0682, found 237.0676.

■ ASSOCIATED CONTENT

Supporting Information. Copies of NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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