RSC Advances

PAPER

Cite this: *RSC Adv.*, 2023, **13**, 26948

Selectfluor-mediated tandem cyclization of enaminones with diselenides toward the synthesis of 3-selenylated chromones†

Ji-Hong Xia,[a] Qian Chen,[b] Jin-Wei Yuan, *[b] Wei-Shuo Shi,[b] Liang-Ru Yang *[b] and Yong-Mei Xiao[b]

Received 3rd August 2023
Accepted 4th September 2023

DOI: 10.1039/d3ra05246j

rsc.li/rsc-advances

A practical and metal-free approach for the regioselective selenation of chromones employing Selectfluor reagent under mild conditions is described. The developed method is suitable for a wide substrate scope and affords 3-selenylated chromones in good to excellent yield with high selectivity. An ionic mechanism is proposed for this transformation. Furthermore, the application of potassium thiocyanate with enaminones for the synthesis of thiocyano chromones in this transformation is also successful.

Introduction

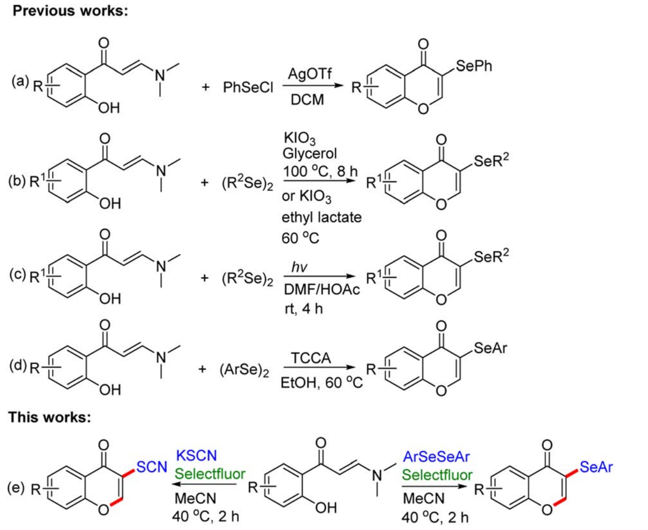
A chromone moiety is the central structure in numerous natural products such as flavonoids, isoflavonoids, as well as other functionalized chromone molecules.[1] As privileged heterocyclic scaffolds, chromone and its derivatives, including both naturally occurring and laboratory synthesized ones, have been proved with high application potential in drug discovery.[2] Moreover, chromones have also exhibited attractive application in organic synthesis as well as the designation of molecules with useful optical functions.[3] In particular, C3-substituted chromones have recently been drawing considerable attention as they exhibit a variety of physiological and biological activities, including anti-inflammatory,[4] anti-dyslipidemic,[5] antioxidant,[6] antimicrobial,[7] antitumor,[8] anticancer,[9] *etc.* Thus, considerable attention has been devoted to developing novel and efficient protocols for the synthesis of C3-substituted chromone derivatives, and several significant achievements have been reported for the synthesis of 3-substituted chromone derivatives.[10]

Organoselenium compounds have attracted considerable attention in medicinal chemistry owing to their well-known biological activities, which are mainly attributed to the fact that selenium atoms may serve as an electron donor or a hydrogen bond acceptor in these applications, altering the chemical characteristics of enzyme active sites.[11] Moreover, they have gained considerable interest due to their well-known fluorescent properties,[12] and wide applications in food chemistry and material science.[13] In particular, recent studies revealed that chromones containing selenyl-substituents show unique bioactivities and chemical properties, and are widely adopted in drug design and regulation of biological processes.[14] Therefore, many efforts have been devoted to the synthesis of more valuable 3-selenochromone derivatives.[15] As the straightforward approach, the direct functionalization on naturally available or prior prepared chromone compounds offers access to 3-substituted chromone derivatives. Through this strategy, a seleno group could be introduced into the chromone framework.[16] However, the limited natural sources or tedious preparation of chromone substrates have led to a high demand for alternative synthetic methods using easy and abundant industrial chemicals.

Among the readily available main building blocks, 2-hydroxyphenyl enaminones have been identified as particularly excellent candidates in the synthesis of functionalized chromones by means of tandem alkenyl C–H elaboration and chromone annulation.[17] In the past decade, the enaminone-based chromone synthesis has gained splendid success by offering practical accesses to chromones containing different substituents.[18] As 3-selenochromones are an important class of compounds, much efforts has been devoted to the assembly of this compound based on the featured chromone annulation of easily available 2-hydroxyphenyl enaminones. In 2016, Blond's group reported AgOTf-catalyzed synthesis of 3-selenochromones through the reaction of 2-hydroxyphenyl enaminones and pre-synthesized electrophilic selenium species (PhSeCl) (Scheme 1a).[19] In 2017, Braga's group and Wan's group developed KIO_3-mediated synthesis of 3-selenochromones through the reaction of *o*-hydroxyphenyl enaminones and diaryl diselenides, employing green solvents such as glycerol and ethyl lactate, respectively (Scheme 1b).[20] In recent years, photoredox catalysis enabled by visible light has emerged as a fascinating and powerful synthetic protocol to promote a wide range of synthetically useful organic transformations.[21] In 2021, a visible-light-promoted synthesis of 3-selenochromones was

[a]ENOVA Pharmaceutical Research (Nanjing) Co. Ltd, Nanjing 210033, P. R. China
[b]School of Chemistry & Chemical Engineering, Henan University of Technology, Zhengzhou 450001, China. E-mail: yuanjinweigs@126.com

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3ra05246j



Scheme 1 Different methods to 3-selenochromones from 2-hydroxyphenyl enaminones. (a) AgOTf-catalyzed cyclization; (b) KIO_3-mediated cyclization; (c) visible-light-promoted cyclization; (d) TCCA-mediated cyclization; (e) selectfluor-mediated cyclization.

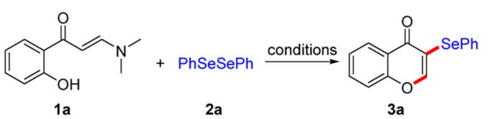
realized *via* the selenylation/cyclization of 2-hydroxyphenyl enaminones with diaryl diselenides in the presence of HOAc (Scheme 1c).[22] Very recently, Braga's group developed trichloroisocyanuric acid (TCCA)-mediated synthesis of 3-selenochromones from 2-hydroxyphenyl enaminones with diaryl diselenides (Scheme 1d).[23] Regardless of their merits, the current strategies suffer from some disadvantages such as transition-metal as a catalyst, limited substrate scope, the inevitability of a strong oxidant, high reaction temperature, or complex reaction conditions. Therefore, more general and mild approaches for the construction of diversely 3-selenochromones are yet highly desirable to satisfy the requirement of discovering more chromone-based functional molecules or lead compounds.

Selectfluor is commercially available, exceptionally stable, and useful for a mild oxidant.[24] Several functionalized heterocyclic compounds have been synthesized successfully employing Selectfluor as an oxidant.[25] Recently, some functionalized heterocycles have been constructed by our group using Selectfluor reagent as an electrophilic reagent or oxidant.[26] Expanding the application of Selectfluor for the cross-coupling reaction is still challenging works. To the best of our knowledge, using stable and readily available diaryl diselenides as selenylating reagent, transition-metal free Selectfluor-promoted selenylation/cyclization of 2-hydroxyphenyl enaminones to access 3-arylselenenyl chromones remains yet elusive. As a part of our continuous interest in forming C–Se bond promoted by Selectfluor reagent, herein, we reported a practical and metal-free approach for the regioselective selenation of chromones employing Selectfluor reagent under mild conditions. Furthermore, the application of potassium thiocyanate with enaminones for the synthesis of 3-thiocyano chromones in this transformation is also successful (Scheme 1e). This protocol features a wide substrate scope, good to excellent yields, high selectivity, without the need for toxic metals, ligands, and bases, and could serve as an efficient approach for the construct 3-arylseleno/3-thiocyano chromones under mild conditions.

Results and discussion

Initially, the reaction of enaminone **1a** and diphenyl diselenide **2a** was screened as a model reaction to identify suitable reaction conditions (Table 1). To our delight, the reaction was performed in CH_3CN using *tert*-butyl hydroperoxide (TBHP, 70% water) as an oxidant at 90 °C for 6 h, and 30% yield of 3-arylseleno chromone **3a** was obtained (entry 1, Table 1). Encouraged by this preliminary result, other oxidants including di-*tert*-butyl peroxide (DTBP), $(NH_4)_2S_2O_8$, $K_2S_2O_8$, Selectfluor, $PhI(OAc)_2$, and $PhI(OCOCF_3)_2$ were screened, the result showed that DTBP was noneffective, however Selectfluor could provide the highest yield (83%, entries 2–9, Table 1). Then, the effect of Selectfluor loading was investigated, and 1.0 equiv. was the best choice to give 83% yield (entries 5, 8 and 9, Table 1). The investigation of various solvents such as DMF, DMSO, THF, CH_3OH, DCE, dioxane, and H_2O, revealing that CH_3CN was the optimal

Table 1 Optimization of reaction conditions[a]



Entry	Oxidant (equiv.)	Solvent	Temp (°C)	Time (h)	Yield[b] (%)
1	TBHP (1.0)	CH_3CN	90	6	30
2	DTBP (1.0)	CH_3CN	90	6	0
3	$(NH_4)_2S_2O_8$ (1.0)	CH_3CN	90	6	52
4	$K_2S_2O_8$ (1.0)	CH_3CN	90	6	60
5	Selectfluor (1.0)	CH_3CN	90	6	83
6	$PhI(OAc)_2$ (1.0)	CH_3CN	90	6	79
7	$PhI(OCOCF_3)_2$ (1.0)	CH_3CN	90	6	60
8	Selectfluor (0.5)	CH_3CN	90	6	78
9	Selectfluor (1.5)	CH_3CN	90	6	83
10	Selectfluor (1.0)	DMF	90	6	40
11	Selectfluor (1.0)	DMSO	90	6	45
12	Selectfluor (1.0)	THF	90	6	38
13	Selectfluor (1.0)	CH_3OH	90	6	42
14	Selectfluor (1.0)	DCE	90	6	Trace
15	Selectfluor (1.0)	Dioxane	90	6	Trace
16	Selectfluor (1.0)	H_2O	90	6	0
17[c]	Selectfluor (1.0)	CH_3CN	90	6	76
18[d]	Selectfluor (1.0)	CH_3CN	90	6	83
19	Selectfluor (1.0)	CH_3CN	20	6	65
20	Selectfluor (1.0)	CH_3CN	40	6	85
21	Selectfluor (1.0)	CH_3CN	60	6	85
22	Selectfluor (1.0)	CH_3CN	40	1	75
23	Selectfluor (1.0)	CH_3CN	40	2	85
24	Selectfluor (1.0)	CH_3CN	40	3	85
25	—	CH_3CN	40	2	0

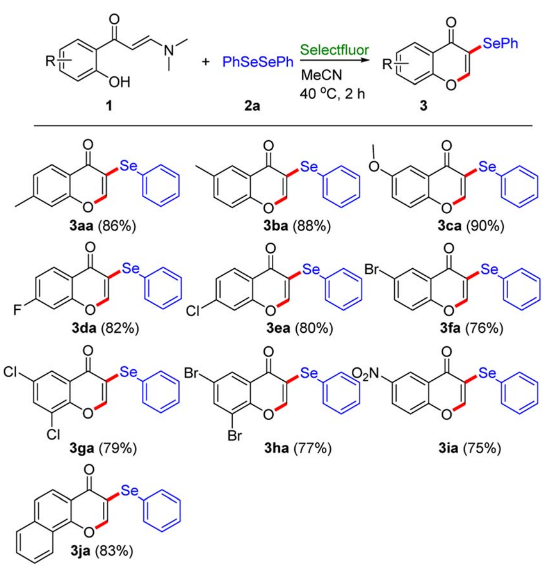
[a] Reaction conditions: enaminone **1a** (0.2 mmol, 38.2 mg), diphenyl diselenide **2a** (0.2 mmol, 62.8 mg), Selectfluor agent in solvent (2.0 mL). [b] Isolated yield. [c] The molar ratio of **1a** and **2a** is 1 : 0.5. [d] The molar ratio of **1a** and **2a** is 1 : 1.5.

solvent for this reaction and afforded **3a** in 83% yield (entries 5 and 10–16). The molar ratio of **1a** and **2a** was also screened. Decreasing the amount of **2a** from 1.0 to 0.5 equiv., the yield of **3a** was reduced to 76%, and no obvious change in yield was observed increasing **2a** loading for 1.0 to 1.5 equiv. (entries 5, 17 and 18, Table 1). Changing the temperature from 20 °C to 90 °C, 40 °C was the best to provide 85% yield (entries 5, 19–21, Table 1). Moreover, the effect of reaction time was also tested. 2 h was proved be optimal time, and provided **3a** in 85% yield (entries 5 and 22–24, Table 1). No desired product **3a** was detected in the absence of Selectfluor reagent (entry 25, Table 1), which indicated that Selectfluor was crucial for the reaction to occur. Therefore, the best conditions for the synthesis of **3a** were identified as follows: the molar ratio of **1a** and **2a** is 1 : 1, 1.0 equiv. Selectfluor as the oxidant in CH_3CN at 40 °C for 2 h.

With the optimal reaction conditions identified, the scope and generality of this transformation were firstly evaluated using divergent enaminones (Table 2). Generally, the process is compatible for enaminones with different R groups at the benzene ring containing electron-donating (Me, OMe) and electron-withdrawing (F, Cl, and Br) substituents, which reacted with diphenyl diselenide **2a** gave the corresponding products **3aa–3fa** in 76–90% yields under the standard conditions. It is noteworthy that an exclusive C-3 site selectivity in this selenylation/cyclization was observed for all the different enaminones. Of particular note was the successful synthesis of the expected 3-arylseleno chromones (**3ea**, **3fa**) bearing chloro and bromo moiety, which provided an opportunity for further functional modification. Furthermore, di-substituted substrates were also suitable for this transformation, delivering the respective products (**3ga**, **3ha**) in good to excellent yields. Notedly, when enaminone at the benzene ring with a strong electron-withdrawing $-NO_2$ group was employed, the selenylation/cyclization reaction could tolerate the reaction conditions to provide **3ia** in 75% yield. Gratifyingly, when a fused aromatic substrate (naphthyl) was employed, the reaction could also proceed smoothly to obtain the desired **3ja** in excellent yields (83%).

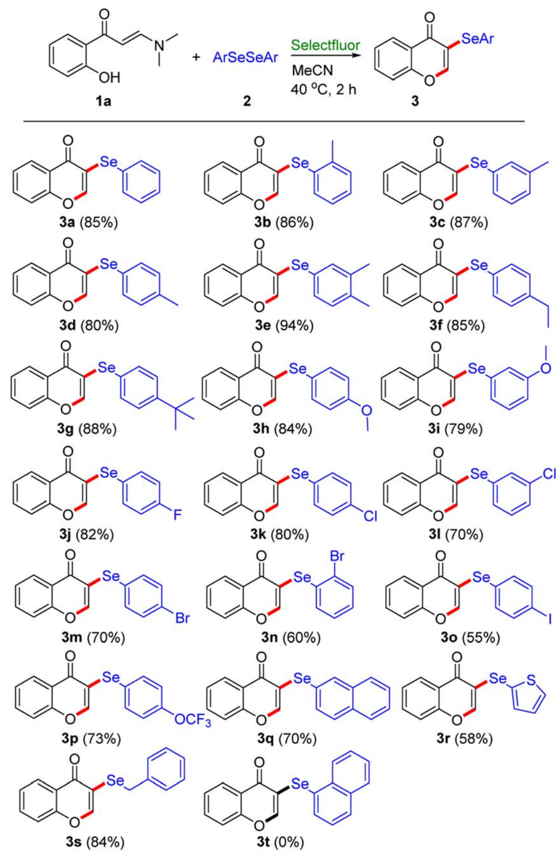
Subsequently, we turned our attention to explore the substrate range of diselenides under the standard conditions (Table 3). All of diaryl diselenides **2** with various groups (Me, Et, *t*-Bu, OMe, F, Cl, Br, I, and OCF_3) work well with 2-hydroxyphenyl enaminone **1a**, providing the corresponding 3-arylselenenyl enaminone derivatives in good to excellent yields (**3a–3p**, 55–94%). The diaryl diselenides with electron-donating groups (–Me, –Et, $-^t$Bu, –OMe) could provide higher yields than those with electron-withdrawing (–F, –Cl, –Br, –I, $-OCF_3$) substituents. Gratifyingly, when diaryl diselenide with electron-withdrawing group ($-OCF_3$) was employed, this transformation could proceed smoothly to obtain the corresponding product **3p** in 73% yield. Moreover, the reaction proceeded smoothly with 1,2-di(naphthalen-2-yl) diselane, furnishing the desired product **3q** in 70% yield. Unfortunately, 1,2-di(naphthalen-1-yl)diselane was used as

Table 2 Scope of enaminones for the tandem cyclization[a,b]



[a] Reaction conditions: enaminone **1** (0.2 mmol), diphenyl diselenide **2a** (0.2 mmol, 62.8 mg), Selectfluor agent (0.2 mmol, 70.8 mg) in CH_3CN (2.0 mL) at 40 °C for 2.0 h. [b] Isolated yield.

Table 3 Scope of diselenides on the tandem cyclization of enaminones[a,b]

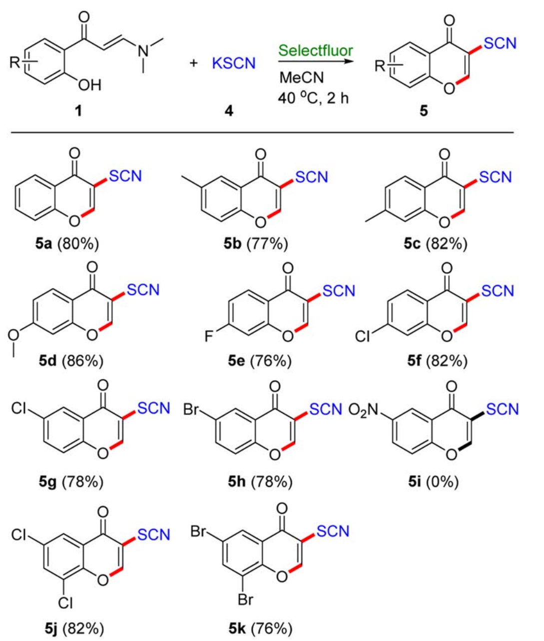


[a] Reaction conditions: enaminone **1a** (0.2 mmol, 38.2 mg), diaryl diselenide **2** (0.2 mmol), Selectfluor agent (0.2 mmol, 70.8 mg) in CH_3CN (2.0 mL) at 40 °C for 2.0 h. [b] Isolated yield.

substrate under the standard conditions, this reaction failed to afford the desired product **3t**, which suggests that the steric effect had an important effect on this transformation. Besides the generally good results employing conventional diaryl diselenides, a notable point was that heteroaryl diselenide, 1,2-di(thiophen-2-yl)diselane, also exhibited satisfactory tolerance to the synthetic protocol to provide the desired product **3r**, albeit in low yield (58%). Interestingly, when aliphatic diselenide, 1,2-dibenzyldiselane, was employed, the reaction could also proceed smoothly to obtain the desired product **3s** in excellent yields (84%).

Organic thiocyanates as key skeletal structures are moieties possessing enriched biological and pharmaceutical activities in both synthesized and naturally occurring molecules.[27] Moreover, the enriched reactivity of the thiocyano group also endows organic thiocyanates with widespread application as building blocks in organic synthesis.[28] However, the synthesis of thiocyanochromenones is rare.[29] In order to testify the utility and robustness of this protocol, Selectfluor-promoted synthesis of 3-thiocyanochromenone derivatives was explored (Table 4). We were glad to find that our protocol was applied well in the synthesis of 3-thiocyanochromenone derivatives using KSCN as a thiocyano source under the standard conditions. In general, all of enaminones **1** at the benzene ring with either electron-donating groups (Me, OMe) or electron-withdrawing groups (F, Cl, and Br) reacted smoothly to provide the corresponding products **5a–5h** in good yields (76–86%). Unfortunately, enaminone with strong electron-withdrawing group ($-NO_2$) failed to provide the desired product (**5i**), potentially due to the low reactivity of this intermediate, thus producing difficultly the cyclizing product. Gratifyingly, disubstituted enaminones also actively participated in this transformation to dispense the desired products **5j** and **5k** in 82% and 76% yield, respectively.

Table 4 Synthesis of 3-thiocyanochromones[a,b]

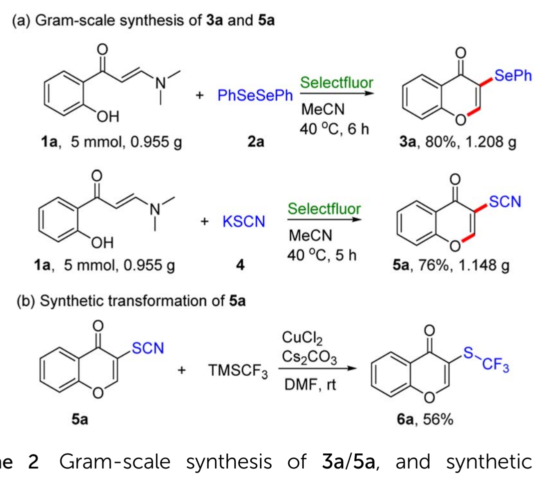


[a] Reaction conditions: enaminones **1** (0.2 mmol), potassium thiocyanate **4** (0.2 mmol, 19.4 mg), Selectfluor agent (0.2 mmol, 70.8 mg) in CH_3CN (2.0 mL) at 40 °C for 2.0 h. [b] Isolated yield.

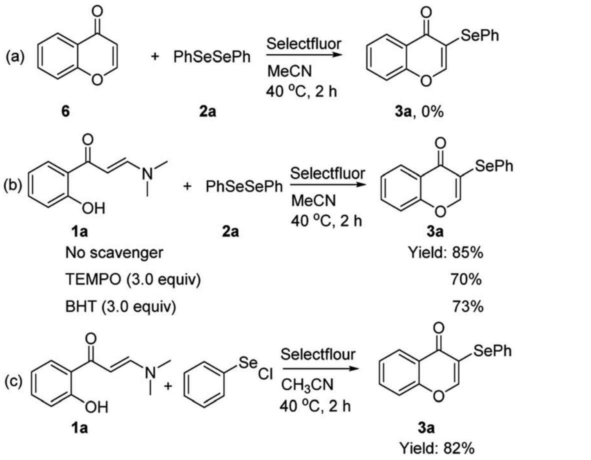
Additionally, to verify the utility of this protocol, gram–scale reactions were conducted using 2-hydroxyphenyl enaminone **1a** (5 mmol, 0.955 g) with diphenyl diselenide **2a** under the standard conditions. As expected, the corresponding desired products **3a** and **5a** were obtained in 80% and 76% yield, respectively (Scheme 2a), which provides promising application in preparative synthesis. Then, the synthetic transformation of **5a** was carried out to explore the thiocyano group with widespread application as a building block in organic synthesis (Scheme 2b).

To investigate the possible process of the reaction, several control experiments were designed as outlined in Scheme 3. Initially, the entry directly employing chromone **6** and diphenyl diselenide **2a** with standard reaction conditions was found to be incapable of yielding target product **3a**, and 92% of the substrate **6** was recovered (Scheme 3a), which showed that the annulation to chromone was not the initial step in the reaction. Subsequently, radical trapping experiments of enaminone **1a** and diphenyl diselenide **2a** were examined in the presence of 2,2,6,6-tetramethyl-1-piperidinyloxyl (TEMPO, 3.0 equiv.) or 2,6-di-*tert*-butyl-4-methylphenol (BHT, 3.0 equiv.) under the standard conditions, and the desired product **3a** was provided in 70% and 73% yield, respectively (Scheme 3b). These results indicate that the reaction might not involve radical intermediates, which was in agreement with the case in previous work.[26a] Furthermore, when phenyl hypochloroselenoite was added to the reaction system instead of diphenyl diselenide **2a** under the standard conditions, the product **3a** was obtained with 82% yield (Scheme 3c), demonstrating that this transformation may proceed *via* an ion pathway, instead of a radical pathway.

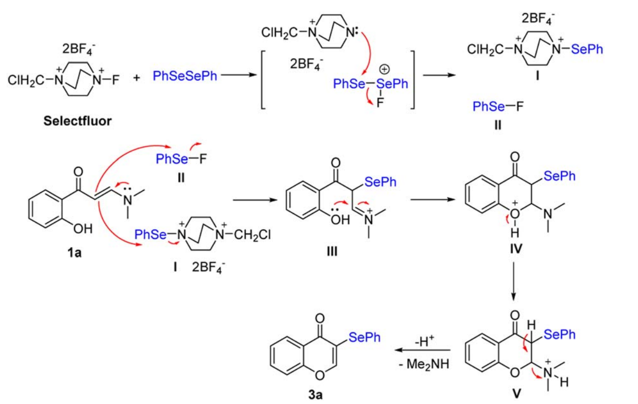
On the basis of these results and previous reports,[19–23] a plausible mechanism for this transformation was proposed (Scheme 4). Initially, the reaction involves the oxidation of diphenyl diselenide by Selectfluor reagent to form the electrophilic species **I** and **II**.[26b,d] Then, these species attack C–C double bond of 2-hydroxyphenyl enaminone **1a** to form



Scheme 2 Gram-scale synthesis of **3a**/**5a**, and synthetic transformation of **5a**.



Scheme 3 Control experiments. (a) Direct selenylation of chromone; (b) radical trapping experiments; (c) phenyl hypochloroselenoite as selenylation reagent.



Scheme 4 Proposed reaction mechanism.

species **III**. Subsequently, the species **III** would afford the cyclic intermediate **IV** through the intramolecular nucleophilic attack of the carbon atom of the C=N moiety. The intermediate **V** is made by the proton transfer. Finally, the elimination of dimethylamine from the intermediate **V** would furnish the expected product **3a**. For the synthetic mechanism of 3-thiocyanochromenone derivatives, the thiocyano cation could be formed with KSCN using Selectfluor reagent as an oxidant. 3-Thiocyanochromenone derivatives could be provided by the similar mechanism.

Conclusions

In conclusion, an intriguing Selectfluor-promoted, metal-free, and efficient synthetic approach to access 3-selenylated chromones have been developed from enaminones and easily available diaryl diselenides. This approach exhibits a broad substrate scope, simple procedure, mild reaction condition, good to excellent yields and high selectivity. Furthermore, the application of potassium thiocyanate with enaminones for the synthesis of 3-thiocyanochromenone derivatives is also successful.

Experimental

General information

All chemicals were commercially available and used as received without further. Column chromatography was performed using 300–400 mesh silica. Nuclear magnetic resonance spectra were recorded on Bruker Avance 400 MHz spectrometer. Chemical shifts for ^{1}H NMR spectra are recorded in parts per million from tetramethylsilane. Data were reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet and br = broad), coupling constant in Hz and integration. Chemical shifts for ^{13}C NMR spectra were recorded in parts per million from tetramethylsilane. Chemical shifts for ^{19}F NMR spectra were recorded in parts per million with fluorobenzene as external standard. High resolution mass spectra (HR MS) were obtained on Thermo Scientific LTQ Orbitrap XL instrument using the ESI technique. IR spectra were recorded on WQF-510 Fourier transform infrared spectrophotometer. Melting points were measured on an XT4A microscopic apparatus uncorrected.

General experimental procedure for the synthesis of 3-arylselenenyl chromones (3)

Enaminones **1** (0.2 mmol), diaryl diselenides **2** (0.2 mmol), Selectfluor agent (0.2 mmol, 70.8 mg), and acetonitrile (2.0 mL) were added to a 10 mL reaction tube. The mixture was stirred at 40 °C for 2 h. After completion of the reaction, the solvent was distilled under vacuum. Then, the resulting mixture was dissolved with ethyl acetate (20 mL), washed with saturated sodium chloride solution (10 mL × 2). The organic phase was dried over anhydrous Na_2SO_4 and concentrated under vacuum. The residue was purified by silica gel column chromatography to give 3-arylseleno chromones **3** using ethyl acetate/petroleum ether as eluant.

7-Methyl-3-(phenylselanyl)-4*H*-chromen-4-one (3aa). Light yellow crystal, mp 107–108 °C (lit.[16b] 99–100 °C); IR (KBr) ν (cm^{-1}): 2921, 1644, 1621, 1476, 1435, 1344, 1298, 1064; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.10 (d, J_{H-H} = 8.0 Hz, 1H), 7.85 (s, 1H), 7.59–7.57 (m, 2H), 7.29–7.26 (m, 3H), 7.22–7.20 (m, 2H), 2.46 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.0 (C=O), 156.5, 155.6 (CH), 145.3, 133.7 (CH), 129.5 (CH), 128.3, 128.0 (CH), 127.1 (CH), 126.1 (CH), 120.9, 117.7 (CH), 117.6, 21.8 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ [M + H]$^+$ 317.0075, found 317.0069.

6-Methyl-3-(phenylselanyl)-4*H*-chromen-4-one (3ba). Colorless crystal, mp 96–97 °C (lit.[16b] 99–100 °C); IR (KBr) ν (cm^{-1}): 1640, 1616, 1598, 1477, 1436, 1308, 1227, 1067; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.02 (d, J_{H-H} = 1.0 Hz, 1H), 7.90 (s, 1H), 7.60–7.57 (m, 2H), 7.47 (dd, J_{H-H} = 8.5 Hz, J_{H-H} = 2.0 Hz, 1H), 7.33 (d, J_{H-H} = 8.6 Hz, 1H), 7.29–7.28 (m, 3H), 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.3 (C=O), 155.9 (CH), 154.6 (CH), 135.6, 135.1 (CH), 133.6 (CH), 129.5 (CH), 128.4, 128.0 (CH), 125.6 (CH), 122.8, 117.8 (CH), 117.4, 20.9 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ [M + H]$^+$ 317.0075, found 317.0068.

6-Methoxy-3-(phenylselanyl)-4*H*-chromen-4-one (3ca). Colorless crystal, mp 99–100 °C (lit.[20a] 99–101 °C); IR (KBr) ν (cm^{-1}): 2932, 1630, 1615, 1546, 1487, 1264; ^{1}H NMR (400 MHz,

$CDCl_3$) δ: 7.92 (s, 1H), 7.60–7.58 (m, 3H), 7.37 (d, J_{H-H} = 9.2 Hz, 1H), 7.30–7.24 (m, 4H), 3.88 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.0 (C=O), 157.2, 155.8 (CH), 151.2, 133.6 (CH), 129.5 (CH), 128.4, 128.0 (CH), 124.0 (CH), 123.8, 119.5 (CH), 116.8, 105.2 (CH), 55.9 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_3Se$ $[M + H]^+$ 333.0024, found 333.0019.

7-Fluoro-3-(phenylselanyl)-4*H*-chromen-4-one (3da). Colorless crystal, mp 115–116 °C (lit.[16b] 120–121 °C); IR (KBr) ν (cm^{-1}): 1605, 1474, 1431, 1349, 1251, 1092; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.26–8.22 (m, 1H), 7.79 (s, 1H), 7.61–7.59 (m, 2H), 7.32–7.30 (m, 3H), 7.16–7.11 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 174.3 (C=O), 165.6 (d, J_{F-C} = 254.2 Hz), 157.3 (d, J_{F-C} = 13.2 Hz), 155.3 (CH), 134.1 (CH), 129.6 (CH), 129.0 (CH), 128.9 (CH), 128.3 (CH), 127.6, 119.9 (d, J_{F-C} = 2.3 Hz), 118.4, 114.4 (d, J_{F-C} = 22.7 Hz, CH), 104.7 (d, J_{F-C} = 25.2 Hz, CH); ^{19}F NMR (376 MHz, $CDCl_3$) δ: −102.1. HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}FO_2Se$ $[M + H]^+$ 320.9825, found 320.9818.

7-Chloro-3-(phenylselanyl)-4*H*-chromen-4-one (3ea). Light yellow crystal, mp 111–112 °C (lit.[16b] 112–113 °C); IR (KBr) ν (cm^{-1}): 1651, 1602, 1576, 1477, 1339, 1282, 1021; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.13 (d, J_{H-H} = 8.6 Hz, 1H), 7.76 (s, 1H), 7.60–7.58 (m, 2H), 7.40 (d, J_{H-H} = 1.8 Hz, 1H), 7.35–7.27 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 174.3 (C=O), 156.3, 155.0 (CH), 139.8, 134.2 (CH), 129.6 (CH), 128.4 (CH), 127.6 (CH), 127.5, 126.4 (CH), 121.4, 118.6, 118.0 (CH); HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}ClO_2Se$ $[M + H]^+$ 336.9529, found 336.9519.

6-Bromo-3-(phenylselanyl)-4*H*-chromen-4-one (3fa). Colorless crystal, mp 90–91 °C (lit.[16b] 90–91 °C); IR (KBr) ν (cm^{-1}): 1645, 1601, 1540, 1422, 1348, 1297, 1058; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.34 (d, J_{H-H} = 2.4 Hz, 1H), 7.83 (s, 1H), 7.73 (dd, J_{H-H} = 8.9 Hz, J_{H-H} = 2.4 Hz, 1H), 7.61–7.58 (m, 1H), 7.33–7.30 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.9 (C=O), 155.4 (CH), 155.0, 136.8 (CH), 134.1 (CH), 129.6 (CH), 128.8 (CH), 128.4 (CH), 127.5, 124.2, 120.0 (CH), 118.9, 118.3; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}BrO_2Se$ $[M + H]^+$ 380.9024, found 380.9010.

6,8-Dichloro-3-(phenylselanyl)-4*H*-chromen-4-one (3ga). Light yellow crystal, mp 114–115 °C (lit.[20a] 113–115 °C); IR (KBr) ν (cm^{-1}): 1644, 1591, 1447, 1356, 1296, 1197; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.08 (d, J_{H-H} = 2.5 Hz, 1H), 7.76 (s, 1H), 7.68 (d, J_{H-H} = 2.5 Hz, 1H), 7.64–7.61 (m, 2H), 7.36–7.30 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.5 (C=O), 154.2 (CH), 150.6, 134.8 (CH), 133.9 (CH), 131.1, 129.8 (CH), 128.8 (CH), 126.6, 124.4, 124.3 (CH), 119.3; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_9Cl_2O_2Se$ $[M + H]^+$ 370.9139, found 370.9141.

6,8-Dibromo-3-(phenylselanyl)-4*H*-chromen-4-one (3ha). Orange yellow crystal, mp 115–116 °C (lit.[20a] 118–119 °C); IR (KBr) ν (cm^{-1}): 1656, 1540, 1449, 1345, 1288, 1069; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.29 (d, J_{H-H} = 2.4 Hz, 1H), 8.00 (d, J_{H-H} = 2.4 Hz, 1H), 7.77 (s, 1H), 7.64–7.62 (m, 2H), 7.37–7.31 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.5 (C=O), 154.2 (CH), 152.0, 139.5 (CH), 134.8 (CH), 129.8 (CH), 128.8 (CH), 128.2 (CH), 126.6, 124.7, 119.3, 118.7, 112.8; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_9Br_2O_2Se$ $[M + H]^+$ 458.8129, found 458.8134.

6-Nitro-3-(phenylselanyl)-4*H*-chromen-4-one (3ia). Yellow crystal, mp 108–109 °C (lit.[16b] 115–116 °C); IR (KBr) ν (cm^{-1}): 1637, 1574, 1437, 1344, 1206, 1089; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.08 (d, J_{H-H} = 2.7 Hz, 1H), 8.48 (dd, J_{H-H} = 9.1 Hz, J_{H-H} = 2.4 Hz, 1H), 7.76 (s, 1H), 7.65–7.63 (m, 2H), 7.59 (d, J_{H-H} = 9.2 Hz, 1H), 7.39–7.32 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.9 (C=O), 159.0, 154.4 (CH), 144.9, 134.9 (CH), 129.8 (CH), 128.9 (CH), 128.0 (CH), 126.4, 123.0 (CH), 122.7, 120.0, 119.9 (CH); HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}NO_4Se$ $[M + H]^+$ 347.9770, found 347.9773.

3-(Phenylselanyl)-4*H*-benzo[*h*]chromen-4-one (3ja). Light yellow crystal, mp 110–112 °C (lit.[16b] 105–106 °C); IR (KBr) ν (cm^{-1}): 1618, 1559, 1464, 1301, 1260, 1155; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.35 (d, J_{H-H} = 8.2 Hz, 1H), 8.13 (d, J_{H-H} = 8.8 Hz, 1H), 7.90–7.87 (m, 2H), 7.72 (d, J_{H-H} = 8.7 Hz, 1H), 7.69–7.59 (m, 4H), 7.34–7.31 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.0 (C=O), 153.8 (CH), 135.7, 134.4 (CH), 129.7 (CH), 129.4 (CH), 128.4 (CH), 128.1 (CH), 127.5, 127.2 (CH), 125.6 (CH), 123.8, 122.1 (CH), 121.0 (CH), 120.2, 119.1; HR MS (ESI) *m*/*z*: calcd for $C_{19}H_{13}O_2Se$ $[M + H]^+$ 353.0075, found 353.0069.

3-(Phenylselanyl)-4*H*-chromen-4-one (3a). Light yellow crystal, mp 63–64 °C (lit.[22] yellow liquid); IR (KBr) ν (cm^{-1}): 1626, 1610, 1461, 1342, 1110; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.24–8.21 (m, 1H), 7.89 (s, 1H), 7.68–7.63 (m, 1H), 7.60–7.58 (m, 2H), 7.43–7.38 (m, 2H), 7.31–7.27 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.2 (C=O), 156.3, 155.8 (CH), 133.9 (CH), 133.8 (CH), 129.5 (CH), 128.1 (CH), 126.3 (CH), 125.5 (CH), 123.1, 118.0 (CH), 117.8; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{11}O_2Se$ $[M + H]^+$ 302.9919, found 302.9911.

3-(*o*-Tolylselanyl)-4*H*-chromen-4-one (3b). Light yellow crystal, mp 95–96 °C (lit.[22] 118–119 °C); IR (KBr) ν (cm^{-1}): 2920, 1643, 1610, 1343, 1251, 1073; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.25 (dd, J_{H-H} = 8.5 Hz, J_{H-H} = 1.8 Hz, 1H), 7.69–7.65 (m, 2H), 7.48 (dd, J_{H-H} = 7.5 Hz, J_{H-H} = 0.8 Hz, 1H), 7.44–7.41 (m, 2H), 7.25–7.23 (m, 2H), 7.21–7.08 (m, 1H), 2.50 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.3 (C=O), 156.4, 154.7 (CH), 140.6, 134.4 (CH), 133.8 (CH), 130.5 (CH), 128.5 (CH), 128.4, 127.0 (CH), 126.3 (CH), 125.5 (CH), 122.9, 118.0 (CH), 117.3, 22.3 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ $[M + H]^+$ 317.0075, found 317.0070.

3-(*m*-Tolylselanyl)-4*H*-chromen-4-one (3c). Light yellow crystal, mp 73–74 °C; IR (KBr) ν (cm^{-1}): 2915, 1651, 1551, 1455, 1359, 1334, 1306, 1069; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.23 (dd, J_{H-H} = 8.4 Hz, J_{H-H} = 1.7 Hz, 1H), 7.85 (s, 1H), 7.68–7.63 (m, 1H), 7.43–7.38 (m, 4H), 7.18 (t, J_{H-H} = 7.6 Hz, 1H), 7.11 (d, J_{H-H} = 7.6 Hz, 1H), 2.31 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.2 (C=O), 156.3, 155.4 (CH), 139.4, 134.5 (CH), 133.7 (CH), 131.0 (CH), 129.3 (CH), 129.0 (CH), 127.7, 126.3 (CH), 125.5, 123.1, 118.0 (CH), 21.3 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ $[M + H]^+$ 317.0075, found 317.0070.

3-(*p*-Tolylselanyl)-4*H*-chromen-4-one (3d). Light yellow crystal, mp 85–86 °C (lit.[22] 83–84 °C); IR (KBr) ν (cm^{-1}): 2918, 1641, 1606, 1550, 1486, 1360, 1341, 1326, 1207; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.23 (dd, J_{H-H} = 8.5 Hz, J_{H-H} = 1.9 Hz, 1H), 7.77 (s, 1H), 7.67–7.63 (m, 1H), 7.53 (d, J_{H-H} = 8.1 Hz, 2H), 7.42–7.38 (m, 2H), 7.12 (d, J_{H-H} = 7.8 Hz, 2H), 2.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.2 (C=O), 156.3, 154.8 (CH), 138.5, 134.6 (CH), 133.7 (CH), 130.4 (CH), 126.2 (CH), 125.4 (CH), 123.8, 123.0, 118.6, 118.0 (CH), 21.2 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ $[M + H]^+$ 317.0075, found 317.0070.

3-((3,4-Dimethylphenyl)selanyl)-4*H*-chromen-4-one (3e). Light yellow crystal, mp 110–111 °C; IR (KBr) ν (cm^{-1}): 2917, 1620, 1606, 1554, 1450, 1312, 1107; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23(dd, J_{H-H} = 8.0 Hz, J_{H-H} = 1.6 Hz, 1H), 7.74 (s, 1H), 7.67–7.63 (m, 1H), 7.42–7.35 (m, 4H), 7.07 (d, J_{H-H} = 7.8 Hz, 1H),2.24 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.2 (C═O), 156.3, 154.5 (CH), 138.2, 137.2, 135.7 (CH), 133.7 (CH), 132.2 (CH), 130.8 (CH), 126.3 (CH), 125.4 (CH), 123.9, 123.0, 118.7, 118.0 (CH), 19.6 (CH$_3$), 19.5 (CH$_3$); HR MS (ESI) *m*/*z*: calcd for $C_{17}H_{15}O_2Se$ [M + H]$^+$ 331.0232, found 331.0226.

3-((4-Ethylphenyl)selanyl)-4*H*-chromen-4-one (3f). Light yellow crystal, mp 98–99 °C (lit.[30] yellow oil liquid); IR (KBr) ν (cm^{-1}): 2963, 1636, 1610, 1462, 1342, 1309, 1109, 1057; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.24 (dd, J_{H-H} = 8.4 Hz, J_{H-H} = 1.8 Hz, 1H), 7.79 (s, 1H), 7.68–7.64 (m, 1H), 7.55 (d, J_{H-H} = 8.2 Hz, 2H), 7.43–7.39 (m, 2H), 7.15 (d, J_{H-H} = 8.2 Hz, 2H), 2.63 (q, J_{H-H} = 7.6 Hz, 2H), 1.22 (t, J_{H-H} = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.4 (C═O), 156.3 (CH), 154.9 (CH), 144.8, 134.6 (CH), 133.7 (CH), 129.2 (CH), 126.3 (CH), 125.4 (CH), 124.1, 123.0, 118.5, 118.0 (CH), 28.5 (CH$_2$), 15.4 (CH$_3$); HR MS (ESI) *m*/*z*: calcd for $C_{17}H_{15}O_2Se$ [M + H]$^+$ 331.0232, found 331.0227.

3-((4-(*tert*-Butyl)phenyl)selanyl)-4*H*-chromen-4-one (3g). Light yellow crystal, mp 110–111 °C; IR (KBr) ν (cm^{-1}): 2959, 2922, 1642, 1607, 1555, 1459, 1342, 1111; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.24 (dd, J_{H-H} = 8.4 Hz, J_{H-H} = 1.5 Hz, 1H), 7.82 (s, 1H), 7.65 (td, J_{H-H} = 7.8 Hz, J_{H-H} = 1.7 Hz, 1H), 7.55 (d, J_{H-H} = 8.4 Hz, 2H), 7.42–7.39 (m, 2H), 7.33 (d, J_{H-H} = 8.5 Hz, 2H), 1.30 (s, 9H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.3 (C═O), 156.3, 155.0 (CH), 151.6, 134.2 (CH), 133.7 (CH), 126.7 (CH), 126.3 (CH), 125.4 (CH), 124.1, 123.0, 118.3, 118.0 (CH), 34.6, 31.2 (CH$_3$); HR MS (ESI) *m*/*z*: calcd for $C_{19}H_{19}O_2Se$ [M + H]$^+$ 359.0545, found 259.0538.

3-((4-Methoxyphenyl)selanyl)-4*H*-chromen-4-one (3h). Light yellow crystal, mp 125–126 °C (lit.[22] 131–132 °C); IR (KBr) ν (cm^{-1}): 2959, 1643, 1581, 1552, 1462, 1245, 1022; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.22 (dd, J_{H-H} = 8.3 Hz, J_{H-H} = 1.6 Hz, 1H), 7.66–7.59 (m, 4H), 7.41–7.37 (m, 2H), 6.86 (d, J_{H-H} = 8.8 Hz, 2H), 3.80 (s, 3H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.3 (C═O), 160.2, 156.3, 153.8 (CH), 137.1 (CH), 133.6 (CH), 126.1 (CH), 125.3 (CH), 122.8, 119.3, 118.0 (CH), 117.0, 115.3 (CH), 55.3 (CH$_3$); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_3Se$ [M + H]$^+$ 333.0024, found 333.0018.

3-((3-Methoxyphenyl)selanyl)-4*H*-chromen-4-one (3i). Light yellow crystal, mp 89–90 °C (lit.[16b] 88–89 °C); IR (KBr) ν (cm^{-1}): 2962, 1648, 1586, 1551, 1454, 1288, 1038; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 7.9 Hz, J_{H-H} = 1.4 Hz, 1H), 7.91 (s, 1H), 7.68–7.64 (m, 1H), 7.43–7.39 (m, 2H), 7.20 (t, J_{H-H} = 7.8 Hz, 1H), 7.18–7.14 (m, 2H), 6.84–6.81 (m, 1H), 3.77 (s, 3H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.1 (C═O), 160.0, 156.3, 155.8 (CH), 133.8 (CH), 130.3 (CH), 129.0, 126.3 (CH), 125.8 (CH), 125.5 (CH), 123.1, 118.9 (CH), 118.0 (CH), 117.6, 113.9 (CH), 55.3 (CH$_3$); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_3Se$ [M + H]$^+$ 333.0024, found 333.0018.

3-((4-Fluorophenyl)selanyl)-4*H*-chromen-4-one (3j). Light yellow crystal, mp 93–94 °C (lit.[16b] 94–95 °C); IR (KBr) ν (cm^{-1}): 1643, 1361, 1221, 1064; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 8.3 Hz, J_{H-H} = 1.5 Hz, 1H), 7.90 (s, 1H), 7.69–7.65 (m, 1H), 7.64–7.60 (m, 2H), 7.44–7.40 (m, 2H), 7.00 (t, J_{H-H} = 8.7 Hz, 2H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.2 (C═O), 162.9 (d, J_{F-C} = 247.0 Hz), 156.3, 155.5 (CH), 136.4 (d, J_{F-C} = 7.9 Hz), 133.9, 126.3, 125.6, 123.1, 122.6, 122.5, 118.0, 116.7 (d, J_{F-C} = 21.3 Hz); ^{19}F NMR (376 MHz, CDCl$_3$) δ: −112.9. HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}FO_2Se$ [M + H]$^+$ 320.9825, found 320.9818.

3-((4-Chlorophenyl)selanyl)-4*H*-chromen-4-one (3k). Light yellow crystal, mp 133–134 °C (lit.[22] 133–134 °C); IR (KBr) ν (cm^{-1}): 1628, 1551, 1460, 1308, 1249, 1075; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 8.0 Hz, J_{H-H} = 1.4 Hz, 1H), 8.01 (s, 1H), 7.71–7.66 (m, 1H), 7.52 (d, J_{H-H} = 8.5 Hz, 2H), 7.46–7.41 (m, 2H), 7.26–7.24 (m, 2H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.0 (C═O), 156.4 (CH), 156.3, 134.8 (CH), 134.3, 133.9 (CH), 129.6 (CH), 126.6, 126.4 (CH), 125.7 (CH), 123.2, 118.1 (CH), 117.2; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}ClO_2Se$ [M + H]$^+$ 336.9529, found 336.9519.

3-((3-Chlorophenyl)selanyl)-4*H*-chromen-4-one (3l). Light yellow crystal, mp 89–90 °C (lit.[16b] 90–91 °C); IR (KBr) ν (cm^{-1}): 1652, 1605, 1564, 1552, 1405, 1360, 1308, 1101; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.24 (dd, J_{H-H} = 8.0 Hz, J_{H-H} = 1.4 Hz, 1H), 8.09 (s, 1H), 7.72–7.67 (m, 1H), 7.53 (t, J_{H-H} = 1.6 Hz, 1H), 7.47–7.42 (m, 3H), 7.25–7.18 (m, 2H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.0 (C═O), 157.1 (CH), 156.4, 134.9, 134.0 (CH), 132.4 (CH), 130.9 (CH), 130.4 (CH), 128.0 (CH), 126.4 (CH), 125.8 (CH), 123.3, 118.1 (CH), 116.6; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}ClO_2Se$ [M + H]$^+$ 336.9529, found 336.9521.

3-((4-Bromophenyl)selanyl)-4*H*-chromen-4-one (3m). Light yellow crystal, mp 124–125 °C (lit.[16b] 129–130 °C); IR (KBr) ν (cm^{-1}): 1627, 1608, 1549, 1379, 1329, 1100; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 8.0 Hz, J_{H-H} = 1.6 Hz, 1H), 8.03 (s, 1H), 7.71–7.66 (m, 1H), 7.46–7.38 (m, 6H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.0 (C═O), 156.6 (CH), 156.3, 134.9 (CH), 134.0 (CH), 132.5 (CH), 127.4, 126.4 (CH), 125.7 (CH), 123.2, 122.4, 118.1 (CH), 117.0; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}BrO_2Se$ [M + H]$^+$ 380.9024, found 380.9014.

3-((2-Bromophenyl)selanyl)-4*H*-chromen-4-one (3n). Yellow crystal, mp 130–131 °C; IR (KBr) ν (cm^{-1}): 1637, 1610, 1549, 1436, 1313, 1167; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 8.0 Hz, J_{H-H} = 1.6 Hz, 1H), 8.05 (s, 1H), 7.71–7.67 (m, 1H), 7.59 (d, J_{H-H} = 8.4 Hz, 2H), 7.46–7.41 (m, 2H), 7.30 (d, J_{H-H} = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.0 (C═O), 159.3 (CH), 156.5, 134.1 (CH), 133.0, 132.9 (CH), 131.1 (CH), 128.1 (CH), 128.0 (CH), 126.6 (CH), 125.9 (CH), 124.3, 123.6, 118.2 (CH), 115.2; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}BrO_2Se$ [M + H]$^+$ 380.9024, found 380.9013.

3-((4-Iodophenyl)selanyl)-4*H*-chromen-4-one (3o). Light yellow crystal, mp 121–122 °C; IR (KBr) ν (cm^{-1}): 1629, 1548, 1458, 1309, 1063; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.23 (dd, J_{H-H} = 7.9 Hz, J_{H-H} = 1.6 Hz, 1H), 8.05 (s, 1H), 7.71–7.67 (m, 1H), 7.59 (d, J_{H-H} = 8.3 Hz, 2H), 7.46–7.42 (m, 2H), 7.30 (d, J_{H-H} = 8.4 Hz, 2H); ^{13}C NMR (100 MHz, CDCl$_3$) δ: 175.0 (C═O), 156.8, 156.4, 138.4, 134.9, 134.0, 128.5, 126.4, 125.7, 123.3, 118.1, 116.9, 93.8; HR MS (ESI) *m*/*z*: calcd for $C_{15}H_{10}IO_2Se$ [M + H]$^+$ 428.8885, found 428.8874.

3-((4-(Trifluoromethoxy)phenyl)selanyl)-4*H*-chromen-4-one (3p). Light yellow crystal, mp 90–91 °C; IR (KBr) ν (cm^{-1}): 1640, 1611, 1554, 1461, 1112, 1062; ^{1}H NMR (400 MHz, CDCl$_3$) δ: 8.24

(dd, $J_{H-H} = 7.8$ Hz, $J_{H-H} = 1.6$ Hz, 1H), 8.07 (s, 1H), 7.71–7.67 (m, 1H), 7.61 (d, $J_{H-H} = 8.8$ Hz, 2H), 7.46–7.42 (m, 2H), 7.13 (dd, $J_{H-H} = 8.7$ Hz, $J_{H-H} = 0.7$ Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.1 (C═O), 156.9 (CH), 156.4, 149.1 (q, $J_{F-C} = 1.5$ Hz), 134.8 (CH), 134.0 (CH), 126.9, 126.4 (CH), 125.8 (CH), 123.3, 121.9 (CH), 118.1 (CH), 116.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ: −57.8. HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{10}F_3O_3Se$ [M + H]$^+$ 386.9742, found 386.9734.

3-(Naphthalen-2-ylselanyl)-4*H*-chromen-4-one (3q). Light yellow crystal, mp 77–78 °C (lit.[22] white liquid); IR (KBr) ν (cm^{-1}): 1627, 1604, 1554, 1499, 1253, 1108; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.40 (d, $J_{H-H} = 7.8$ Hz, 1H), 8.25 (dd, $J_{H-H} = 8.0$ Hz, $J_{H-H} = 1.6$ Hz, 1H), 7.96 (dd, $J_{H-H} = 7.1$ Hz, $J_{H-H} = 1.1$ Hz, 1H), 7.90 (d, $J_{H-H} = 8.2$ Hz, 1H), 7.86 (dd, $J_{H-H} = 7.0$ Hz, $J_{H-H} = 1.6$ Hz, 1H), 7.65–7.61 (m, 1H), 7.57–7.50 (m, 2H), 7.44–7.38 (m, 2H), 7.34 (d, $J_{H-H} = 8.5$ Hz, 1H), 7.32 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.4 (C═O), 156.2, 153.3 (CH), 135.4 (CH), 134.3, 134.2, 133.7 (CH), 130.2 (CH), 128.7 (CH), 127.7 (CH), 127.4 (CH), 126.6 (CH), 126.1 (CH), 125.9, 125.4 (CH), 122.7, 118.3, 118.0 (CH); HR MS (ESI) *m*/*z*: calcd for $C_{19}H_{13}O_2Se$ [M + H]$^+$ 353.0075, found 353.0069.

3-(Thiophen-2-ylselanyl)-4*H*-chromen-4-one (3r). Light yellow crystal, mp 119–120 °C (lit.[16b] 120–121 °C); IR (KBr) ν (cm^{-1}): 1629, 1609, 1548, 1458, 1329, 1201, 1063; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.22 (dd, $J_{H-H} = 8.3$ Hz, $J_{H-H} = 1.7$ Hz, 1H), 7.69–7.64 (m, 1H), 7.59 (s, 1H), 7.49 (d, $J_{H-H} = 8.4$ Hz, 1H), 7.43–7.40 (m, 3H), 7.07–7.05 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.1 (C═O), 156.3, 153.3 (CH), 137.9 (CH), 133.8 (CH), 132.7 (CH), 128.6 (CH), 126.1 (CH), 125.5 (CH), 122.7, 120.0, 119.9, 118.0 (CH); HR MS (ESI) *m*/*z*: calcd for $C_{13}H_9O_2SSe$ [M + H]$^+$ 308.9483, found 308.9477.

3-(Benzylselanyl)-4*H*-chromen-4-one (3s). Light yellow crystal, mp 109–110 °C (lit.[16b] 94–95 °C); IR (KBr) ν (cm^{-1}): 1610, 1556, 1463, 1378, 1073; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.27 (dd, $J_{H-H} = 8.0$ Hz, $J_{H-H} = 1.6$ Hz, 1H), 7.87 (s, 1H), 7.69–7.64 (m, 1H), 7.45–7.39 (m, 2H), 7.23–7.13 (m, 5H), 4.10 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 175.8 (C═O), 157.5 (CH), 156.3, 138.5, 133.7 (CH), 128.9 (CH), 128.4 (CH), 126.8 (CH), 126.3 (CH), 125.6 (CH), 123.3, 118.1 (CH), 114.2, 29.7 (CH_2); HR MS (ESI) *m*/*z*: calcd for $C_{16}H_{13}O_2Se$ [M + H]$^+$ 317.0075, found 317.0070.

General experimental procedure for the synthesis of 3-thiocyano chromones (5)

Enaminones **1** (0.2 mmol), potassium thiocyanate **4** (0.2 mmol, 19.4 mg), Selectfluor agent (0.2 mmol, 70.8 mg), and acetonitrile (2.0 mL) were added to a 10 mL reaction tube. The mixture was stirred at 40 °C for 2 h. After completion of the reaction, the solvent was distilled under vacuum. Then, the resulting mixture was dissolved with ethyl acetate (20 mL), washed with saturated sodium chloride solution (10 mL × 2). The organic phase was dried over anhydrous Na_2SO_4 and concentrated under vacuum. The residue was purified by silica gel column chromatography to give 3-thiocyano chromones **5** using ethyl acetate/petroleum ether as eluant.

3-Thiocyanato-4*H*-chromen-4-one (5a). Light yellow crystal, mp 139–140 °C (lit.[29d] 149–150 °C); IR (KBr) ν (cm^{-1}): 1651, 1550, 1457, 1363, 1204, 1086; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.34 (s, 1H), 8.25 (dd, $J_{H-H} = 8.0$ Hz, $J_{H-H} = 1.5$ Hz, 1H), 7.80–7.76 (m, 1H), 7.56–7.50 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.0 (C═O), 156.3, 155.4 (CH), 135.0 (CH), 126.6 (CH), 126.1 (CH), 122.6, 118.4 (CH), 112.5, 108.9; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_6NO_2S$ [M + H]$^+$ 204.0114, found 204.0109.

6-Methyl-3-thiocyanato-4*H*-chromen-4-one (5b). Light yellow crystal, mp 124–125 °C (lit.[29e] 134–135 °C); IR (KBr) ν (cm^{-1}): 3070, 1648, 1559, 1479, 1331, 1147, 1125; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.31 (s, 1H), 8.02 (d, $J_{H-H} = 1.1$ Hz, 1H), 7.58 (dd, $J_{H-H} = 8.6$ Hz, $J_{H-H} = 2.0$ Hz, 1H), 7.44 (d, $J_{H-H} = 8.6$ Hz, 1H), 2.48 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.0 (C═O), 155.3 (CH), 154.6, 136.9, 136.2 (CH), 125.3 (CH), 122.3, 118.1 (CH), 112.2, 109.0, 21.0 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{11}H_8NO_2S$ [M + H]$^+$ 218.0270, found 218.0266.

7-Methyl-3-thiocyanato-4*H*-chromen-4-one (5c). Colorless crystal, mp 135–136 °C; IR (KBr) ν (cm^{-1}): 2922, 1608, 1436, 1245, 1211, 1199, 1092; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.18 (d, $J_{H-H} = 8.9$ Hz, 1H), 8.07 (d, $J_{F-H} = 3.2$ Hz, 1H), 7.02 (dd, $J_{H-H} = 8.9$ Hz, $J_{H-H} = 2.2$ Hz, 1H), 6.86 (d, $J_{F-H} = 2.2$ Hz, 1H), 3.91 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 164.4 (C═O), 157.7, 150.6, 148.1, 142.5, 142.1, 127.3, 127.2, 114.9, 100.3, 55.9 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{11}H_8NO_2S$ [M + H]$^+$ 218.0270, found 218.0267.

7-Methoxy-3-thiocyanato-4*H*-chromen-4-one (5d). Light yellow crystal, mp 157–158 °C (lit.[29e] 159–160 °C); IR (KBr) ν (cm^{-1}): 2923, 2162, 1729, 1614, 1433, 1375, 1276, 1241, 1081; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.23 (s, 1H), 8.13 (d, $J_{H-H} = 8.9$ Hz, 1H), 7.05 (dd, $J_{H-H} = 8.9$ Hz, $J_{H-H} = 2.4$ Hz, 1H), 6.89 (d, $J_{F-H} = 2.4$ Hz, 1H), 3.93 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 172.2 (C═O), 165.0, 158.2, 154.5 (CH), 127.4 (CH), 116.3, 115.9 (CH), 112.7, 109.1, 100.5 (CH), 56.0 (CH_3); HR MS (ESI) *m*/*z*: calcd for $C_{11}H_8NO_3S$ [M + H]$^+$ 234.0219, found 234.0212.

7-Fluoro-3-thiocyanato-4*H*-chromen-4-one (5e).[29c] Colorless crystal, mp 120–121 °C; IR (KBr) ν (cm^{-1}): 1638, 1439, 1375, 1234, 1141; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.31 (s, 1H), 8.30–8.26 (m, 1H), 7.28–7.22 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 172.0 (C═O), 166.2 (d, $J_{F-C} = 256.7$ Hz), 157.3 (d, $J_{F-C} = 13.2$ Hz), 155.1 (CH), 128.8 (d, $J_{F-C} = 10.8$ Hz, CH), 119.5 (d, $J_{F-C} = 2.3$ Hz), 115.6 (d, $J_{F-C} = 22.7$ Hz, CH), 113.2, 108.6, 105.2 (d, $J_{F-C} = 25.6$ Hz, CH); ^{19}F NMR (376 MHz, $CDCl_3$) δ: −99.5; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_5FNO_2S$ [M + H]$^+$ 222.0020, found 222.0014.

7-Chloro-3-thiocyanato-4*H*-chromen-4-one (5f). Colorless crystal, mp 165–166 °C (lit.[29f] 176–178 °C); IR (KBr) ν (cm^{-1}): 2158, 1634, 1607, 1423, 1347, 1163, 1066; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.30 (s, 1H), 8.19 (d, $J_{H-H} = 8.6$ Hz, 1H), 7.52 (d, $J_{H-H} = 1.8$ Hz, 1H), 7.48 (d, $J_{H-H} = 8.6$ Hz, $J_{H-H} = 1.8$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 172.2 (C═O), 156.3 (CH), 155.0, 141.3 (CH), 127.5, 127.4 (CH), 121.1, 118.5 (CH), 113.3, 108.5; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_5ClNO_2S$ [M + H]$^+$ 237.9724, found 237.9720.

6-Chloro-3-thiocyanato-4*H*-chromen-4-one (5g). Colorless crystal, mp 137–138 °C (lit.[29d] 136–137 °C); IR (KBr) ν (cm^{-1}): 2160, 1647, 1605, 1556, 1462, 1301, 1093, 836; ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.33 (s, 1H), 8.20 (d, $J_{H-H} = 2.5$ Hz, 1H), 7.72 (d, $J_{H-H} = 9.0$ Hz, $J_{H-H} = 2.5$ Hz, 1H), 7.52 (d, $J_{H-H} = 9.0$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 171.9 (C═O), 155.3 (CH), 154.6, 135.2 (CH), 132.7, 125.4 (CH), 123.5, 120.1 (CH), 112.9, 108.5; HR MS

(ESI) *m*/*z*: calcd for $C_{10}H_5ClNO_2S$ $[M + H]^+$ 237.9724, found 237.9720.

6-Bromo-3-thiocyanato-4*H*-chromen-4-one (5h). Light yellow crystal, mp 180–181 °C (lit.[29f] 189–191 °C); IR (KBr) ν (cm^{-1}): 2919, 1648, 1458, 1377, 1299, 1019; ^1H NMR (400 MHz, DMSO-d_6) δ: 9.06 (s, 1H), 8.20 (d, $J_{H-H} = 2.4$ Hz, 1H), 8.07 (dd, $J_{H-H} = 9.0$ Hz, $J_{H-H} = 2.4$ Hz, 1H), 7.76 (d, $J_{H-H} = 9.0$ Hz, 1H); ^{13}C NMR (100 MHz, DMSO-d_6) δ: 171.9 (C=O), 161.5, 155.3, 138.3, 127.8, 124.6, 121.9, 119.5, 110.9, 110.8; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_5BrNO_2S$ $[M + H]^+$ 281.9219, found 281.9215.

6,8-Dichloro-3-thiocyanato-4*H*-chromen-4-one (5j). Colorless crystal, mp 123–124 °C; IR (KBr) ν (cm^{-1}): 2166, 1630, 1555, 1444, 1309, 1108, 876; ^1H NMR (400 MHz, $CDCl_3$) δ: 8.39 (s, 1H), 8.31 (d, $J_{H-H} = 2.5$ Hz, 1H), 7.82 (d, $J_{H-H} = 2.5$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 171.4 (C=O), 154.7 (CH), 150.7, 135.1 (CH), 132.5, 124.9, 124.2, 124.1 (CH), 113.8, 108.0; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_4Cl_2NO_2S$ $[M + H]^+$ 271.9334, found 271.9330.

6,8-Dibromo-3-thiocyanato-4*H*-chromen-4-one (5k). Colorless crystal, mp 139–140 °C; IR (KBr) ν (cm^{-1}): 2163, 1630, 1589, 1541, 1449, 1431, 1305, 1092, 775; ^1H NMR (400 MHz, $CDCl_3$) δ: 8.41 (s, 1H), 8.31 (d, $J_{H-H} = 2.2$ Hz, 1H), 8.13 (d, $J_{H-H} = 2.2$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 171.3 (C=O), 154.9 (CH), 152.0, 140.8 (CH), 127.9 (CH), 124.4, 120.1, 113.6, 113.2, 108.0; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_4Br_2NO_2S$ $[M + H]^+$ 359.8324, found 359.8317.

Synthesis of 3-((trifluoromethyl)thio)-4*H*-chromen-4-one (6a). A mixture of 3-thiocyanato-4*H*-chromen-4-one **5a** (0.3 mmol, 60.9 mg), trimethyl(trifluoromethyl)silane ($TMSCF_3$, 0.45 mmol, 63.9 mg), $CuCl_2$ (0.06 mmol, 8.0 mg), Cs_2CO_3 (0.3 mmol, 97.8 mg) and DMF (5.0 mL) was added to a 25 mL reaction tube. The mixture was stirred at room temperature. After completion of the reaction, the solvent was distilled under vacuum. Then, the resulting mixture was dissolved with ethyl acetate (20 mL), washed with saturated sodium chloride solution (10 mL × 2). The organic phase was dried over anhydrous Na_2SO_4 and concentrated under vacuum. The residue was purified by silica gel column chromatography to give 3-((trifluoromethyl)thio)-4*H*-chromen-4-one **6a** using ethyl acetate/petroleum ether as eluant.

Colorless crystal, mp 120–121 °C (lit.[31] 122–123 °C); ^1H NMR (400 MHz, $CDCl_3$) δ: 8.39 (s, 1H), 8.29 (dd, $J_{H-H} = 7.8$ Hz, $J_{H-H} = 1.3$ Hz, 1H), 7.77–7.73 (m, 1H), 7.52–7.48 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 174.3 (C=O), 162.3, 156.2, 134.6, 138.9 (q, $J_{F-C} = 306.2$ Hz), 126.7, 126.5, 123.9, 118.2, 111.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ: −42.8; HR MS (ESI) *m*/*z*: calcd for $C_{10}H_6F_3O_2S$ $[M + H]^+$ 247.0035, found 247.0036.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Henan Provincial Colleges and Universities in Henan University of Technology (No. 2017RCJH08).

Notes and references

1 (*a*) Y. S. Jin, Recent advances in natural antifungal flavonoids and their derivatives, *Bioorg. Med. Chem. Lett.*, 2019, **29**, 126589; (*b*) M. P. Beller and U. Koert, Synthetic studies on chromone natural products: the preussochromones, *Synthesis*, 2022, **54**, 2778–2786; (*c*) K. S. Masters and S. Bräse, Xanthones from fungi, lichens, and bacteria: the natural products and their synthesis, *Chem. Rev.*, 2012, **112**, 3717–3776; (*d*) S. K. Sharma, S. Kumar, K. Chand, A. Kathuria, A. Gupta and R. Jain, An update on natural occurrence and biological activity of chromones, *Curr. Med. Chem.*, 2011, **18**, 3825–3852.

2 (*a*) T. Y. Wang, Q. Li and K. S. Bi, Bioactive flavonoids in medicinal plants: structure, activity and biological fate, *Asian J. Pharm. Sci.*, 2018, **13**, 12–23; (*b*) R. S. Keri, S. Budagumpi, R. K. Pai and R. G. Balakrishna, Chromones as a privileged scaffold in drug discovery: a review, *Eur. J. Med. Chem.*, 2014, **78**, 340–374; (*c*) A. Gaspar, M. J. Matos, J. Garrido, E. Uriarte and F. Borges, Chromone: a valid scaffold in medicinal chemistry, *Chem. Rev.*, 2014, **114**, 4960–4992; (*d*) T. E. Ali, M. A. Assiri, A. A. Shati, M. Y. Alfaifi and S. E. I. Elbehairi, One-pot three-component synthesis of a series of 2-amino-4-(4-oxo-4H-chromen-3-yl)-5-(2,2,2-trifluoroacetyl)-6-(trifluoromethyl)-4H-pyrans and 2-amino-4-(4-oxo-4H-chromen-3-yl)-5-(thiophene-2-carbonyl)-6-(trifluoromethyl)-4H-pyrans as promising anticancer agents, *Russ. J. Org. Chem.*, 2022, **58**, 584–591.

3 (*a*) M. Zhang, Y. Gong, Y. Zhou, Y. Zhou and X. L. Liu, Recent advances of chromone-based reactants in the catalytic asymmetric domino annulation reaction, *Org. Chem. Front.*, 2021, **8**, 3968–3989; (*b*) S. W. Ng, L. H. Chung, C. F. Yeung, H. S. Lo, H. L. Shek, T. S. Kang, C. H. Leung, D. L. Ma and C. Y. Wong, Metalated chromene and chromone complexes: pH switchable metal–carbon bonding interaction, photo-triggerable chromone delivery application, and antioxidative activity, *Chem. – Eur. J.*, 2018, **24**, 1779–1783; (*c*) N. Yadav, R. Kumar, A. K. Singh, S. Mohiyuddin and P. Gopinath, Systematic approach of chromone skeleton for detecting Mg^{2+}, ion: applications for sustainable cytotoxicity and cell imaging possibilities, *Spectrochim. Acta, Part A*, 2020, **235**, 118290; (*d*) L. Fan, J. C. Qin, T. R. Li, B. D. Wang and Z. Y. Yang, A novel rhodamine chromone-based "Off-On" chemosensor for the differential detection of Al(III) and Zn(II) in aqueous solutions, *Sens. Actuators, B*, 2014, **203**, 550–556.

4 (*a*) H. H. Lee, J. S. Shin, W. S. Lee, B. Ryu, D. S. Jang and K. T. Lee, Biflorin, isolated from the flower buds of Syzygium aromaticum L., suppresses LPS-induced inflammatory mediators via STAT1 inactivation in macrophages and protects mice from endotoxin shock, *J. Nat. Prod.*, 2016, **79**, 711–720; (*b*) C. F. M. Silva, D. C. G. A. Pinto and A. M. S. Silva, Chromones: a promising ring system for new anti-inflammatory drugs, *ChemMedChem*, 2016, **11**, 2252–2260; (*c*) Y. Chen, Y. Xu,

H. Zhang, J. Yin, X. Fan, D. Liu, H. Fu and B. Wan, Emodin alleviates jejunum injury in rats with sepsis by inhibiting inflammation response, *Biomed. Pharmacother.*, 2016, **84**, 1001–1007.

5 Q. Sun and G. Chou, Isoflavonoids from Crotalaria albida inhibit adipocyte differentiation and lipid accumulation in 3T3-L1 cells via suppression of PPAR-γ pathway, *PLoS One*, 2015, **10**, e0135893.

6 (*a*) S. Martens and A. Mithöfer, Flavones and flavone synthases, *Phytochemistry*, 2005, **66**, 2399–2407; (*b*) S. Tong, C. Chu, Y. Wei, L. Wang, X. Gao, X. Xu and J. Yu, Preparation and effects of 2,3-dehydrosilymarin, a promising and potent antioxidant and free radical scavenger, *J. Pharm. Pharmacol.*, 2011, **63**, 238–244.

7 S. Lin, J. J. Koh, T. T. Aung, W. L. W. Sin, L. Wang, R. Lakshminarayanan, L. Zhou, H. Tan, D. Cao, R. W. Beuerman, L. Ren and S. Liu, Semisynthetic flavone-derived antimicrobials with therapeutic potential against methicillin-resistant Staphylococcus aureus (MRSA), *J. Med. Chem.*, 2017, **60**, 6152–6165.

8 S. Gobbi, A. Rampa, A. Bisi, F. Belluti, L. Piazzi, P. Valenti, A. Caputo, A. Zampiron and M. Carrara, Synthesis and biological evaluation of 3-alkoxy analogues of flavone-8-acetic acid, *J. Med. Chem.*, 2003, **46**, 3662–3669.

9 (*a*) G. H. Yan, X. F. Li, B. C. Ge, X. D. Shi, Y. F. Chen, X. M. Yang, J. P. Xu, S. W. Liu, P. L. Zhao, Z. Z. Zhou, C. Q. Zhou and W. H. Chen, Synthesis and anticancer activities of 3-arylflavone-8-acetic acid derivatives, *Eur. J. Med. Chem.*, 2015, **90**, 251–257; (*b*) S. Mei, H. Ma and X. Chen, Anticancer and anti-inflammatory properties of mangiferin: a review of its molecular mechanisms, *Food Chem. Toxicol.*, 2021, **149**, 111997–112010.

10 For selected examples, see: (*a*) T. Guo, L. Bi, M. Zhang, C. J. Zhu, L. B. Yuan and Y. H. Zhao, Access to sulfur-containing bisheterocycles through base-promoted consecutive tandem cyclization/sulfenylation with elemental sulfur, *J. Org. Chem.*, 2022, **87**, 16907–16912; (*b*) T. Luo, J. P. Wan and Y. Y. Liu, Toward C2-nitrogenated chromones by copper-catalyzed β-C(sp^2)–H N-heteroarylation of enaminones, *Org. Chem. Front.*, 2020, **7**, 1107–1112; (*c*) P. N. Bagle, M. V. Mane, S. P. Sancheti, A. B. Gade, S. R. Shaikh, M. H. Baik and N. T. Patil, Gold(I)-catalyzed hydroxy group assisted C(sp^2)–H alkylation of enaminones with diazo compounds to access 3-alkyl chromones, *Org. Lett.*, 2019, **21**, 335–339; (*d*) H. Xiang, Q. Zhao, Z. Tang, J. Xiao, P. Xia, C. Wang, C. Yang, X. Chen and H. Yang, Visible-light-driven, Radical-triggered tandem cyclization of o-hydroxyaryl enaminones: Facile access to 3-CF_2/CF_3-containing chromones, *Org. Lett.*, 2017, **19**, 146–149; (*e*) S. Mkrtchyan and V. O. Iaroshenko, Visible-light-mediated arylation of ortho-hydroxyarylenaminones: Direct access to isoflavones, *Chem. Commun.*, 2020, **56**, 2606–2609; (*f*) T. Luo, H. Wu, L. H. Liao, J. P. Wan and Y. Liu, Synthesis of 3,3-dihalogenated 2-aminochromanones via tandem dihalogenation and cyclization of o-hydroxyarylenaminones with NXS (X = Cl or Br), *J. Org. Chem.*, 2021, **86**, 15785–15791; (*g*) L. Fu, Z. Xu, J. P. Wan and Y. Liu, The domino chromone annulation and a transient halogenation-mediated C–H alkenylation toward 3-vinyl chromones, *Org. Lett.*, 2020, **22**, 9518–9523; (*h*) Y. Guo, Y. Xiang, L. Wei and J. P. Wan, Thermoinduced free-radical C–H acyloxylation of tertiary enaminones: Catalyst-free synthesis of acyloxyl chromones and enaminones, *Org. Lett.*, 2018, **20**, 3971–3974.

11 (*a*) Z. Chen, H. Lai, L. Hou and T. Chen, Rational design and action mechanisms of chemically innovative organoselenium in cancer therapy, *Chem. Commun.*, 2020, **56**, 179–196; (*b*) Q. Miao, J. Xu, A. Lin, X. Wu, L. Wu and W. Xie, Recent advances for the synthesis of selenium-containing small molecules as potent antitumor agents, *Curr. Med. Chem.*, 2018, **25**, 2009–2033; (*c*) L. Kursvietiene, A. Mongirdiene, J. Bernatoniene, J. Sulinskiene and I. Staneviciene, selenium anticancer properties and impact on cellular redox status, *Antiox*, 2020, **9**, 80–90.

12 (*a*) E. E. Frieben, S. Amin and A. K. Sharma, Development of isoselenocyanate compounds' syntheses and biological applications, *J. Med. Chem.*, 2019, **62**, 5261–5275; (*b*) M. Fourmigue and A. Dhaka, Chalcogen bonding in crystalline diselenides and selenocyanates: From molecules of pharmaceutical interest to conducting materials, *Coord. Chem. Rev.*, 2020, **403**, 213084–213100.

13 (*a*) J. Vahter, K. Viht, A. Uri, G. B. Manoharan and E. Enkvist, Thiazole-and selenazole-comprising high-affinity inhibitors possess bright microsecond-scale photoluminescence in complex with protein kinase CK2, *Bioorg. Med. Chem.*, 2018, **26**, 5062–5068; (*b*) M. Tian, Y. Yang, F. W. Avila, T. Fish, H. Yuan, M. Hui, T. W. Thannhauser, L. Li, M. Tian and S. Pan, Effects of selenium supplementation on glucosinolate biosynthesis in broccoli, *J. Agric. Food Chem.*, 2018, **66**, 8036–8044; (*c*) A. Csonka, A. Kincses, M. Nove, Z. Vadas, G. Spengler, A. Csonka, C. Sanmartin, C. Sanmartin and E. Dominguez-Alvarez, Selenoesters and selenoanhydrides as novel agents against resistant breast cancer, *Anticancer Res.*, 2019, **39**, 3777–3783.

14 (*a*) X. Meng, P. Zhong, Y. Wang, H. Wang, H. Tang and Y. Pan, Electrochemical difunctionalization of olefines: Access to selenomethyl-substituted cyclic rthers or lactones, *Adv. Synth. Catal.*, 2020, **362**, 506–511; (*b*) S. F. Fonseca, N. B. Padilha, S. Thurow, J. A. Roehrs, L. Savegnago, M. N. de Souza, M. G. Fronza, T. Collares, J. Buss, F. K. Seixas, D. A. Eder and J. Lenardão, Ultrasound-promoted copper-catalyzed synthesis of bis-arylselanyl chrysin derivatives with boosted antioxidant and anticancer activities, *Ultrason. Sonochem.*, 2017, **39**, 827–836.

15 (*a*) C. Feng, J. Zhu, Q. Tang and A. Zhou, Synthesis of ArSe-substituted flavone derivatives using Se powder, *Chin. J. Org. Chem.*, 2019, **39**, 1187–1192; (*b*) P. Xu, Z. Zhong, H. Huang and A. Zhou, Selenation of 2-hydroxyphenyl enaminones with Se powder to generate ArSe-subsituted chromone derivatives, *ChemistrySelect*, 2022, **7**, e202202854.

16 (*a*) J. Zhu, B. Xu, J. Yu, Y. Ren, J. Wang, P. Xie, C. U. Pittman and A. Zhou, Copper-catalyzed generation of flavone

selenide and thioether derivatives using KSeCN and KSCN via C–H functionalization, *Org. Biomol. Chem.*, 2018, **16**, 5999–6005; (*b*) C. Ding, Y. Yu, Q. Yu, Z. Xie, Y. Zhou, J. Zhou, G. Liang and Z. Song, NIS/TBHP induced regioselective selenation of (hetero)arenes via direct C–H functionalization, *ChemCatChem*, 2018, **10**, 5397–5401.

17 (*a*) L. Fu and J. P. Wan, C3-functionalized chromones synthesis by tandem C–H elaboration and chromone annulation of enaminones, *Asian J. Org. Chem.*, 2019, **8**, 767–776; (*b*) X. Y. Chen, X. Zhang and J. P. Wan, Recent advances in transition metal-free annulation toward heterocycle diversity based on the C–N bond cleavage of enaminone platform, *Org. Biomol. Chem.*, 2022, **20**, 2356–2369.

18 For selected examples, see: (*a*) T. Zhang, W. Yao, J. P. Wan and Y. Liu, Transition-metal-free $C(sp^2)$-H dithiocarbamation and chromone annulation cascade for 3-dithiocarbamyl chromone synthesis, *Adv. Synth. Catal.*, 2021, **363**, 4811–4816; (*b*) G. S. Sorabad and M. R. Maddani, Metal-free, facile synthesis of sulfenylated chromones and indoles promoted by an aqueous HBr-DMSO system, *Asian J. Org. Chem.*, 2019, **8**, 1336–1343; (*c*) H. Xiang and C. Yang, A facile and general approach to 3-((trifluoromethyl)thio)-4H-chromen-4-one, *Org. Lett.*, 2014, **16**, 5686–5689; (*d*) J. P. Wan, Z. Tu and Y. Wang, Transient and recyclable halogenation coupling (TRHC) for isoflavonoid synthesis with site-selective arylation, *Chem. - Eur. J.*, 2019, **25**, 6907–6910; (*e*) Y. Lin, J. P. Wan and Y. Liu, Cascade in Situ iodination, chromone annulation, and cyanation for site-selective synthesis of 2-cyanochromones, *J. Org. Chem.*, 2023, **88**, 4017–4023.

19 J. Joussot, A. Schoenfelder, L. Larquetoux, M. Nicolas, J. Suffert and G. Blond, Synthesis of 3-substituted chromones and quinolones from enaminones, *Synthesis*, 2016, **48**, 3364–3372.

20 (*a*) J. Rafique, S. Saba, A. R. Schneider, M. S. Franco, S. M. Silva and A. L. Braga, Metal- and solvent-free approach to access 3-Se/S-chromones from the cyclization of enaminones in the presence of dichalcogenides catalyzed by KIO_3, *ACS Omega*, 2017, **2**, 2280–2290; (*b*) S. Zhong, Y. Liu, X. Cao and J. P. Wan, KIO_3-catalyzed domino $C(sp^2)$–H bond sulfenylation and C–N bond oxygenation of enaminones toward the synthesis of 3-sulfenylated chromones, *ChemCatChem*, 2017, **9**, 465–468.

21 Selective examples: (*a*) N. A. Romero and D. A. Nicewicz, Organic photoredox catalysis, *Chem. Rev.*, 2016, **116**, 10075–10166; (*b*) K. L. Skubi, T. R. Blum and T. P. Yoon, Dual catalysis strategies in photochemical synthesis, *Chem. Rev.*, 2016, **116**, 10035–10074; (*c*) D. A. Nicewicz and D. W. C. MacMillan, Merging photoredox catalysis with organocatalysis: the direct asymmetric alkylation of aldehydes, *Science*, 2008, **322**, 77–80; (*d*) J. Xuan and W. J. Xiao, Visible-light photoredox catalysis, *Angew. Chem., Int. Ed.*, 2012, **51**, 6828–6838; (*e*) T. P. Yoon, M. A. Ischay and J. Du, Visible light photocatalysis as a greener approach to photochemical synthesis, *Nat. Chem.*, 2010, **2**, 527–532; (*f*) L. Shi and W. Xia, Photoredox functionalization of C–H bonds adjacent to a nitrogen atom, *Chem. Soc. Rev.*, 2012, **41**, 7687–7697.

22 H. Y. Liu, J. R. Zhang, G. B. Huang, Y. H. Zhou, Y. Y. Chen and Y. L. Xu, Visible light-promoted selenylation/cyclization of enaminones toward the formation of 3-selanyl-4H-chromen-4-ones, *Adv. Synth. Catal.*, 2021, **363**, 1656–1661.

23 C. V. Doerner, J. S. S. Neto, C. R. Cabreira, S. Saba, L. P. Sandjo, J. Rafique, A. L. Braga and F. F. de Assis, Synthesis of 3-selanyl-isoflavones from 2-hydroxyphenyl enaminones using trichloroisocyanuric acid (TCCA): a sustainable approach, *New J. Chem.*, 2023, **47**, 5598–5602.

24 (*a*) Y. L. Ban, L. You, K. W. Feng, F. C. Ma, X. L. Jin and Q. Liu, Meyer-Schuster-Type rearrangement of propargylic alcohols into α-selenoenals and-enones with diselenides, *J. Org. Chem.*, 2021, **86**, 5274–5283; (*b*) L. Y. Xie, J. Qu, S. Peng, K. J. Liu, Z. Wang, M. H. Ding, Y. Wang, Z. Cao and W. M. He, Selectfluor-mediated regioselective nucleophilic functionalization of N-heterocycles under metal- and base-free conditions, *Green Chem.*, 2018, **20**, 760–764; (*c*) P. Xu, S. Guo, L. Wang and P. Tang, Silver-catalyzed oxidative activation of benzylic C–H bonds for the synthesis of difluoromethylated arenes, *Angew. Chem., Int. Ed.*, 2014, **53**, 5955–5958; (*d*) J. L. Li, E. Lin, X. L. Han, Q. Li and H. Wang, Synthesis of α-fluorinated imides via direct fluorohydroxylation of ynamides, *Org. Lett.*, 2019, **21**, 4255–4258; (*e*) P. Liu, Y. Gao, W. Gu, Z. Shen and P. Sun, Regioselective fluorination of imidazo[1,2-a]pyridines with selectfluor in aqueous condition, *J. Org. Chem.*, 2015, **80**, 11559–11565.

25 Selective examples: (*a*) L. Niu, J. Liu, X. A. Liang, S. Wang and A. Lei, Visible light-induced direct α C–H functionalization of alcohols, *Nat. Commun.*, 2019, **10**, 467; (*b*) H. Fei, Z. Xu, H. Wu, L. Zhu, H. B. Jalani, G. Li, Y. Fu and H. Lu, Stereospecific electrophilic fluorocyclization of α,β-unsaturated amides with Selectfluor, *Org. Lett.*, 2020, **22**, 2651–2656; (*c*) J. D. Galloway, D. N. Mai and R. D. Baxter, Silver-catalyzed Minisci reactions using selectfluor as a mild oxidant, *Org. Lett.*, 2017, **19**, 5772–5775; (*d*) Y. Kong, X. Sun and J. Weng, Selectfluor as “fluorine-free” functional reagent applied to organic synthesis under transition metal-free conditions, *Chin. J. Org. Chem.*, 2020, **40**, 2641–2657; (*e*) X. Wang, Q. Wang, Y. Xue, K. Sun, L. Wu and B. Zhang, An organoselenium-catalyzed N1- and N2-selective aza-Wacker reaction of alkenes with benzotriazoles, *Chem. Commun.*, 2020, **56**, 4436–4439.

26 (*a*) J. W. Yuan, G. C. Huang, L. L. Wang, X. Y. Wang, L. R. Yang, S. R. Zhang, P. Mao, Y. M. Xiao and L. B. Qu, Chalcogenative spirocyclization of N-aryl propiolamides with diselenides/disulfides promoted by Selectfluor, *Z. Naturforsch.*, 2022, **77b**, 75–85; (*b*) J. W. Yuan, Q. Chen, W. T. Wu, J. J. Zhao, L. R. Yang, Y. M. Xiao, P. Mao and L. B. Qu, Selectfluor-mediated construction of 3-arylselenenyl and 3, 4-bisarylselenenyl spiro[4.5]trienones via cascade annulation of N-phenylpropiolamides with diselenides, *New J. Chem.*, 2022, **46**, 9451–9460; (*c*) W. P. Mai, J. W. Yuan, J. L. Zhu, Q. Q. Li, L. R. Yang,

Y. M. Xiao, P. Mao and L. B. Qu, Selectfluor-mediated direct C–H phosphonation of quinoxalin-2(1H)-ones under base and transition-metal free conditions, *ChemistrySelect*, 2019, **4**, 11066–11070; (*d*) J. Yuan, F. Zeng, W. Mai, L. Yang, Y. Xiao, P. Mao and D. Wei, Fluorination-triggered tandem cyclization of styrene-type carboxylic acids to access 3-aryl isocoumarin derivatives under microwave irradiation, *Org. Biomol. Chem.*, 2019, **17**, 5038–5046; (*e*) J. W. Yuan, Y. Zhang, G. C. Huang, M. Y. Ma, T. Y. Yang, L. R. Yang, S. R. Zhang, P. Mao and L. B. Qu, Site-specific C–H chalcogenation of quinoxalin-2(1H)-ones enabled by Selectfluor reagent, *Org. Chem. Front.*, 2021, **8**, 6937–6949.

27 (*a*) R. J. Capon, C. Skene, E. H. T. Liu, E. Lacey, J. H. Gill, K. Heiland and T. Friedel, The isolation and synthesis of novel nematocidal dithiocyanates from an australian marine sponge, Oceanapia sp., *J. Org. Chem.*, 2001, **66**, 7765–7769; (*b*) S. Dutta, H. Abe, S. Aoyagi, C. Kibayashi and K. S. Gates, DNA damage by fasicularin, *J. Am. Chem. Soc.*, 2005, **127**, 15004–15005; (*c*) L. J. Dean and M. R. Prinsep, The chemistry and chemical ecology of nudibranchs, *Nat. Prod. Rep.*, 2017, **34**, 1359–1390.

28 (*a*) L. Zhen, K. Yuan, X. Li, C. Zhang, J. Yang, H. Fan and L. Jiang, Cascade reaction of propargyl amines with $AgSCF_3$, as well as one-pot reaction of propargyl amines, $AgSCF_3$, and di-tert-butyl peroxide: access to allenyl thiocyanates and allenyl trifluoromethylthioethers, *Org. Lett.*, 2018, **20**, 3109–3113; (*b*) W. L. Lei, T. Wang, K. W. Feng, L. Z. Wu and Q. Liu, Visible-light-driven synthesis of 4-alkyl/aryl-2-aminothiazoles promoted by in situ generated copper photocatalyst, *ACS Catal.*, 2017, **7**, 7941–7945; (*c*) B. Bayarmagnai, C. Matheis, K. Jouvin and L. J. Goossen, Synthesis of difluoromethyl thioethers from difluoromethyl trimethylsilane and organothiocyanates generated in situ, *Angew. Chem., Int. Ed.*, 2015, **54**, 5753–5756.

29 (*a*) Y. Gao, Y. Liu and J. P. Wan, Visible light-induced thiocyanation of enaminone C–H bond to access polyfunctionalized alkenes and thiocyano chromones, *J. Org. Chem.*, 2019, **84**, 2243–2251; (*b*) Z. Yang, L. Hu, T. Cao, L. An, L. Li, T. Yang and C. Zhou, PIDA-mediated α-C–H functionalization of enaminones: the synthesis of thiocyano enaminones and chromones in water, *New J. Chem.*, 2019, **43**, 16441–16444; (*c*) X. Z. Zhang, D. L. Ge, S. Y. Chen and X. Q. Yu, A catalyst-free approach to 3-thiocyanato-4 H-chromen-4-ones, *RSC Adv.*, 2016, **6**, 66320–66323; (*d*) J. A. Xiao, X. L. Cheng, R. F. Meng, X. S. Qin, H. Peng, J. W. Ren, Z. Z. Xie, J. G. Cui and Y. M. Huang, Straightforward synthesis of 3-selenocyanato-substituted chromones through electrophilic selenocyanation of enaminones under grinding conditions, *Synthesis*, 2021, **53**, 954–960; (*e*) Y. Gao, Y. Liu and J. P. Wan, Visible light-induced thiocyanation of enaminone C–H bond to access polyfunctionalized alkenes and thiocyano chromones, *J. Org. Chem.*, 2019, **84**, 2243–2251; (*f*) Z. Yang, Y. Wang, L. Hu, J. Yu, A. Li, L. Li, T. Yang and C. Zhou, Electrochemically induced thiocyanation of enaminones: synthesis of functionalized alkenes and chromones, *Synthesis*, 2020, **52**, 711–718.

30 M. Jakubczyk, S. Mkrtchyan, I. D. Madura, P. H. Marek and V. O. Iaroshenko, Copper-catalyzed direct C-H arylselenation of 4-nitro-pyrazoles and other heterocycles with selenium powder and aryl iodides. Access to unsymmetrical heteroaryl selenides, *RSC Adv.*, 2019, **9**, 25368–25376.

31 H. Xiang and C. Yang, A facile and general approach to 3-((trifluoromethyl)thio)-4H-chromen-4-one, *Org. Lett.*, 2014, **16**, 5686–5689.