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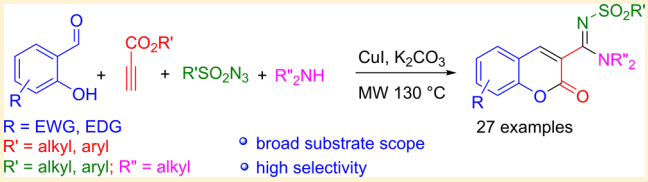
Microwave-Assisted Copper-Catalyzed Four-Component Tandem Synthesis of 3-*N*-Sulfonylamidine Coumarins

Govindarasu Murugavel and Tharmalingam Punniyamurthy*

Department of Chemistry, Indian Institute of Technology Guwahati, Guwahati-781039, India

Supporting Information

ABSTRACT: Microwave-assisted copper-catalyzed four-component tandem synthesis of 3-*N*-sulfonylamidine coumarins has been accomplished by the coupling of salicylaldehydes, propiolates, sulfonyl azides, and secondary amines. This one-pot protocol affords an effective route for the construction of functionalized coumarin structural frameworks in a single operation with moderate to high yields.



INTRODUCTION

Coumarins are an important class of heterocyclic scaffolds that exist widely in nature[1] with numerous interesting biological and medicinal properties (Figure 1).[2] Moreover, coumarins serve as excellent fluorescent probes in biology and medicine,[3] as well as dyes in laser technology.[4] Classically, coumarin core structure is constructed via Knoevenagel condensation (Scheme 1a). However, this traditional approach often suffers due to limited substrate scope and troublesome chemical processes.[5] Development of effective methods for the construction of functionalized coumarin structural frameworks is thus important in organic synthesis (Scheme 1b).[6]

Multicomponent one-pot tandem reaction affords a powerful tool for the conversion of simple substrates into diverse complex molecules in a single operation.[7] Furthermore, microwave organic synthesis provides the advantages of greater reactivity, mild reaction conditions, and high selectivity.[8] Recently, click chemistry has been considerably explored for the formation of ketenimine and subsequent reaction with nucleophiles for the construction of diverse structural scaffolds.[9] In continuation of our studies on ketenimine reactions,[9q] we here report an efficient microwave-assisted copper(I)-catalyzed four-component synthesis of 3-*N*-sulfonylamidine coumarins by the coupling of salicylaldehydes, propiolates, sulfonyl azides, and secondary amines (Scheme 1c). This protocol is selective and affords a potential route for the construction of functionalized 3-*N*-sulfonylamidine coumarins in moderate to high yields.[10]

RESULTS AND DISCUSSION

Initially, optimization of the reaction was carried out employing salicylaldehyde **1a**, ethyl propiolate **2a**, tosyl azide **3a**, and diisopropylamine **4a** as model substrates using a series of copper salts in the presence of different bases (Table 1). The coupling of ethyl propiolate **2a**, tosyl azide **3a**, and diisopropylamine **4a** readily took place to afford amidine[10a] **5** as the sole product, and the aldehyde **1a** failed to react when the substrates were stirred with 10 mol % CuI and 1.2 equiv K_3PO_4 for 0.5 h in 1,4-dioxane at room temperature (entry 1). However, increasing the reaction temperature to reflux for 24 h led to the coupling of all the substrates to afford ester **6** and coumarin **7a** in 19% and 30%, respectively, along with amidine **5** in 48% (entry 2). Subsequent screening of the base led to an increase in the formation of **7a** to 50% using K_2CO_3, while Cs_2CO_3 exhibited inferior results (entries 3 and 4). In contrast, Na_2CO_3, and organic bases such as DBU, Et_3N, and 2,6-lutidine, failed to produce the target heterocycle **7a** (entries 5−7). In a set of copper sources screened, CuI, CuCl, CuBr, and $Cu(acac)_2$, the former gave the best results (entries 8−10). Dioxane was found to be the solvent of choice, while reactions using DMSO, toluene, and DMF gave inferior results (entries 11−13). Recrystallization of **6** in MeOH gave a single crystal whose structure was confirmed by X-ray analysis (see Supporting Information).

Next, the reaction was examined using microwave heating, and the results are summarized in Table 2. These reactions exhibited greater reactivity and selectivity compared to the conventional heating reactions described in Table 1. The best results observed at 130 °C [150 W, closed vial] to afford the target heterocycle **7a** in 1 h with up to 88% along with 7% of **6**. Further increase of the reaction temperature to 140 °C led to drop in yield to 81% due to decomposition of the product **7a**. Likewise, lowering the catalyst loading (5 mol %) or the reaction temperature (120 °C) or increasing the quantity of the base (2 equiv) led to a drop in yield to <70%. A control experiment confirmed that without the copper source the coupling reaction was not observed. Furthermore, the reaction in sealed tube without microwave irradiation afforded **7a** in 34% yield (entry 7).

Having the optimized reaction conditions, we explored the substrate scope with a series of substituted salicylaldehydes (Scheme 2). Aldehydes **1b−d** having substitution at the 3-position with chloro, methoxy, and *tert*-butyl groups underwent

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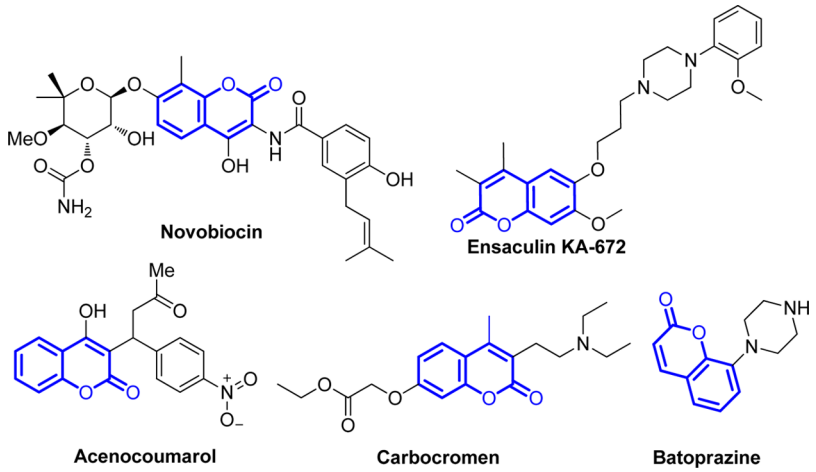
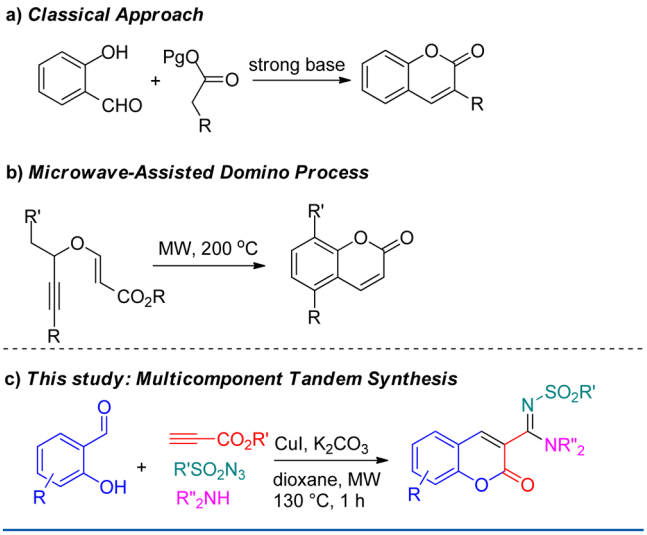


Figure 1. Some examples of biologically important coumarin derivatives.

Scheme 1. Methods for Coumarin Syntheses



reaction to provide the coumarin derivatives **7b–d** in 60–83% yields. The reaction of aldehydes **1e–g** bearing alkoxy groups at the 4-position furnished **7e–g** in 25–67% yields. Likewise, aldehydes **1h–j** and **1l–n** having bromo, chloro, fluoro, methoxy, and methyl substituents at the 5-position readily reacted to give coumarin derivatives **7h–j** and **7l–n** in 65–78% yields, while the reaction of aldehydes **1k** and **1o** with strong electron-withdrawing groups 5-CHO and 5-NO_2 was less-successful. Furthermore, sterically hindered disubstituted aldehydes **1p,q** with 5-iodo-3-*tert*-butyl and 3,5-di-*tert*-butyl groups underwent reaction to produce heterocycles **7p,q** in 76–80% yields. In addition, 2-naphthaldehyde reacted to furnish **7r** in good yield, which upon recrystallization in MeOH–CH_2Cl_2 (1:1) gave single crystals whose structure was confirmed by X-ray analysis (see Supporting Information). These results suggest that the reactions can tolerate substantial steric hindrance, and the aldehydes with electron-donating groups exhibit superior results compared to those having electron-withdrawing groups.

The utility of the protocol was extended to the reaction of various sulfonyl azides (Scheme 3). Methanesufonyl azide **3b** underwent reaction to furnish the coumarin derivative **7s** in 72% yield. The reaction of phenyl sulfonyl azide **3c** occurred to produce **7t** in 80% yield. Likewise, phenyl sulfonyl azides **3d–f** having 4-chloro, 4-methoxy, and 2,4,6-trimethyl groups underwent reaction to afford the corresponding coumarin derivatives **7u–w** in 68–82% yields. These results suggest that the reaction can be compatible with aliphatic as well as aromatic sulfonyl azides with good yields.

Next, the reactions of different propiolates were examined (Scheme 4). Benzyl propiolate **2b** proceeded reaction with 22% yield, while the reaction of *p*-tolyl propiolate **2c** produced the target heterocycle **7a** in 14% yield. Finally, the reaction of different amines was investigated (Scheme 5). The reactions of cyclohexylamine and morpholine failed to produce the coupled products due to decomposition. However, benzyl cyclohexylamine **4b** underwent reaction to give **7x** as a 3:1 mixture of isomers in 9% yield. Likewise, the reaction of isopropyl cyclohexylamine **4c** gave **7y** as a 1:1 mixture of isomers in a 9% yield. These results suggest that the nature of propiolate and secondary amine plays a crucial role in the coupling reaction.

To gain insight into the catalytic pathway, the reaction of **1a**, **2**, **3a**, and **4a** was stopped at 10 min, and the resulting mixture was analyzed using ESI mass analysis. Three major species **5**, **6**, and **7a** were found (see Supporting Information). Furthermore, substrates **2**, **3a**, and **4a** readily underwent coupling to provide **5** that could be readily reacted with the aldehyde **1a** to furnish **7a** in 78% yield (Scheme 6a). In addition, ester **6** readily underwent cyclization to furnish **7a** in 85% yield (Scheme 6b). These results suggest that the reaction may take place via intermediates **5** and **6** to yield the target heterocycle **7a**. Thus, the cycloaddition of **2** with **3** may produce ketenimine[9] **B** via **A**. Nucleophilic addition of the amine to the intermediate **B** may furnish **5** that can react with the aldehyde **1** to give **C**, which may cyclize to produce **7** by transesterification (Scheme 7).

In conclusion, copper(I)-catalyzed four-component tandem synthesis of 3-*N*-sulfonylamidine coumarin has been developed via the coupling of salicylaldehydes, propiolates, sulfonyl azides, and secondary amines. The reaction using microwave irradiation is found to be superior to the conventional heating processes. The greater reactivity, mild condition, and high selectivity constitute the significant practical advantages. This study may open new avenues for further development of multcomponent studies for the synthesis of highly functionalized coumarin derivatives.

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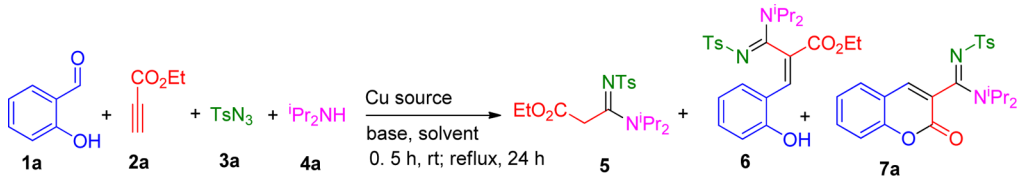
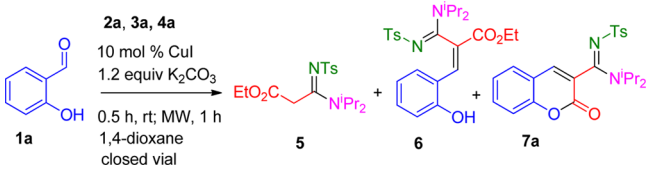
Table 1. Optimization of the Reaction Conditions[a]



				yield (%)[b]		
entry	[Cu]	base	solvent	5	6	7a
1	CuI	K_3PO_4	1,4-dioxane	<99	n.d.	n.d.[c]
2	CuI	K_3PO_4	1,4-dioxane	48	19	30
3	CuI	K_2CO_3	1,4-dioxane	34	14	50
4	CuI	Cs_2CO_3	1,4-dioxane	38	39	16
5	CuI	Na_2CO_3	1,4-dioxane	83	17	n.d.
6	CuI	Et_3N/lutidine	1,4-dioxane	<99	n.d.	n.d.
7	CuI	DBU	1,4-dioxane	75	25	n.d.
8	CuBr	K_2CO_3	1,4-dioxane	44	12	37
9	CuCl	K_2CO_3	1,4-dioxane	30	25	39
10	$Cu(acac)_2$	K_2CO_3	1,4-dioxane	60	25	9
11	CuI	K_2CO_3	DMSO	71	n.d.	23
12	CuI	K_2CO_3	toluene	50	8	36
13	CuI	K_2CO_3	DMF	64	19	n.d.

[a]Aldehyde **1a** (0.5 mmol), ethyl propiolate **2** (0.5 mmol), tosyl azide **3a** (0.6 mmol), amine **4** (0.6 mmol), Cu source (10 mol %), base (0.6 mmol), solvent (1 mL), 0.5 h, rt; reflux, 24 h. [b]Determined by 400 MHz ^{1}H NMR. [c]0.5 h, rt. n.d.= not detected.

Table 2. Effect of Microwave Heating[a]



		yield (%)[b]		
entry	T (°C)	5	6	7a
1	130	n.d	7	88
2	130	n.d	3	70[c]
3	130	n.d	25	72[d]
4	120	14	54	30
5	140	n.d.	n.d.	81
6	130	16	18	63[d]
7	130	27	38	34[e]

[a]Aldehyde **1a** (0.5 mmol), ethyl propiolate **2** (0.5 mmol), tosyl azide **3a** (0.6 mmol), amine **4a** (0.6 mmol), CuI (10 mol %), K_2CO_3 (0.6 mmol), 1,4-dioxane (1 mL), 0.5 h, rt; MW, 130 °C, 1 h. [b]Determined by 400 MHz ^{1}H NMR. [c]5 mol % CuI. [d]2 equiv K_2CO_3. [e]Sealed tube without MW, 1 h. n.d.= not detected.

EXPERIMENTAL SECTION

General Information. The reaction was performed in closed vial using CEM Discover LabMate microwave reactor equipped with surface sensor for temperature measurement. NMR spectra were recorded on 400 and 600 MHz spectrometers using $CDCl_3$ as a solvent, and the data are accounted as follows: chemical shifts (δ ppm) (multiplicity, coupling constant (Hz), integration). The abbreviations for multiplicity are as follows: s = singlet, d = doublet, t = triplet, m = multiplet and dd = doublet of doublets. Infrared spectra were recorded on an FT-IR spectrometer. Melting points were determined with melting point apparatus and are uncorrected. HRMS mass spectra were analyzed using Q-TOF instrument. For single crystal X-ray analysis, the intensity data were collected using a CCD diffractometer, equipped with 1.75 kW sealed-tube Mo Kα irradiation (λ = 0.71073 Å) at 298(2) K, and the structures were solved by direct methods using SHELXL-97 (Göttingen, Germany) and refined with full-matrix least-squares on F^2 using SHELXL-97. CuI (98%) of Aldrich, CuBr (97%) of Alfa Aesar and CuCl (98%) of Rankem were used as received. 2,6-Lutidine (98%), ethyl propiolate (99%), Cs_2CO_3 (99%), K_3PO_4 (98%), Na_2CO_3 (99%), and DBU (98%) were purchased from commercial suppliers and used as received. Solvents were purchased from commercial sources and purified prior to use.[11] Substituted salicylaldehydes[12,13] and sulfonyl azides[14] were prepared according to literature procedures. The reactions were monitored by analytical TLC on silica gel G/GF 254 plates, and column chromatography was performed with 60−120 mesh silica gel.

Benzyl Propiolate ***2b.***[15] Analytical TLC on silica gel, 1:19 ethyl acetate−hexane R_f = 0.50; colorless liquid; yield 70% (561 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.37 (m, 5H), 5.23 (s, 2H), 2.90 (s, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 152.8, 134.7, 128.93, 128.9, 128.8, 75.3, 74.7, 68.1; FT-IR (neat) 2961, 2924, 2855, 2120, 1716, 1605, 1383, 1223, 1020, 749, 696, 668, 562 cm^{-1}.

p-Tolyl Propiolate ***2c.***[16] Analytical TLC on silica gel, 1:19 ethyl acetate−hexane R_f = 0.30; colorless liquid; yield 53% (424 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (d, J = 8.4 Hz, 2H), 7.03 (d, J = 8.4 Hz, 2H), 3.06 (s, 1H), 2.35 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 151.4, 147.8, 136.6, 130.3, 121.1, 76.8, 74.5, 21.1; FT-IR (neat) 2962, 2924, 2855, 2125, 1731, 1504, 1384, 1217, 1197, 1018, 909, 807, 744, 607, 502 cm^{-1}.

General Procedure for the Synthesis of Coumarins. To a stirred solution of propiolate **2** (0.5 mmol), sulfonyl azide **3** (0.6 mmol), and CuI (0.05 mmol, 9.5 mg) in 1,4-dioxane (1 mL) were added secondary amine **4** (0.5 mmol), salicylaldehyde **1** (0.5 mmol), and K_2CO_3 (0.6 mmol, 82.9 mg) at room temperature under air. After 0.5 h (arrested N_2 bubbles), the reaction vial was sealed with a cap and stirred at 130 °C [150 W] for 1 h using microwave-irradiation. The solvent was then evaporated in vacuo, and the residue was diluted with CH_2Cl_2 (30 mL) and washed with saturated NH_4Cl (10 mL) and water (10 mL). Drying (Na_2SO_4) and evaporation of the solvent gave a residue that was purified on silica gel column chromatography using *n*-hexane/ethyl acetate as eluent.

Compound ***5.***[10a] Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.40; colorless solid; mp 122−123 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (d, J = 8.0 Hz, 2H), 7.24 (d, J = 7.6 Hz, 2H), 4.16−4.11 (m, 4H), 3.95−3.88 (m, 1H), 3.61 (br. s, 1H), 2.38 (s, 3H),

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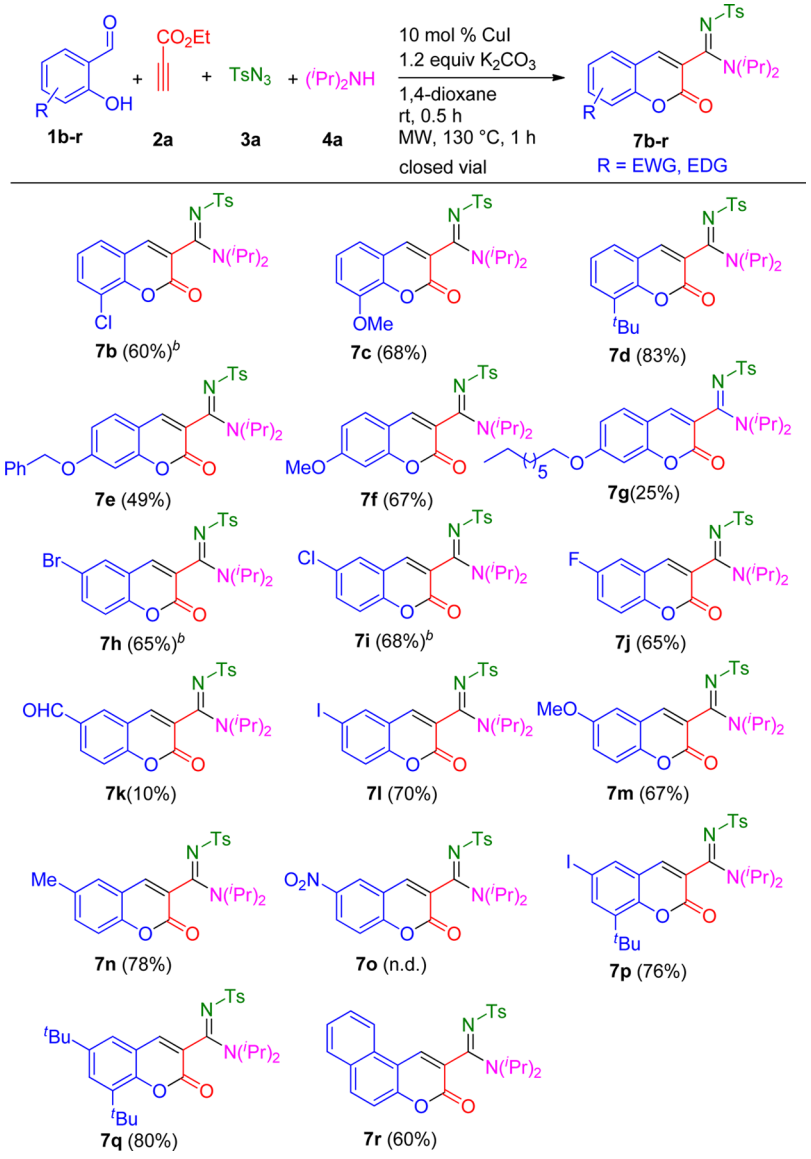
Scheme 2. Reaction of Various Substituted Salicylaldehydes[a]



[a]Aldehyde **1** (0.5 mmol), **2** (0.5 mmol), **3a** (0.6 mmol), **4a** (0.6 mmol), CuI (10 mol %), K_2CO_3 (0.6 mmol), 1,4-dioxane (1 mL), rt, 0.5 h, air; MW, 130 °C, 1 h. [b]Ester (~5%) was obtained as byproduct. n.d. = not detected.

1.38 (d, J = 6.8 Hz, 6H), 1.27–1.21 (m, 9H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 166.9, 157.9, 141.7, 141.1, 129.0, 126.2, 61.7, 48.4, 37.6, 21.4, 20.2, 19.9, 14.0; FT-IR (KBr) 3015, 2983, 2936, 2907, 1729, 1547, 1484, 1441, 1369, 1325, 1276, 1201, 1135, 1083, 1055, 960, 885, 810, 763, 715, 663, 551, 542 cm^{-1}; HRMS (ESI) m/z calcd for $C_{18}H_{29}N_2O_4S$ $[M + H]^+$: 369.1848, found: 369.1875.

Compound ***6***. Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.32; colorless solid; mp 206–207 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.22 (s, 1H), 7.87 (s, 1H), 7.72 (d, J = 8.4 Hz, 2H), 7.43 (dd, J = 8.4, 1.6 Hz, 1H), 7.11–7.06 (m, 3H), 6.86 (d, J = 7.6 Hz, 1H), 6.62 (t, J = 8.0 Hz, 1H), 4.30–4.22 (m, 2H), 4.09–4.01 (m, 1H), 3.63–3.55 (m, 1H), 2.28 (s, 3H), 1.57 (d, J = 6.8 Hz, 3H), 1.49 (d, J = 6.8 Hz, 3H), 1.30 (t, J = 7.2 Hz, 3H), 1.11 (d, J = 6.4 Hz, 3H), 0.74 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 165.0, 160.9, 156.8, 141.8, 40.5, 136.7, 132.5, 129.0, 129.0, 126.6, 122.9, 119.8, 119.6, 116.7, 61.7, 52.4, 48.4, 21.5, 20.2, 19.7, 19.0, 14.2; FT-IR (KBr) 3390, 2973, 2924, 2853, 1717, 1700, 1618, 1606, 1536, 1463, 1443, 1367, 1279, 1253, 1219, 1142, 1084, 1036, 1017, 906, 813, 776, 760, 675, 596, 554 cm^{-1}; HRMS (ESI) m/z calcd for $C_{25}H_{33}N_2O_5S$ $[M + H]^+$: 473.2110, found: 473.2117.

(Z)-N,N-Diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7a***. Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.40; colorless solid; yield 75% (160 mg); mp 257–258 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.72 (s, 1H, H-4), 7.65 (d, J = 7.8 Hz, 2H, Ar-H (tosyl)), 7.58 (t, J = 7.8 Hz, 1H, H-7), 7.54 (d, J = 7.8 Hz, 1H, H-5), 7.34–7.30 (m, 2H, H-6 and H-8), 7.16 (d, J = 7.8 Hz, 2H, Ar-H (tosyl)), 3.89–3.85 (m, 1H, -N-CH-), 3.70–3.66 (m, 1H, -N-CH-), 2.36 (s, 3H, CH_3 (tosyl)), 1.58 (d, J = 6.6 Hz, 3H, CH_3 (isopropyl)), 1.42 (d, J = 7.2 Hz, 3H, CH_3 (isopropyl)), 1.26 (d, J = 6.6 Hz, 3H, CH_3 (isopropyl)), 1.14 (d, J = 6.6 Hz, 3H, CH_3 (isopropyl)); ^{13}C {^{1}H}NMR (150 MHz, $CDCl_3$) δ 157.5 (C), 157.4 (C), 154.2 (C), 142.1 (C), 141.6 (CH), 140.8 (C), 132.9 (CH), 129.2 (CH), 129.0 (CH), 126.5 (CH), 125.1 (CH), 123.3 (C), 118.2 (C), 117.1 (CH), 52.8 (CH), 48.6 (CH), 21.6 (CH_3), 20.7 (CH_3), 20.2 (CH_3), 20.1 (CH_3), 19.7 (CH_3); FT-IR (KBr) 3035, 2969, 2932, 1717, 1628, 1608, 1547, 1445, 1371, 1279, 1251, 1210, 1142, 1087, 1013, 901, 812, 780, 759, 676, 595, 553 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{27}N_2O_4S$ $[M + H]^+$: 427.1692, found: 427.1692.

(Z)-8-Chloro-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7b***. Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.37; colorless solid; 60% (138 mg); mp 285–286 °C; ^{1}H

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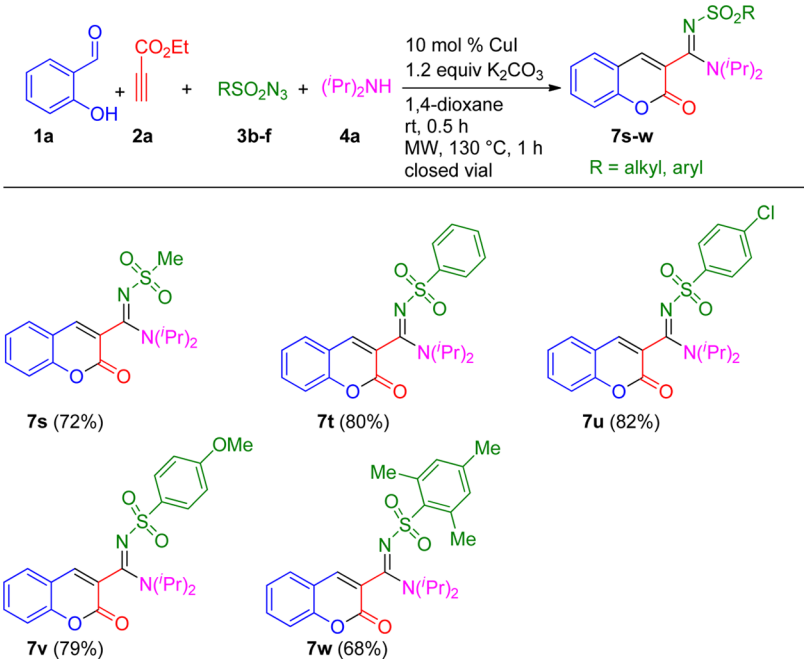
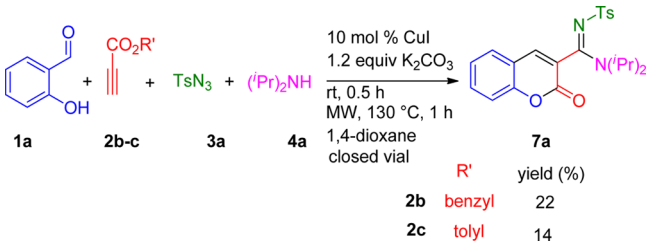
Scheme 3. Reaction of Various Sulfonyl Azides[a]



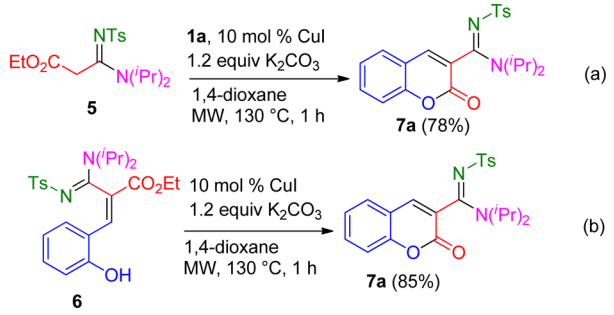
[a]Aldehyde **1a** (0.5 mmol), **2a** (0.5 mmol), **3b–f** (0.6 mmol), **4a** (0.6 mmol), CuI (10 mol %), K_2CO_3 (1.2 equiv), 1,4-dioxane (1 mL), rt, 0.5 h, air; MW, 130 °C, 1 h.

Scheme 4. Reactions with Different Propiolates



Scheme 5. Reactions with Different Amines

Scheme 6. Mechanistic Studies



NMR (400 MHz, $CDCl_3$) δ 7.75 (s, 1H), 7.66–7.62 (m, 3H), 7.48 (d, J = 7.6 Hz, 1H), 7.30 (d, J = 8.0 Hz, 1H), 7.17 (d, J = 7.6 Hz, 2H), 3.86–3.81 (m, 1H), 3.72–3.66 (m, 1H), 2.38 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H), 1.43 (d, J = 7.2 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.16 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 156.8, 156.3, 149.9, 142.3, 141.2, 140.6, 133.2, 129.2, 127.5, 126.6, 125.2, 124.0, 122.1, 119.5, 52.9, 48.7, 21.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3079, 2998, 2973, 2927, 1727, 1623, 1600, 1547, 1476, 1442, 1367, 1270, 1208, 1138, 1087, 1055, 1014, 903, 838, 787, 756, 682, 593, 551 cm^{-1}; HRMS (APCI) m/z calcd for $C_{23}H_{26}ClN_2O_4S$ [M + H]$^+$: 461.1302, found: 461.1301.

(Z)-N,N-Diisopropyl-8-methoxy-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7c.*** Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.50; colorless solid; yield 68% (155 mg); mp 294–295 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (s, 1H), 7.66 (d, J = 8.0 Hz, 2H), 7.26 (d, J = 10.0 Hz, 1H), 7.17–7.11 (m, 4H), 3.97 (s, 3H), 3.88–3.84 (m, 1H), 3.69–3.65 (m, 1H), 2.37 (s, 3H), 1.59 (d, J = 6.8 Hz, 3H), 1.41 (d, J = 6.8 Hz, 3H), 1.25 (d, J = 6.8 Hz, 3H), 1.14 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.3, 156.9, 147.4, 143.9, 142.0, 141.7, 140.8, 129.1, 126.6, 124.9, 123.5, 120.3, 118.8, 114.8, 56.5, 52.7, 48.5, 21.6, 20.6, 20.2, 20.1, 19.7; FT-IR (KBr) 3080, 3032, 2995, 2967, 2936, 2844, 1723, 1623, 1610, 1578, 1543, 1489, 1453, 1369, 1267, 1213, 1175, 1135, 1104, 1085, 1059, 1016, 975, 950, 904, 839, 809, 787, 752, 677, 595, 551 cm^{-1}; HRMS (APCI) m/z calcd for $C_{24}H_{29}N_2O_5S$ [M + H]$^+$: 457.1797, found: 457.1797.

(Z)-8-(tert-Butyl)-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7d.*** Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.53; colorless solid; yield 83% (200 mg); mp 249–250 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (s, 1H), 7.59 (d, J = 8.0 Hz, 3H), 7.42 (d, J = 7.6 Hz, 1H), 7.26 (t, J = 8.0 Hz, 1H), 7.13 (d, J = 8.0 Hz, 2H), 3.87–3.84 (m, 1H), 3.71–3.68 (m, 1H), 2.33 (s, 3H), 1.61 (d, J = 7.2 Hz, 3H), 1.48 (s, 12H), 1.27 (d, J = 6.0 Hz, 3H), 1.15 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.7, 156.6, 152.8, 143.2, 141.9, 140.7, 138.1, 130.6, 129.1, 127.5, 126.5, 124.6, 121.4, 118.4, 52.7, 48.5, 35.1, 30.0, 21.5, 20.6, 20.2, 20.0, 19.6; FT-IR (KBr) 2996, 2973, 2936, 2881, 1727, 1626, 1593, 1542, 1449, 1432, 1370, 1278, 1213, 1172, 1142, 1122, 1085, 1059, 1016, 941, 909, 819, 801, 754, 678, 592, 549 cm^{-1}; HRMS (APCI) m/z calcd for $C_{27}H_{35}N_2O_4S$ [M + H]$^+$: 483.2318, found: 483.2318.

(Z)-7-(Benzyloxy)-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7e.*** Analytical TLC on silica gel, 2:3 ethyl acetate–hexane R_f = 0.30; yellow solid; yield 49% (131 mg); mp 222–

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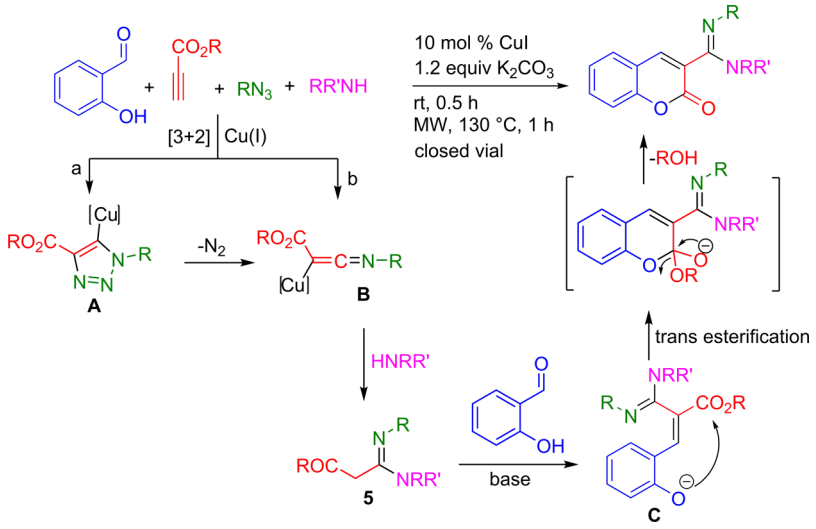
Scheme 7. Proposed Catalytic Cycle



223 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.66 (s, 1H), 7.64 (d, J = 7.8 Hz, 2H), 7.42−7.41 (m, 5H), 7.36 (d, J = 6.0 Hz, 1H), 7.14 (d, J = 7.2 Hz, 2H), 6.96 (d, J = 7.8 Hz, 1H), 6.86 (s, 1H), 5.15 (s, 2H), 3.89−3.87 (m, 1H), 3.66 (s, 1H), 2.35 (s, 3H), 1.58 (d, J = 6.6 Hz, 3H), 1.43 (d, J = 6.0 Hz, 3H), 1.25 (d, J = 6.0 Hz, 3H), 1.13 (d, J = 6.0 Hz, 3H); ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) δ 162.8, 157.9, 157.7, 156.1, 142.0, 141.9, 140.9, 137.8, 130.1, 129.1, 129.0, 128.6, 127.6, 126.5, 119.4, 114.0, 112.0, 102.1, 70.8, 52.7, 48.5, 21.7, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 2967, 2923, 2856, 1729, 1616, 1538, 1451, 1373, 1267, 1243, 1122, 1082, 808, 754, 679, 619, 550 cm^{-1}; HRMS (ESI) m/z calcd for $C_{30}H_{33}N_2O_5S$ [M + H]: 533.2105, found: 533.2112.

(Z)-N,N-Diisopropyl-7-methoxy-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7f.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.58; colorless solid; yield 67% (153 mg); mp 265−266 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (s, 1H), 7.65 (d, J = 8.0 Hz, 2H), 7.45 (d, J = 8.4 Hz, 1H), 7.17 (d, J = 7.6 Hz, 2H), 6.90 (dd, J = 8.8, 1.2 Hz, 1H), 6.81 (s, 1H), 3.91−3.86 (m, 4H), 3.70−3.64 (m, 1H), 2.37 (s, 3H), 1.58 (d, J = 6.8 Hz, 3H), 1.43 (d, J = 6.8 Hz, 3H), 1.26 (d, J = 6.8 Hz, 3H), 1.14 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (150 MHz, $CDCl_3$) δ 163.8, 157.9, 157.7, 156.2, 141.95, 141.91, 140.9, 130.0, 129.1, 126.5, 119.4, 113.3, 111.8, 101.0, 56.1, 52.7, 48.5, 21.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3093, 3052, 2972, 2934, 2849, 1730, 1614, 1540, 1512, 1473, 1459, 1444, 1371, 1271, 1244, 1202, 1125, 1080, 1057, 1024, 972, 901, 854. 807, 763, 726, 675, 593, 550 cm^{-1}; HRMS (APCI) m/z calcd for $C_{24}H_{29}N_2O_5S$ [M + H]$^+$: 457.1797, found; 457.1798.

(Z)-N,N-Diisopropyl-7-(octyloxy)-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7g.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.32; pale yellow solid; yield 25% (69 mg); mp 198−199 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.66 (s, 1H), 7.65 (d, J = 7.8 Hz, 2H), 7.43 (d, J = 8.4 Hz, 1H), 7.17 (d, J = 7.8 Hz, 2H), 6.88 (dd, J = 9.0, 1.8 Hz, 1H), 6.79 (s, 1H), 4.03 (t, J = 6.6 Hz, 2H), 3.91−3.89 (m, 1H), 3.68−3.66 (m, 1H), 2.37 (s, 3H), 1.84−1.80 (m, 2H), 1.58 (d, J = 6.6 Hz, 3H), 1.49−1.44 (m, 2H), 1.43 (d, J = 7.2 Hz, 3H), 1.37−1.29 (m, 8H), 1.26 (d, J = 6.6 Hz, 3H), 1.14 (d, J = 6.6 Hz, 3H), 0.90 (t, J = 6.6 Hz, 3H); ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) δ 163.4, 158.0, 157.8, 156.2, 142.0, 141.9, 141.0, 130.0, 129.1, 126.6, 119.1, 113.7, 111.6, 101.5, 69.0, 52.7, 48.5, 32.0, 29.5, 29.4, 29.1, 26.1, 22.8, 21.6, 20.7, 20.2, 20.1, 19.7, 14.3; FT-IR (KBr) 2967, 2922, 2855, 1728, 1619, 1539, 1373, 1294, 1272, 1251, 1138, 1081, 806, 789, 682, 552 cm^{-1}; HRMS (ESI) m/z calcd for $C_{30}H_{33}N_2O_5S$ [M + H]: 555.2887, found: 555.2895.

(Z)-6-Bromo-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7h.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.70; yellow solid; yield 65% (164 mg); mp 308−309 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (d, J = 6.4 Hz, 5H), 7.25 (d, J = 8.8 Hz, 1H), 7.19 (d, J = 8.0 Hz, 2H), 3.85−3.82 (m, 1H), 3.70−3.66 (m, 1H), 2.38 (s, 3H), 1.57 (d, J = 6.4 Hz, 3H), 1.41 (d, J = 6.4 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.15 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 156.9, 156.8, 153.0, 142.1, 140.7, 140.0, 135.5, 131.2, 129.2, 126.5, 124.6, 119.7, 118.8, 117.6, 52.9, 48.6, 21.6, 20.6, 20.1, 19.7; FT-IR (KBr) 3110, 3045, 2980, 2966, 2925, 1726, 1623, 1602, 1542, 1471, 1448, 1372, 1271, 1241, 1207, 1136, 1083, 1016, 941, 904, 828, 809, 761, 683, 621, 549 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{26}BrN_2O_4S$ [M + H]$^+$: 505.0797, found: 505.0800.

(Z)-6-Chloro-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7i.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.58; yellow solid; yield 68% (156 mg); mp 314−315 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (d, J = 6.0 Hz, 3H), 7.52 (s, 2H), 7.31 (d, J = 9.6 Hz, 1H), 7.19 (d, J = 7.6 Hz, 2H), 3.85−3.80 (m, 1H), 3.69−3.64 (m, 1H), 2.37 (s, 3H), 1.57 (d, J = 7.2 Hz, 3H), 1.40 (d, J = 6.8 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.15 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.0, 156.8, 152.6, 142.1, 140.7, 140.1, 132.7, 130.4, 129.2, 128.2, 126.5, 124.6, 119.2, 118.5, 52.9, 48.6, 21.6, 20.7, 20.1, 19.7; FT-IR (KBr) 3044, 2981, 2925, 1727, 1625, 1544, 1473, 1447, 1413, 1373, 1271, 1241, 1208, 1134, 1084, 1058, 1017, 920, 837, 828, 809, 762, 684, 549 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{26}ClN_2O_4S$ [M + H]$^+$: 461.1302, found: 461.1296.

(Z)-6-Fluoro-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7j.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.47; yellow solid; yield 65% (144 mg); mp 303−304 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68 (d, J = 8.4 Hz, 3H), 7.33−7.28 (m, 2H), 7.24 (d, J = 6.4 Hz, 1H), 7.20 (d, J = 8.0 Hz, 2H), 3.86−3.81 (m, 1H), 3.70−3.65 (m, 1H), 2.38 (s, 3H), 1.58 (d, J = 6.8 Hz, 3H), 1.41 (d, J = 6.4 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.16 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (150 MHz, $CDCl_3$) δ 159.9 (d, J_{C-F} = 244.5 Hz), 157.2, 156.9, 150.4, 142.1, 140.7, 140.3, 129.2, 126.5, 124.7, 120.4 (d, J_{C-F} = 24 Hz), 118.9 (d, J_{C-F} = 13.5 Hz), 118.7 (d, J_{C-F} = 9 Hz), 114.3 (d, J_{C-F} = 24 Hz), 52.8, 48.6, 21.6, 20.7, 20.1, 19.7; ^{19}F NMR (376 MHz, $CDCl_3$, CF_3COOH as internal reference = −76.55) −116.6; FT-IR (KBr) 3045, 2984, 2925, 1725, 1577, 1545, 1490, 1432, 1376, 1267, 1211, 1136, 1085, 1018, 883, 775, 755, 686, 549 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{25}FN_2O_4S$ [M + H]$^+$: 445.1597, found: 445.1589.

(Z)-6-Formyl-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7k.*** Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.33; colorless solid; yield 10% (23 mg); mp 261−262 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ 10.04 (s, 1H), 8.11 (dd, J = 8.4, 1.8 Hz, 1H), 8.08 (d, J = 1.2 Hz, 1H), 7.82 (s, 1H), 7.69 (d, J = 7.8 Hz, 2H), 7.50 (d, J = 8.4 Hz, 1H), 7.20 (d, J = 8.4 Hz, 2H), 3.89−3.85 (m, 1H), 3.72−3.67 (m, 1H), 2.38 (s, 3H), 1.58 (d, J = 7.2 Hz, 3H), 1.41 (d, J = 7.2 Hz, 3H), 1.28 (d, J = 6.6 Hz, 3H), 1.17 (d, J = 6.6 Hz, 3H); ^{13}C {^{1}H}NMR (150 MHz, $CDCl_3$) δ 190.0, 157.8, 156.7, 156.6, 142.3, 140.6, 140.5, 133.3, 133.0, 131.4, 129.3, 126.5, 124.9, 118.6, 118.3,

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53.0, 48.7, 21.7, 20.8, 20.2, 20.1, 19.7; FT-IR (KBr) 2981, 2965, 2924, 2852, 1737, 1700, 1623, 1547, 1447, 1373, 1269, 1168, 1136, 1114, 1084, 1056, 103, 947, 907, 644, 810, 762, 684, 549 cm^{-1}; HRMS (ESI) m/z calcd for $C_{24}H_{27}N_2O_5S$ $[M + H]^+$: 455.1641, found: 455.1640.

(Z)-6-Iodo-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7l***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.66; colorless solid; yield 70% (193 mg); mp 277−278 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86−7.83 (m, 2H), 7.67 (d, J = 7.6 Hz, 2H), 7.63 (s, 1H), 7.19 (d, J = 8.4 Hz, 2H), 7.12 (d, J = 8.4 Hz, 1H), 3.85−3.82 (m, 1H), 3.70−3.66 (m, 1H), 2.38 (s, 3H), 1.58 (d, J = 6.8 Hz, 3H), 1.41 (d, J = 6.8 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.15 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 156.8, 153.8, 142.2, 141.3, 140.7, 139.9, 137.3, 129.2, 126.5, 124.4, 120.2, 119.0, 87.8, 52.9, 48.6, 21.6, 20.7, 20.1, 19.7; FT-IR (KBr) 2981, 2924, 2850, 1727, 1543, 1451, 1371, 1275, 1140, 1083, 1057, 1014, 943, 903, 828, 810, 761, 683, 550 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{26}IN_2O_4S$ $[M + H]^+$: 553.0658, found: 553.0654.

(Z)-N,N-Diisopropyl-6-methoxy-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7m***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.34; colorless solid; yield 67% (153 mg); mp 264−265 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (s, 1H), 7.66 (d, J = 7.2 Hz, 2H), 7.28 (s, 1H), 7.17 (d, J = 6.8 Hz, 3H), 6.97 (s, 1H), 3.86 (s, 4H), 3.70−3.67 (m, 1H), 2.37 (s, 3H), 1.59 (d, J = 6.8 Hz, 3H), 1.43 (d, J = 6.4 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.15 (d, J = 6.0 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.6, 157.5, 156.5, 148.7, 142.0, 141.5, 140.8, 129.2, 126.6, 123.5, 121.0, 118.5, 118.1, 110.7, 56.0, 52.7, 48.5, 21.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3035, 2966, 2932, 1713, 1578, 1550, 1497, 1448, 1367, 1280, 1212, 1142, 1089, 1037, 1017, 965, 904, 879, 814, 806, 768, 755, 680, 595, 553 cm^{-1}; HRMS (ESI) m/z calcd for $C_{24}H_{29}N_2O_5S$ $[M + H]^+$: 457.1797, found: 457.1805.

(Z)-N,N-Diisopropyl-6-methyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7n***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.41; yellow solid; yield 78% (172 mg); mp 295−296 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (s, 1H), 7.66 (d, J = 8.4 Hz, 2H), 7.40 (d, J = 8.4 Hz, 1H), 7.33 (s, 1H), 7.24 (d, J = 8.4 Hz, 1H), 7.17 (d, J = 7.6 Hz, 2H), 3.88−3.83 (m, 1H), 3.70−3.64 (m, 1H), 2.42 (s, 3H), 2.37 (s, 3H), 1.59 (d, J = 7.2 Hz, 3H), 1.43 (d, J = 6.8 Hz, 3H), 1.26 (d, J = 6.8 Hz, 3H), 1.14 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.65, 157.61, 152.3, 141.9, 141.7, 140.8, 134.8, 133.9, 129.1, 128.8, 126.5, 122.9, 117.9, 116.7, 52.7, 48.5, 21.6, 20.8, 20.6, 20.2, 20.0, 19.6; FT-IR (KBr) 3080, 3025, 2982, 2965, 2924, 1718, 1627, 1580, 1542, 1492, 1447, 1373, 1269, 1211, 1175, 1135, 1084, 1061, 1018, 948, 906, 843, 810, 772, 685, 592, 570, 548 cm^{-1}; HRMS (ESI): m/z calcd for $C_{24}H_{29}N_2O_4S$ $[M + H^+]$: 441.1848, found: 441.1864.

(Z)-8-(tert-Butyl)-6-iodo-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7p***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.61; yellow solid; yield 76% (231 mg); mp 244−245 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (s, 1H)), 7.73 (s, 1H), 7.65 (s, 1H), 7.62 (d, J = 8.0 Hz, 2H), 7.16 (d, J = 8.4 Hz, 2H), 3.84−3.80 (m, 1H), 3.71−3.68 (m, 1H), 2.35 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H), 1.49−1.46 (m, 12H), 1.28 (d, J = 6.0 Hz, 3H), 1.15 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) 157.1, 156.1, 152.6, 142.0, 141.5, 140.7, 140.6, 139.2, 135.8, 129.2, 126.5, 122.6, 120.3, 88.2, 52.9, 48.6, 35.3, 29.9, 21.6, 20.7, 20.2, 20.1, 19.6; FT-IR (KBr) 2966, 2924, 1737, 1630, 1541, 1479, 1369, 1282, 1211, 1147, 1086, 1017, 970, 904, 828, 765, 748, 674, 664, 592, 551 cm^{-1}; HRMS (ESI) m/z calcd for $C_{27}H_{34}IN_2O_4S$ $[M + H]^+$: 609.1284, found: 609.1288.

(Z)-6,8-tert-Butyl-N,N-diisopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7q***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.40; colorless solid; yield 80% (215 mg); mp 242−243 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 (s, 1H), 7.62 (d, J = 8.0 Hz, 3H), 7.36 (s, 1H), 7.15 (d, J = 8.0 Hz, 2H), 3.88−3.85 (m, 1H), 3.71−3.67 (m, 1H), 2.34 (s, 3H), 1.61 (d, J = 6.4 Hz, 3H), 1.49−1.47 (m, 12H), 1.36 (s, 9H), 1.26 (d, J = 6.4 Hz, 3H), 1.14 (d, J = 6.0 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) 158.0, 157.0, 151.0, 147.3, 143.7, 141.9, 140.9, 137.6, 129.2, 128.4, 126.6, 123.7, 121.3, 117.9, 52.7, 48.6, 35.3, 34.9, 31.5, 30.1, 21.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 2961, 2871, 1731, 1629, 1586, 1543, 1479, 1451, 1371, 1271, 1018, 953, 903, 842, 810, 767, 689, 594, 552 cm^{-1}; HRMS (ESI) m/z calcd for $C_{31}H_{43}N_2O_4S$ $[M + H]^+$: 539.2944, found: 539.2958.

(Z)-N,N-Diisopropyl-3-oxo-N′-tosyl-3H-benzo[f]chromene-2-carboximidamide ***7r***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.46; colorless solid; yield 60% (143 mg); mp 290−291 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.44 (s, 1H), 8.20 (d, J = 8.4 Hz, 1H), 8.05 (d, J = 9.2 Hz, 2H), 7.93 (d, J = 8.0 Hz, 1H), 7.68 (t, J = 8.0 Hz, 1H), 7.64 (d, J = 8.0 Hz, 2H), 7.58 (t, J = 8.0 Hz, 1H), 7.46 (d, J = 8.8 Hz, 1H), 7.12 (d, J = 8.0 Hz, 2H), 3.94−3.91 (m, 1H), 3.74−3.71 (m, 1H), 2.35 (s, 3H), 1.66 (d, J = 6.8 Hz, 3H), 1.50 (d, J = 6.8 Hz, 3H), 1.30 (d, J = 6.8 Hz, 3H), 1.16 (d, J = 6.8 Hz, 3H). ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.9, 157.5, 154.3, 142.0, 140.9, 137.6, 134.4, 130.5, 129.4, 129.2, 128.7, 126.5, 122.0, 121.9, 116.9, 112.6, 52.8, 48.6, 21.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3058, 2991, 2934, 1716, 1573, 1539, 1477, 1440, 1367, 1279, 1213, 1139, 1087, 1015, 955, 901, 849, 817, 669, 552 cm^{-1}; HRMS (ESI) m/z calcd for $C_{27}H_{29}N_2O_4S$ $[M + H]^+$: 477.1848, found: 477.1860.

(Z)-N,N-Diisopropyl-N′-(methylsulfonyl)-2-oxo-2H-chromene-3-carboximidamide ***7s***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.25; colorless solid; yield 72% (126 mg); mp 249−250 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (s, 1H), 7.58−7.53 (m, 2H), 7.36 (d, J = 8.4 Hz, 1H), 7.30 (t, J = 8.0 Hz, 1H), 3.92−3.89 (m, 1H), 3.75−3.72 (m, 1H), 2.96 (s, 3H), 1.61 (d, J = 6.4 Hz, 6H), 1.30 (d, J = 6.4 Hz, 3H), 1.17 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.8, 157.7, 154.2, 141.4, 132.8, 129.0, 125.0, 123.4, 118.1, 117.1, 52.6, 48.3, 43.1, 20.6, 20.2, 20.1, 19.8; FT-IR (KBr) 2924, 2853, 1719, 1608, 1541, 1449, 1376, 1275, 1214, 1112, 1061, 1018, 961, 908, 816, 756, 726, 518 cm^{-1}; HRMS (ESI) m/z calcd for $C_{17}H_{23}N_2O_4S$ $[M + H]^+$: 351.1379, found: 351.1376.

(Z)-N,N-Diisopropyl-2-oxo-N′-(phenylsulfonyl)-2H-chromene-3-carboximidamide ***7t***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.36; colorless solid; yield 80% (165 mg); mp 259−260 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, J = 6.8 Hz, 2H), 7.73 (s, 1H), 7.59−7.53 (m, 2H), 7.44−7.42 (m, 1H), 7.38−7.30 (m, 4H), 3.88−3.85 (m, 1H), 3.69−3.66 (m, 1H), 1.58 (d, J = 6.8 Hz, 3H), 1.41 (d, J = 6.8 Hz, 3H), 1.26 (d, J = 6.0 Hz, 3H), 1.14 (d, J = 6.0 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.5, 157.4, 154.2, 143.6, 141.6, 132.9, 131.6, 129.0, 128.6, 126.5, 125.1, 123.3, 118.2, 117.1, 52.9, 48.6, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3036, 2969, 2934, 1720, 1628, 1608, 1545, 1482, 1444, 1366, 1278, 1262, 1143, 1088, 1013, 901, 802, 755, 690, 612, 547 cm^{-1}; HRMS (ESI) m/z calcd for $C_{22}H_{25}N_2O_4S$ $[M + H]^+$: 413.1535, found: 413.1535.

(Z)-N′-((4-Chlorophenyl)sulfonyl)-N,N-diisopropyl-2-oxo-2H-chromene-3-carboximidamide ***7u***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.40; colorless solid; yield 82% (183 mg); mp 293−294 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 (s, 1H), 7.75 (d, J = 8.8 Hz, 2H), 7.62−7.55 (m, 2H), 7.37−7.32 (m, 4H), 3.92−3.89 (m, 1H), 3.71−3.68 (m, 1H), 1.57 (d, J = 6.4 Hz, 3H), 1.39 (d, J = 7.2 Hz, 3H), 1.28 (d, J = 6.4 Hz, 3H), 1.17 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.6, 157.5, 154.2, 142.2, 141.5, 137.8, 133.1, 129.0, 128.8, 128.0, 125.1, 123.4, 118.1, 117.2, 53.0, 48.7, 20.6, 20.1, 19.8; FT-IR (KBr) 3033, 2980, 2928, 1714, 1627, 1609, 1550, 1483, 1444, 1368, 1295, 1271, 1213, 1144, 1088, 1012, 903, 819, 804, 765, 747, 655, 623, 550 cm^{-1}; HRMS (ESI) m/z calcd for $C_{22}H_{24}ClN_2O_4S$ $[M + H]^+$: 447.1145, found: 447.1149.

(Z)-N,N-Diisopropyl-N′-((4-methoxyphenyl)sulfonyl)-2-oxo-2H-chromene-3-carboximidamide ***7v***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.70; colorless solid; yield 79% (175 mg); mp 259−260 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (s, 1H), 7.71 (d, J = 8.4 Hz, 2H), 7.61−7.54 (m, 2H), 7.35−7.31 (m, 2H), 6.86 (d, J = 8.8 Hz, 2H), 3.91−3.86 (m, 1H), 3.82 (s, 1H) 3.72−3.67 (m, 1H), 1.59 (d, J = 6.8 Hz, 3H), 1.44 (d, J = 6.8 Hz, 3H), 1.27 (d, J = 6.8 Hz, 3H), 1.15 (d, J = 6.4 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 162.0, 157.5, 157.3, 154.2, 141.5, 135.8, 132.9, 129.0, 128.5, 125.0, 123.3, 118.2, 117.1, 113.7, 55.6, 52.7, 48.5, 20.7, 20.2, 20.1, 19.7; FT-IR (KBr) 3034, 2975, 2931, 2839, 1718, 1627, 1609, 1597, 1548, 1496, 1445, 1371, 1353, 1314, 1142, 1128, 1087, 1060, 1014, 901, 809, 790, 758, 677, 596, 556 cm^{-1}; HRMS (ESI) m/z calcd for $C_{23}H_{27}N_2O_4S$ $[M + H]$: 443.1641, found: 443.1641.

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(Z)-N,N-Diisopropyl-N′-(mesitylsulfonyl)-2-oxo-2H-chromene-3-carboximidamide ***7w***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.43; yellow solid; yield 68% (154 mg); mp 289−290 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (s, 1H), 7.57 (t, J = 7.6 Hz, 1H), 7.51 (d, J = 7.6 Hz, 1H), 7.32−7.25 (m, 2H), 6.74 (s, 2H), 3.82−3.79 (m, 1H), 3.70−3.66 (m, 1H), 2.48 (s, 6H), 2.24 (s, 3H), 1.60 (d, J = 6.8 Hz, 3H), 1.47 (d, J = 7.2 Hz, 3H), 1.27 (d, J = 6.4 Hz, 3H), 1.14 (d, J = 6.8 Hz, 3H); ^{13}C {^{1}H}NMR (100 MHz, $CDCl_3$) δ 157.2, 157.1, 154.1, 140.9, 140.8, 138.3, 137.7, 132.8, 131.3, 129.0, 124.9, 123.3, 118.2, 116.9, 52.7, 48.4, 22.8, 21.0, 20.7, 20.4, 20.1, 19.9; FT-IR (KBr) 3037, 2970, 2933, 1721, 1626, 1607, 1540, 1540, 1481, 1445, 1364, 1350, 1281, 1212, 1129, 1061, 1008, 971, 902, 854, 797, 758, 673, 596, 522 cm^{-1}; HRMS (ESI) m/z calcd for $C_{25}H_{31}N_2O_4S$ [M + H]$^+$: 455.2005, found: 455.2005.

(Z)-N-Benzyl-N-cyclohexyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7x***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.35; colorless solid; yield 9% (22 mg, 3:1 isomers); mp 205−206 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.88 (s, 1H), 7.64 (d, J = 8.4 Hz, 0.5H), 7.64−7.60 (m, 2H), 7.52−7.50 (m, 0.6H), 7.42 (d, J = 8.4 Hz, 1H), 7.36 (t, J = 7.2 Hz, 1H), 7.33−7.31 (m, 4H), 7.29−7.26 (m, 3H), 7.25−7.19 (m, 2H), 7.17 (d, J = 7.2 Hz, 1H), 7.10 (d, J = 7.2 Hz, 0.6H), 7.00 (d, J = 7.8 Hz, 2H), 5.02 (d, J = 15.6 Hz, 1H), 4.67 (s, 0.3H), 4.61 (d, J = 15.6 Hz, 1H), 4.56 (d, J = 17.4 Hz, 0.3H), 4.40 (d, J = 16.8 Hz, 0.3H), 3.58−3.54 (m, 1H), 2.38 (s, 0.9H), 2.32 (s, 3H), 2.02 (d, J = 12.6 Hz, 1H), 1.76−1.71 (m, 0.6H), 1.63−1.59 (m, 3.6H), 1.55−1.53 (m, 2H), 1.39−1.33 (m, 3H), 1.14−1.07 (m, 2.4H), 1.00 (t, J = 12.6 Hz, 1.3H); ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) δ 160.5, 159.4, 157.6, 157.4, 154.4, 154.1, 143.7, 142.6, 142.4, 142.0, 140.5, 140.3, 137.7, 136.9, 133.2, 133.0, 129.2, 129.1, 129.0, 128.9, 128.6, 127.8, 126.8, 126.7, 126.6, 126.5, 125.2, 125.0, 122.3, 121.9, 118.1, 117.8, 117.3, 116.9, 60.7, 58.4, 49.2, 47.5, 32.1, 31.8, 31.0, 30.32, 30.3, 25.84, 25.8, 25.62, 25.6, 25.1, 21.7, 21.6; FT-IR (KBr) 3033, 3015, 2958, 2936, 2925, 2852, 1714, 1625, 1609, 1574, 1543, 1452, 1420, 1372, 1282, 1185, 1243, 1088, 1065, 997, 980, 907, 686, 555 cm^{-1}; HRMS (ESI) m/z calcd for $C_{30}H_{31}N_2O_4S$ [M + H]: 515.1999, found: 515.2005.

(Z)-N-Cyclohexyl-N-isopropyl-2-oxo-N′-tosyl-2H-chromene-3-carboximidamide ***7y***. Analytical TLC on silica gel, 2:3 ethyl acetate−hexane R_f = 0.35; colorless solid; yield 9% (20 mg, 1:1 isomers); mp 271−272 °C. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.74 (s, 1H), 7.72 (s, 1H), 7.66 (t, J = 8.4 Hz, 4H), 7.61−7.56 (m, 4H), 7.37−7.31 (m, 4H), 7.17−7.16 (m, 4H), 3.90−3.87 (m, 1H), 3.74−3.72 (m, 1H), 3.37−3.33 (m, 1H), 3.18 (s, 1H), 2.88−2.87 (m, 1H), 2.47−2.39 (m, 2H), 2.38 (s, 3H), 2.37 (s, 3H), 2.02 (d, J = 12.0 Hz, 1H), 1.85 (d, J = 12.0 Hz, 1H), 1.77−1.72 (m, 2H), 1.67 (d, J = 6.6 Hz, 3H), 1.41 (d, J = 7.2 Hz, 3H), 1.25−1.17 (m, 7H), 1.13 (d, J = 6.6 Hz, 3H), 1.10−1.00 (m, 9H); ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) δ 157.6, 157.52, 157.5, 154.3, 142.1, 141.6, 141.5, 140.83, 140.8, 132.9, 129.21, 129.2, 129.1, 129.07, 126.6, 125.1, 123.4, 123.3, 118.24, 118.2, 117.2, 117.1, 61.7, 57.9, 52.9, 49.8, 30.8, 30.3, 29.9, 29.3, 28.6, 26.7, 26.5, 25.62, 25.6, 25.4, 25.1, 21.7, 20.8, 20.2, 19.7; FT-IR (KBr) 2964, 2931, 2849, 1722, 1607, 1540, 1482, 1445, 1383, 1371, 1272, 1143, 1087, 906, 811, 754, 729, 690, 575, 547 cm^{-1}; HRMS (ESI) m/z calcd for $C_{26}H_{31}N_2O_4S$ [M + H]: 467.1999, found: 467.2005.

■ ASSOCIATED CONTENT

Supporting Information

Crystal structures and CIF files of **6** and **7r**, mass spectrum of the reaction mixture of **1a**, **2a**, **3a**, and **4a**, and NMR spectra (^{1}H and ^{13}C) of **2b,c**, **5**, **6**, **7a−n**, and **7o−y**, and 2D (COSY and HSQC) NMR and DEPT of **7a**. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b00738.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: tpunni@iitg.ernet.in.

Notes

The authors declare no competing financial interest.

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