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Photoinduced metal-free α-selenylation of ketones†

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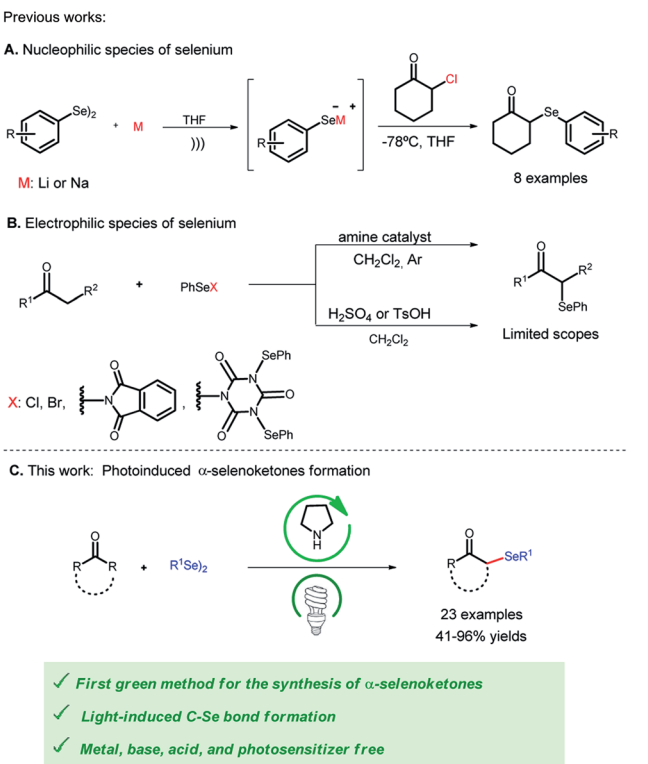
Herein, we report an efficient photoinduced α-selenylation of ketones without metal, additives or under photosensitizer-free conditions, providing a green protocol using light energy to synthesize a variety of α-selenoketones. This new methodology proved to be a mild, simple and eco-friendly tool for the efficient synthesis of the desired products.

Introduction

Nowadays, when evaluating a new synthetic approach, the choice of energy source when an organic transformation is involved is important, and in this context, photochemistry has emerged as an environmentally friendly alternative to assisting organic reactions.[1] Compared with traditional methods, luminous energy-assisted reactions involve mild reaction conditions, simple operation, and a sustainable approach.[2] Among these, photoinduced reactions are of great importance since activation of certain organic molecules occurs without the use of transition metal catalysts, such as ruthenium and iridium complexes or organic dyes such as Eosin Y and Rose Bengal. Photosensitizers usually have high costs and their removal produces harmful waste, which affects the environment and the economy of the reaction.[3]

Thus, photoinduced protocols are environmentally benign and attractive alternatives for the formation of organoselenium compounds through the construction of the light-promoted C–Se bond.[4] Organoselenium compounds are of considerable importance in synthetic[5] and pharmaceutical chemistry.[6] Particularly, α-selenoketones have attracted the attention of synthetic chemists, due to their versatile synthetic applications in organic synthesis[7] and, more recently, their biological activities for disorders such as depression and anxiety.[8] Given their value in chemistry and biological systems, intensive efforts have been devoted to the synthesis of α-selenoketones. However, none of them involve the use of light energy to accomplish this transformation. Most of the α-selenofunctionalisation protocols include the following: *in situ* generation of nucleophilic selenium species[9] (Scheme 1a) and previous formation of an electrophilic species from diselenides[10] (Scheme 1b). The formation of these species usually requires the presence of metals, reducing agents or halogenated reagents.[10c–e,11] In addition, to perform activation in the α position of ketones, acidic or basic media are generally used.[10c,d,12] Another way of activating this position is through the use of secondary amines, such as organocatalysts, but these methodologies also require an electrophilic selenium species.[10c–e,12] Moreover, these protocols for obtaining α-selenoketones have restricted reaction scopes, and are limited to different selenium-bonded substituents.

Therefore, in continuation of our studies on the reactions for obtaining organoselenated compounds[13] promoted by a photoinduced process,[4d] herein we demonstrate an efficient, general,



Scheme 1 Previous works and our approach for α-selenylation of ketones.

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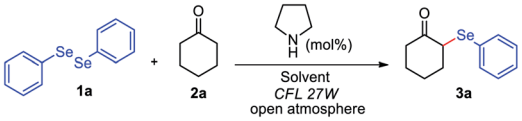
simple and eco-friendly protocol for the preparation of α-selenoketones through the reaction between diselenides, ketones and pyrrolidine in catalytic amounts and in the absence of photosensitizers, halogenated reactants, additives and harsh reaction conditions (Scheme 1c).

Results and discussion

We started our investigations using diphenyl diselenide **1a** and cyclohexanone **2a** as model substrates, in the presence of 10 mol% pyrrolidine in THF, under CFL 27 W irradiation. With these reaction conditions, the desired α-selenoketone **3a** was obtained in a conversion of only 14% (Table 1, entry 1). We then probed the effect of pyrrolidine on the reaction (Table 1, entries 1–4). Catalyst loadings, ranging from 10 to 30 mol%, were evaluated. The best result was observed when 20 mol% of pyrrolidine was used, leading to an improvement in the conversion (Table 1, entry 2). Moreover, when the reaction was conducted in the absence of pyrrolidine no product was obtained (Table 1, entry 4). Furthermore, the stoichiometry was also investigated, and an excess of diphenyl diselenide **1a** or cyclohexanone **2a**, did not affect the reaction (Table 1, entries 5–6). Next, we evaluated the influence of the solvent in the reaction, and different solvents such as DMSO, DCM, and MeCN, were used (Table 1, entries 7–9). MeCN and THF led to the formation of **3a** in a similar manner (Table 1, entry 2 *vs.* 9). However, acetonitrile provided the best result in terms of environmental benefits (Table 1, entry 9). After screening the initial experimental parameters, we evaluated the effect of luminous irradiation (Table 2, entries 1–5). The use of a lower power lamp did not improve the conversion (Table 2, entry 1). Other lamps with different wavelengths were tested and we observed that the reaction in the presence of CFL UVA 26 W provided the best result, with 55% conversion (Table 2, entry 5) showing

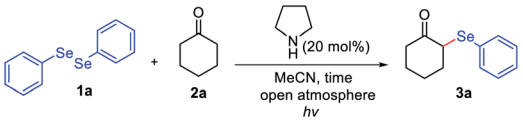
Table 1 Optimization of the reaction conditions[a]



Entry	Pyrrolidine (mol%)	Solvent	Conv.[b](%)
1	10	THF	14
2	20	THF	45
3	30	THF	10
4	—	THF	—
5[c]	20	THF	42
6[d]	20	THF	40
7	20	DMSO	5
8	20	DCM	5
9	20	MeCN	45

[a] The reaction was performed in the presence of **1a** (0.5 mmol), **2a** (0.5 mmol) and pyrrolidine in the solvent (1 mL) for 20 h. [b] Determined by GC, based on the amount of cyclohexanone **2a**. [c] 1.2 equivalents of **1a**. [d] 1.2 equivalents of **2a**.

Table 2 Optimization of the reaction conditions[a]



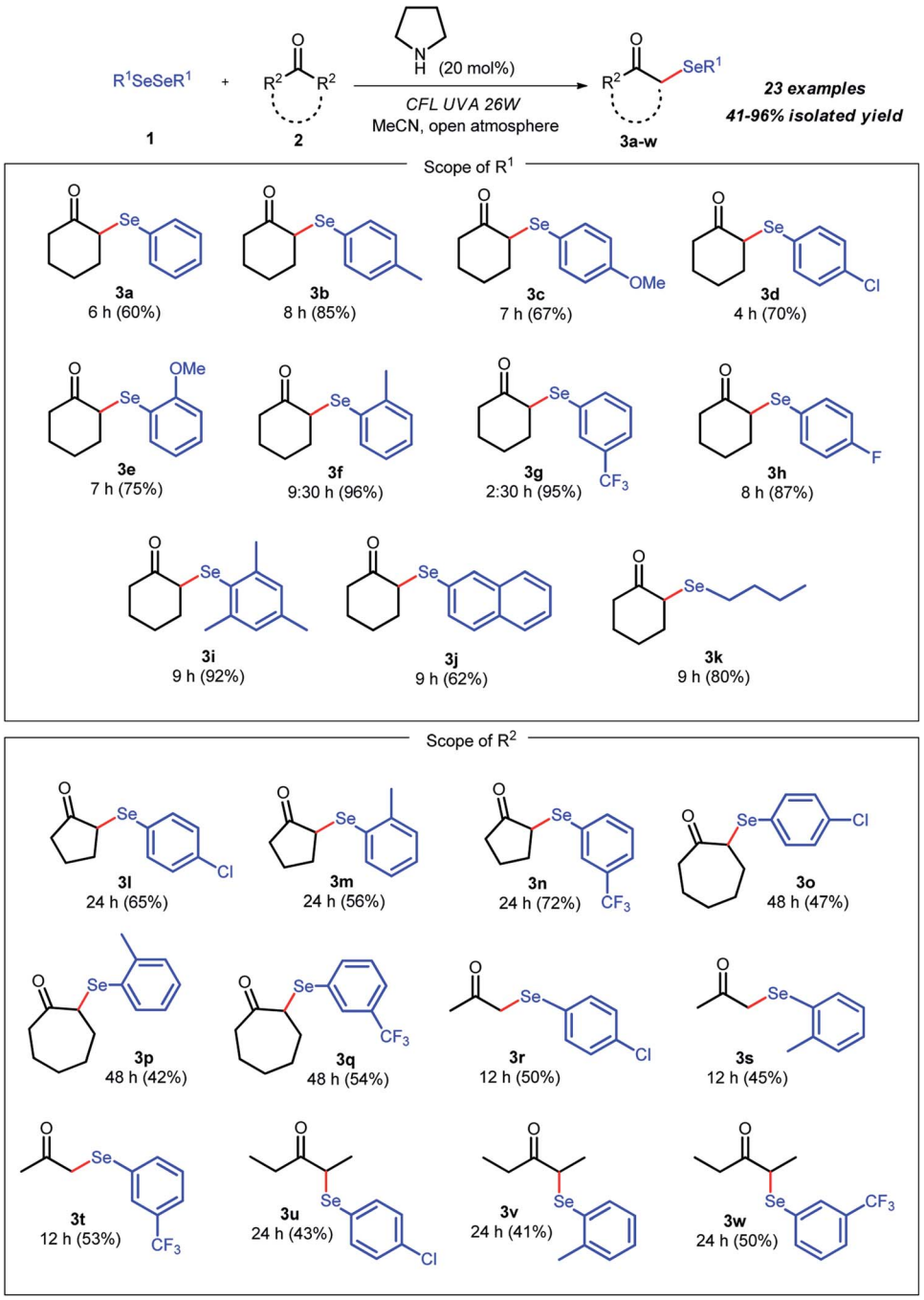
Entry	Lamp	Time (h)	Conv.[b](%)
1	CFL 20 W	20	24
2	Blue 26 W	20	20
3	Green 26 W	20	10
4	CFL UVA 26 W	20	55
5	—	20	Traces
6	CFL UVA 26 W	1	12
7	CFL UVA 26 W	2	37
8	CFL UVA 26 W	4	48
9	**CFL UVA 26 W**	**6**	**61**
10	CFL UVA 26 W	8	50
11[c]	CFL UVA 26 W	6	60
12[d]	CFL UVA 26 W	6	55
13[e]	CFL UVA 26 W	6	26

[a] The reaction was performed in the presence of **1a** (0.5 mmol), **2a** (0.5 mmol) and pyrrolidine (20 mol%) in MeCN (1 mL). [b] Determined by GC, based on the amount of cyclohexanone **2a**. [c] 20 mol% benzoic acid was added. [d] 20 mol% of Bi_2O_3 was added. [e] Under an argon atmosphere.

superiority for this transformation in relation to the others lamps. The presence of light was necessary for this protocol since only traces of the product were observed in the complete absence of luminous energy (Table 2, entry 5). Subsequently, the influence of the reaction time (Table 2, entries 6–10) was examined, and the best results were observed after 6 h (Table 2, entry 9), in which 61% conversion was obtained. Moreover, additives were used in the reaction with the aim of increasing the formation of the product (Table 2, entries 11–12), but neither bismuth oxide nor benzoic acid led to an increase in the yield of α-selenoketone **3a**. Finally, the best condition were used under an argon atmosphere, and a decrease in conversion (26%) was observed (Table 2, entry 13). This is a valuable result because it suggests that atmospheric O_2 is necessary for the formation of the product. Considering the data from Tables 1 and 2, equivalent amounts of **1a** and **2a**, 20 mol% pyrrolidine as organocatalyst and MeCN as the solvent, under irradiation of a CFL UVA 26 W (Table 2, entry 9) were chosen for subsequent studies. It is important mention that the diselenides are very stable, and can be recovered in the purification step, and reused in further reactions. For example, under the optimized conditions, for the synthesis of **3a**, we could recover 106 mg (0.34 mmol) of the diphenyl diselenide, which is almost all the unreacted diselenide (0.38 mmol).

Once the best experimental conditions for the synthesis of **3a** were established (Table 2, entry 9), we evaluated the generality of the method concerning different diorganyldiselenides **1** and ketones **2** (Scheme 2). We first evaluated the influence of the introduction of different substituents in *ortho*, *meta*, and *para* positions of diaryldiselenide, as well as one dialkyldiselenide **1**,

while keeping cyclohexanone constant. The reaction worked well, affording the respective α-selenoketones **3a–k** in good to excellent yields. To analyze the electronic effects on the reaction yield, a range of diaryldiselenides containing electron-donating groups (EDGs) and electron-withdrawing groups corresponding α-selenoketones **3b–h** in excellent yields. Furthermore, introduction of various substituents in different positions of the diaryldiselenide did not affect the reaction, and the corresponding products were isolated in 67–96% yield (**3b–h**). No influence was observed due to the steric hindrance of *ortho*-substituted aryl diselenides as compared to the respective *para* derivatives (**3b–c** *vs.* **3e–f**). The methodology was extended to sterically hindered and bulkier substrates. The selenylated products **3i–j** were obtained in good yields, showing the versatility of this reaction. In addition to diaryldiselenides, dibutyldiselenide was used, and the alkylated ketone **3k** was obtained after 9 h in 80% yield. This significant result reinforces the versatility of the developed methodology. Encouraged by the results of this metal-free approach for α-selenation of ketones using luminous energy and looking to expand this protocol and broaden the scope in relation to the substrate, different cyclic and acyclic ketones were reacted with diselenides. In general,



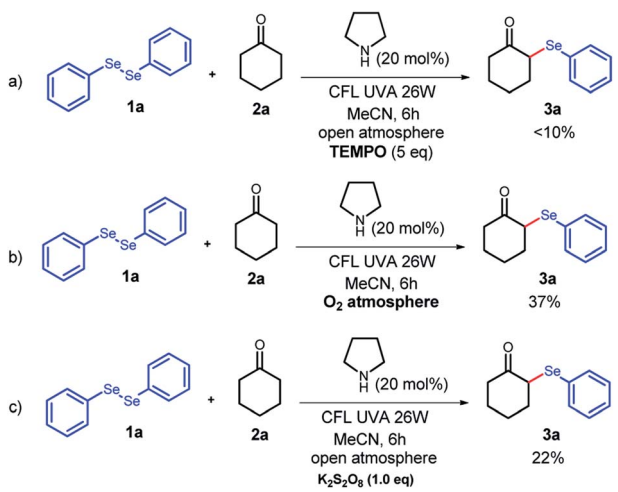
Scheme 2 Scope of the photoinduced metal-free α-selenylation of ketones.

the reaction furnished the respective α-selenoketones **3l–w** in moderate to good yields.

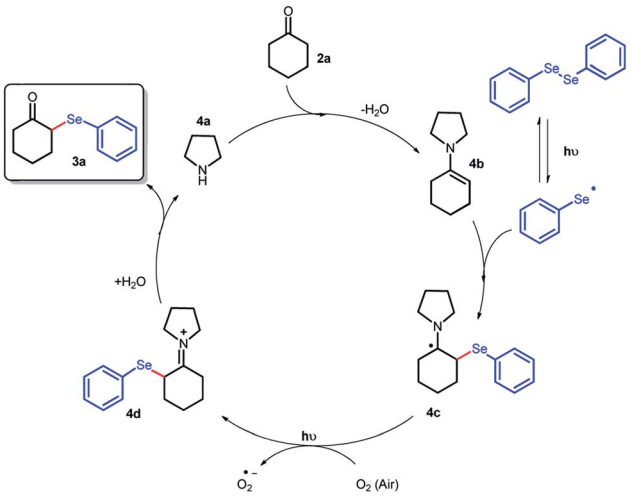
Different cyclic ketones, such as 5, 6, or 7-membered rings, were used, and the corresponding products were isolated in 42–72% yield (**3a**, **3l**, and **3q**). In this case, an influence related to ring size was observed. The 5-membered ketone leaded to the α-selenylated products in better yields and in shorter reaction times compared to the 7-membered ketone (**3l–n** *vs.* **3o–q**). In addition, the protocol was extended to acyclic ketones, and products **3r–w** were obtained in 41–53% yield. It was observed that propanone led to the desired products in similar reaction yields to 3-pentanone, however, in shorter times. The higher reaction times can be explained due to the slow formation of the intermediate enamine. It is important to point out that neither condensation adducts nor double α-phenylselenenylated products were detected in these reactions.

To evaluate the mechanism involved in the α-selenylation of ketones, some control experiments were carried out (Scheme 3). At first, 2,2,6,6-tetramethylpiperidin-1-yloxyl (TEMPO) as a radical inhibitor was added, and following our optimal experimental conditions, only traces of **3a** were obtained (<10%), suggesting a possible involvement of a radical process in this reaction. An interesting observation, during the optimization of the reaction conditions (Table 2, entry 13), was that the reaction under an argon atmosphere did not work well, which imply that an oxidation step can be involved. In this way, two more experiments were performed using stronger oxidant conditions, and under an O_2 atmosphere or by adding $K_2S_2O_8$, a dramatical decrease in the reaction yield was observed. These lower yields observed in a more oxidizing system could be explained by the higher capture rate of selenium radicals under these conditions.[14] This outcome confirms that an open atmosphere plays a crucial role, and the aerobic O_2 acts as a mild oxidant, furnishing the best results.

On the basis of previous reports and the above results, we proposed a plausible mechanism for this transformation (Scheme 4). Enamine **4b** is formed *in situ* from the condensation



Scheme 3 Control experiments.



Scheme 4 Proposed radical mechanism induced by light.

of pyrrolidine **4a** with cyclohexanone **2a**. The next step comprises the reversible homolytic cleavage of the Se–Se bond. The selenium radical specie adds to the enamine **4b**, leading to the formation of α-selenylated intermediate **4c**. The reaction is not efficiently promoted when conducted under an inert atmosphere (Table 2, entry 13), indicating the need for a mild oxidizer such as aerobic O_2. Thus, species **4c** can be oxidized by atmospheric O_2,[15] generating the radical anion ($O_2^{\bullet-}$) and the iminium ion **4d** that undergo hydrolysis, furnishing the desired product **3a** and regenerating the organocatalyst **4a**.

Conclusions

In summary, we developed an alternative method for the synthesis of α-selenoketones using an environmentally friendly, photo-induced process for the first time. A range of α-selenylated products were obtained from substituted diorganoyldiselenides and cyclic and acyclic ketones in moderate to excellent yields, proving the generality of this methodology. Compared with traditional methods, our methodology is a mild, metal-free, simple, and practical tool for the synthesis of a range of α-selenoketones, and it has potential applications in the synthesis of synthetic intermediates in organic chemistry, as well as bioactive compounds.

Experimental

General information

The solvents were used without further purification. Pyrrolidine was previously distilled. Other commercially available materials were used as received. The photoreactions were monitored using Shimadzu GC-MSQP2010 mass spectrometer and thin layer chromatography. The TLC was carried out on Merck silica gel (60 F254) and flash chromatography was performed in silica gel (230–400 mesh). The NMR spectra were recorded on 400 MHz and 500 MHz spectrometer Varian Inova 400, Varian Inova 500 and Bruker Avance 400. Chemical shifts (δ) are expressed in ppm downfield from tetramethylsilane (TMS) as internal

standard. Hydrogen coupling patterns are described as singlet (s), doublet (d), double doublet (dd), double triplet (dt), triplet (t), double quartet (dq), quartet (q), multiplet (m). Coupling constants (*J*) are reported in Hertz. Low-resolution mass spectra were obtained with a Shimadzu GC-MSQP2010 mass spectrometer. GC analysis were conducted on a RESTEC HP-5MS capillary column (30 m, 0.25 mm id, 0.25 μm film thickness) using the products dissolved in ethyl acetate. High-resolution mass spectra were obtained in a Micromass Q-Tof micro mass spectrometer.

General procedure for the synthesis of the α-selenoketones (3)

To a reaction flask was added diselenide (1.0 equiv.) and MeCN (1 mL). Then, ketone (0.5 mmol) and the organocatalyst pyrrolidine (20 mol%) was added. After, the system was arranged in a photoreactor containing a CFL UVA 26 W. The reaction was kept stirring at room temperature by the indicated time (the reaction progress was monitored by GC-MS), then pyrrolidine and solvent were removed in reduced pressure. The product was purified on column chromatography using hexane and diethyl ether as eluent.

2-(Phenylselanyl)cyclohexanone (3a)[10b]

Yield: 77.1 mg (60%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.56–7.51 (m, 2H), 7.31–7.23 (m, 3H), 3.91 (td, J = 4.7, 1.2 Hz, 1H), 3.04–2.92 (m, 1H), 2.34–2.27 (m, 1H), 2.25–2.13 (m, 2H), 2.01–1.91 (m, 1H), 1.92–1.67 (m, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.8, 134.5, 129.1, 128.5, 128.0, 51.5, 38.4, 33.9, 26.8, 22.8.

2-(*p*-Tolylselanyl)cyclohexanone (3b)[9]

Yield: 120 mg (85%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.45–7.41 (m, 2H), 7.11–7.07 (m, 2H), 3.85 (td, J = 5.1, 1.7 Hz, 1H), 3.04–2.94 (m, 1H), 2.38–2.25 (m, 4H), 2.24–2.14 (m, 2H), 2.03–1.91 (m, 1H), 1.91–1.64 (m, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.8, 138.3, 135.0, 129.9, 124.6, 51.6, 38.3, 33.7, 26.8, 22.7, 21.1.

2-((4-Methoxyphenyl)selanyl)cyclohexanone (3c)[9]

Yield: 94.8 mg (67%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.49–7.44 (m, 2H), 6.83–6.79 (m, 2H), 3.82–3.76 (m, 4H), 3.02–2.93 (m, 1H), 2.34–2.24 (m, 1H), 2.21–2.11 (m, 2H), 2.01–1.90 (m, 1H), 1.89–1.63 (m, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$): 207.7, 159.9, 137.1, 118.3, 114.8, 55.1, 51.9, 38.2, 33.5, 26.7, 22.5.

2-((4-Chlorophenyl)selanyl)cyclohexanone (3d)[9]

Yield: 100 mg (70%). Light yellow solid. ^{1}H-NMR (500 MHz, $CDCl_3$): δ 7.48–7.44 (m, 2H), 7.26–7.23 (m, 2H), 3.89 (td, J = 5.4, 1.5 Hz, 1H), 3.01–2.92 (m, 1H), 2.35–2.29 (m, 1H), 2.26–2.14 (m, 2H), 2.00–1.92 (m, 1H), 1.87–1.77 (m, 2H), 1.75–1.67 (m, 1H); ^{13}C-NMR (125 MHz, $CDCl_3$): δ 207.4, 136.0, 134.5, 129.3, 126.6, 51.7, 38.4, 33.8, 26.7, 22.9.

2-((2-Methoxyphenyl)selanyl)cyclohexanone (3e)

Yield: 106.2 mg (75%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.51 (dd, J = 6, 1.7 Hz, 1H), 7.29–7.24 (m, 1H), 6.92–6.83 (m, 2H), 4.05 (td, J = 4.9, 1.6 Hz, 1H), 3.86 (s, 3H), 3.13–3.03 (m, 1H), 2.32–2.18 (m, 3H), 2.05–1.95 (m, 1H), 1.95–1.84 (m, 1H), 1.83–1.68 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$): δ 208.2, 158.3, 134.3, 129.2, 121.4, 117.7, 110.6, 55.8, 48.5, 38.1, 33.6, 27.0, 22.7. MS (relative intensity) m/z: 284 (16.2), 186 (10.8), 108 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{13}H_{16}O_2SeNa$) requires m/z 307.0213, found: m/z 307.0211.

2-(*o*-Tolylselanyl)cyclohexanone (3f)

Yield: 128.3 mg (96%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.54 (dd, J = 7.3, 1.2 Hz, 1H), 7.23–7.17 (m, 2H), 7.13–7.07 (m, 1H), 3.88 (td, J = 5.0, 1.7 Hz, 1H), 3.05–2.95 (m, 1H), 2.44 (s, 3H), 2.35–2.26 (m, 1H), 2.25–2.17 (m, 2H), 2.03–1.95 (m, 1H), 1.94–1.84 (m, 1H), 1.81–1.65 (m, 2H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.8, 140.8, 134.9, 130.0, 129.6, 128.2, 126.6, 50.4, 38.4, 33.8, 26.8, 22.7, 22.7. MS (relative intensity) m/z: 268 (54.6), 170 (59), 91 (100.0). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{13}H_{16}OSeNa$) requires m/z 291.0264, found: m/z 291.0261.

2-((3(Trifluoromethyl)phenyl)selanyl)cyclohexanone (3g)

Yield: 154.5 mg (95%). Yellow oil. ^{1}H-NMR (500 MHz, $CDCl_3$): δ 7.80 (s, 1H), 7.71 (d, J = 7.7 Hz, 1H), 7.54 (d, J = 8.0 Hz, 1H), 7.40 (t, J = 7.7 Hz, 1H), 3.97 (t, J = 5.5 Hz, 1H), 2.99–2.91 (m, 1H), 2.38–2.31 (m, 1H), 2.29–2.15 (m, 2H), 2.01–1.92 (m, 1H), 1.90–1.78 (m, 2H), 1.77–1.69 (m, 1H). ^{13}C-NMR (125 MHz, $CDCl_3$): δ 207.3, 137.5 (q, J = 1.1 Hz), 131.3 (q, J = 32.4 Hz), 130.8 (q, J = 3.8 Hz), 129.6, 129.4, 124.7 (q, J = 3.8 Hz), 123.5 (q, J = 272.8 Hz), 51.7, 38.6, 34.0, 26.8, 23.1. MS (relative intensity) m/z: 322 (22.18), 225 (35.6), 69 (36), 41 (100.0). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{13}H_{13}F_3OSeNa$) requires m/z 344.9981, found: m/z 344.9981.

2-((4-Fluorophenyl)selanyl)cyclohexanone (3h)[9]

Yield: 115.1 mg (87%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.54–7.49 (m, 2H), 7.01–6.94 (m, 2H), 3.84 (td, J = 5.3, 1.7 Hz, 1H), 3.01–2.93 (m, 1H), 2.34–2.27 (m, 1H), 2.24–2.13 (m, 2H), 2.01–1.92 (m, 1H), 1.89–1.75 (m, 2H), 1.75–1.66 (m, 1H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.5, 162.9 (d, J = 248.6 Hz), 137.1 (d, J = 8.0 Hz), 122.9 (d, J = 3.5 Hz), 116.3 (d, J = 21.5 Hz), 51.9, 38.3, 33.7, 26.7, 22.8.

2-(Mesitylselanyl)cyclohexanone (3i)

Yield: 137.2 mg (92%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 6.92 (q, J = 0.5 Hz, 2H), 3.58 (td, J = 4.3, 1.1 Hz, 1H), 3.09–2.98 (m, 1H), 2.48 (s, 6H), 2.34–2.06 (m, 6H), 2.04–1.95 (m, 1H), 1.93–1.83 (m, 1H), 1.76–1.641 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.7, 143.4, 138.8, 128.6, 126.8, 50.6, 38.0, 33.5, 26.5, 24.3, 22.4, 20.9. MS (relative intensity) m/z: 296 (35), 198 (16.2), 119.1 (100.0). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{15}H_{20}OSeNa$) requires m/z 319.0577, found: m/z 319.0575.

2-(Naphthalen-2-ylselanyl)cyclohexanone (3j)

Yield: 90.9 mg (62%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 8.44–8.40 (m, 1H), 7.86–7.81 (m, 3H), 7.59–7.47 (m, 2H), 7.38 (dd, J = 8.2, 7.1 Hz, 1H), 3.92 (td, J = 5.4, 1.5 Hz, 1H), 3.03–2.93 (m, 1H), 2.35–2.27 (m, 1H), 2.24–2.07 (m, 2H), 2.01–1.60 (m, 4H); ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.6, 135.3, 134.7, 134.0, 129.6, 128.6, 127.7, 127.7, 126.9, 126.2, 125.7, 51.4, 38.8, 34.0, 26.8, 23.0. MS (relative intensity) m/z: 304 (55.1), 207 (37.18), 128 (100), 97 (11.8). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{16}H_{16}OSeNa$) requires m/z 327.0264, found: m/z 327.0262.

2-(Butylselanyl)cyclohexanone (3k)

Yield: 128.3 mg (80%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 3.54 (t, J = 3.2 Hz, 1H), 3.22–3.12 (m, 1H), 2.67–2.51 (m, 2H), 2.27–2.20 (m, 1H), 2.20–2.11 (m, 2H), 2.06–1.97 (m, 1H), 1.74–1.58 (m, 5H), 1.43–1.33 (m, 2H), 0.90 (t, J = 7.4 Hz, 3H). NMR (100 MHz, $CDCl_3$): δ 208.2, 45.3, 36.5, 32.9, 32.0, 26.4, 25.2, 22.9, 21.7, 13.5. MS (relative intensity) m/z: 234 (4.6), 98 (100), 55 (14.7). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{10}H_{18}OSeNa$) requires m/z 257.0421, found: m/z 257.0421.

2-((4-Chlorophenyl)selanyl)cyclopentanone (3l)

Yield: 89 mg (65%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.56–7.49 (m, 2H), 7.29–7.23 (m, 2H), 3.75–3.69 (m, 1H), 2.40–2.26 (m, 2H), 2.26–2.14 (m, 1H), 2.13–1.90 (m, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 214.1, 136.6, 134.9, 129.3, 125.9, 46.5, 36.1, 30.5, 20.9. MS (relative intensity) m/z: 274 (11.9), 55 (100), 83 (4.8). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{11}H_{11}ClOSeNa$) requires m/z 296.9561, found: 296.9557.

2-(*o*-Tolylselanyl)cyclopentanone (3m)

Yield: 71.1 mg (56%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.61 (d, J = 7.5 Hz, 1H), 7.25–7.20 (m, 2H), 7.15–7.08 (m, 1H), 3.81–3.76 (m, 1H), 2.49–2.44 (m, 4H), 2.34–2.05 (m, 3H), 2.02–1.91 (m, 2H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 214.2, 141.26, 135.6, 130.0, 129.1, 128.6, 126.5, 45.5, 36.1, 30.5, 22.8, 20.9. MS (relative intensity) m/z: 254 (10.5), 170 (12.8), 91 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{12}H_{14}OSeNa$) requires m/z 277.0108, found: 277.0104.

2-((3-(Trifluoromethyl)phenyl)selanyl)cyclopentanone (3n)

Yield: 110.8 mg (72%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.80 (s, 1H), 7.71 (d, J = 7.7 Hz, 1H), 7.54 (d, J = 8.0 Hz, 1H), 7.41 (t, J = 7.8 Hz, 1H), 3.83–3.78 (m, 1H), 2.43–2.32 (m, 2H), 2.28–2.18 (m, 1H), 2.12–1.95 (m, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 213.9, 138.0 (q, J = 1.2 Hz), 131.3 (q, J = 32.6 Hz), 131.3 (q, J = 3.9 Hz), 129.4, 129.1, 125.0 (q, J = 3.8 Hz), 123.5 (q, J = 272.7 Hz), 46.4, 36.1, 30.6, 21.0. MS (relative intensity) m/z: 308 (21.6), 252 (10.4), 83 (11.3), 55 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{12}H_{11}F_3OSeNa$) requires m/z 330.9825, found: m/z 330.9834.

2-((4-Chlorophenyl)selanyl)cycloheptanone (3o)

Yield: 71 mg (47%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.51–7.45 (m, 2H), 7.28–7.22 (m, 2H), 3.77 (dd, J = 11.2, 5.6 Hz, 1H), 2.77–2.71 (m, 1H), 2.45–2.35 (m, 1H), 2.33–2.23 (m, 1H), 1.98–1.89 (m, 2H), 1.88–1.80 (m, 1H), 1.68–1.56 (m, 1H), 1.52–1.36 (m, 2H), 1.34–1.20 (m, 1H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 209.0, 136.2, 134.7, 129.3, 126.5, 52.5, 39.8, 30.3, 30.2, 27.9, 25.6. MS (relative intensity) m/z: 302 (9.6), 192 (4.8), 83 (14.2), 55 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{13}H_{15}ClOSeNa$) requires m/z 324.9874, found: m/z 324.9868.

2-(*o*-Tolylselanyl)cycloheptanone (3p)

Yield: 59.2 mg (42%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.57 (d, J = 7.7 Hz, 1H), 7.24–7.18 (m, 2H), 7.14–7.07 (m, 1H), 3.78 (dd, J = 11.1, 5.7 Hz, 1H), 2.86–2.78 (m, 1H), 2.44 (s, 3H), 2.43–2.35 (m, 1H), 2.33–2.24 (m, 1H), 1.98–1.89 (m, 2H), 1.87–1.79 (m, 1H), 1.71–1.60 (m, 1H), 1.53–1.39 (m, 2H), 1.35–1.21 (m, 1H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 209.0, 141.0, 135.5, 130.0, 129.5, 128.5, 126.5, 51.4, 39.7, 30.4, 30.3, 27.9, 25.7, 22.8. MS (relative intensity) m/z: 282 (19.8), 172 (16.2), 91 (45.8), 55 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{14}H_{18}OSeNa$) requires m/z 305.0421, found: 305.0419.

2-((3-(Trifluoromethyl)phenyl)selanyl)cycloheptanone (3q)

Yield: 90.7 mg (54%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.81 (s, 1H), 7.72 (d, J = 7.8 Hz, 1H), 7.55 (d, J = 7.8 Hz, 1H), 7.40 (t, J = 7.8 Hz, 1H), 3.87 (dd, J = 11.2, 5.6 Hz, 1H), 2.83–2.75 (m, 1H), 2.46–2.39 (m, 1H), 2.36–2.26 (m, 1H), 1.99–1.90 (m, 2H), 1.89–1.82 (m, 1H), 1.70–1.60 (m, 1H), 1.55–1.40 (m, 2H), 1.36–1.26 (m, 1H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 208.9, 137.6 (q, J = 1.2 Hz), 131.3 (q, J = 32.3 Hz), 130.9 (q, J = 3.8 Hz), 129.4, 128.7, 124.9 (q, J = 3.7 Hz), 123.6 (q, J = 272.5 Hz), 52.4, 39.8, 30.3, 30.2, 28.0, 25.6. MS (relative intensity) m/z: 336 (14.4), 145 (10.7), 83 (42.5), 55 (100). HRMS (ESI+): exact mass calculated for $[M + H]^+$ ($C_{15}H_{15}F_3OSe$) requires m/z 337.0318, found: m/z 337.0313.

1-((4-Chlorophenyl)selanyl)propan-2-one (3r)[16]

Yield: 62 mg (50%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.45–7.41 (m, 2H), 7.26–7.22 (m, 2H), 3.57 (s, 2H), 2.27 (s, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 202.9, 134.4, 134.0, 129.3, 126.6, 36.8, 27.8.

1-(*o*-Tolylselanyl)propan-2-one (3s)[16]

Yield: 51.3 mg (45%). Light yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49 (d, J = 7.5 Hz, 1H), 7.22–7.14 (m, 2H), 7.16–7.10 (m, 1H), 3.58 (s, 2H), 2.45 (s, 3H), 2.28 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 203.4, 139.9, 133.1, 130.2, 129.6, 128.0, 126.8, 35.8, 28.0, 22.3.

2-((3-(Trifluoromethyl)phenyl)selanyl)propan-2-one (3t)[16]

Yield: 74.7 mg (53%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.77 (s, 1H), 7.69 (d, J = 7.8 Hz, 1H), 7.54 (d, J = 7.8 Hz, 1H), 7.41 (t, J = 7.7 Hz, 1H), 3.66 (s, 2H), 2.31 (s, 3H). ^{13}C-NMR

(100 MHz, $CDCl_3$): δ 202.9, 136.0 (q, J = 1.0 Hz), 131.2 (q, J = 32.5 Hz), 129.6, 129.4 (q, J = 3.8 Hz), 129.1, 124.6 (q, J = 3.7 Hz), 123.5 (d, J = 272.7 Hz), 36.7, 28.0.

2-((4-Chlorophenyl)selanyl)pentan-3-one (3u)

Yield: 59 mg (43%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.44–7.40 (m, 2H), 7.28–7.24 (m, 2H), 3.79 (q, J = 7.0 Hz, 1H), 2.79 (dq, J = 17.4, 7.3 Hz, 1H), 2.51 (dq, J = 17.4, 7.3 Hz, 1H), 1.46 (d, J = 7.0 Hz, 3H), 1.09 (t, J = 7.3 Hz, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 207.2, 137.3, 135.3, 129.3, 124.8, 45.0, 32.9, 16.3, 8.4. MS (relative intensity) m/z: 276 (12), 219 (16.7), 139 (100), 57 (24.3). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{11}H_{13}ClOSeNa$) requires m/z 298.9718, found: m/z 298.9715.

2-(*o*-Tolylselanyl)pentan-3-one (3v)

Yield: 52 mg (41%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.52 (d, J = 7.5 Hz, 1H), 7.27–7.21 (m, 2H), 7.15–7.08 (m, 1H), 3.83 (q, J = 7.0 Hz, 1H), 2.75 (dq, J = 17.4, 7.3 Hz, 1H), 2.54–2.41 (m, 4H), 1.51 (d, J = 7.0 Hz, 3H), 1.05 (t, J = 7.3 Hz, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): δ 208.0, 141.6, 136.0, 130.2, 128.9, 128.8, 126.5, 44.8, 32.9, 22.9, 16.5, 8.3. MS (relative intensity) m/z: 256 (4.2), 119 (100), 91 (13.2). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{12}H_{16}OSeNa$) requires m/z 279.0264, found: m/z 279.0262.

2-((3-(Trifluoromethyl)phenyl)selanyl)pentan-3-one (3w)

Yield: 75.9 mg (49%). Light yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.77 (s, 1H), 7.67 (d, J = 7.7 Hz, 1H), 7.60 (d, J = 7.8 Hz, 1H), 7.42 (t, J = 7.8 Hz, 1H), 3.87 (q, J = 7.0 Hz, 1H), 2.80 (dq, J = 17.5, 7.3 Hz, 1H), 2.54 (dq, J = 17.5, 7.3 Hz, 1H), 1.50 (d, J = 7.0 Hz, 3H), 1.09 (t, J = 7.3 Hz, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 207.1, 138.8 (q, J = 1.1 Hz), 132.2 (q, J = 3.9 Hz), 131.3 (q, J = 32.3 Hz), 129.4, 127.9, 125.4 (q, J = 3.6 Hz), 123.5 (q, J = 272.8 Hz), 45.2, 32.8, 16.5, 8.3. MS (relative intensity) m/z: 310 (7.6), 253 (11.6), 145 (7.8), 57 (100). HRMS (ESI+): exact mass calculated for $[M + Na]^+$ ($C_{12}H_{13}F_3OSeNa$) requires m/z 332.9981, found: m/z 332.9983.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 (*a*) N. A. Romero and D. A. Nicewicz, Organic photoredox catalysis, *Chem. Rev.*, 2016, **116**, 10075; (*b*) X. Yang, Y. Zheng, L. Zheng, L. Wu, C. Tung and B. Chen, Visible light-catalytic dehydrogenation of benzylic alcohols to carbonyl compounds by using an eosin Y and nickel–thiolate complex dual catalyst system, *Green Chem.*, 2019, **21**, 1401.

2 (*a*) A. Albini and M. Fagnoni, 1908: Giacomo Ciamician and the Concept of Green Chemistry, *ChemSusChem*, 2008, **1**, 63; (*b*) M. Kozlowski and T. Yoon, Editorial for the special issue on photocatalysis, *J. Org. Chem.*, 2016, **81**, 6895.

3 (*a*) V. Rathore and S. Kumar, Visible-light-induced metal and reagent-free oxidative coupling of sp^2 C–H bonds with organo-dichalcogenides: synthesis of 3-organochalcogenyl indoles, *Green Chem.*, 2019, **21**, 2670; (*b*) E. Barragan, P. A. Noonikara, C. H. Yang, H. Wang and A. Bugarin, Metal-free cross-coupling of π-conjugated triazenes with unactivated arenes *via* photoactivation, *Org. Chem. Front.*, 2019, **6**, 152.

4 (*a*) A. Nomoto, Y. Higuchi, Y. Kobiki and A. Ogawa, Synthesis of selenium compounds by free radical addition based on visible-light-activated Se–Se bond cleavage, *Mini-Rev. Med. Chem.*, 2013, **13**, 814; (*b*) Y. Kobiki, S. I. Kawaguchi and A. Ogawa, Highly regioselective hydroselenation of inactivated terminal alkynes using diselenide–$Ph_2P(O)H$ mixed systems under visible-light irradiation, *Tetrahedron Lett.*, 2013, **54**, 5453; (*c*) D. Yang, G. Li, C. Xing, W. Cui, K. Li and W. Wei, Metal-and photocatalyst-free visible-light-promoted regioselective selenylation of coumarin derivatives *via* oxidation-induced C–H functionalization, *Org. Chem. Front.*, 2018, **5**, 2974; (*d*) A. C. Weber, F. L. Coelho, R. F. Affeldt and P. H. Schneider, Visible-Light Promoted Stereoselective Arylselanyl Functionalization of Alkynes, *Eur. J. Org. Chem.*, 2018, **47**, 6738.

5 (*a*) F. L. Coelho, E. S. Gil, P. F. B. Gonçalves, L. F. Campo and P. H. Schneider, Intramolecular Hydroamination of Selenoalkynes to 2-Selenylindoles in the Absence of Catalyst, *Chem. - Eur. J.*, 2019, **25**, 1; (*b*) Q. Zhang, Y. Ban, P. Yuan, S. Peng, J. Fang, L. Wu and Q. Liu, Visible-light-mediated aerobic selenation of (hetero)arenes with diselenides, *Green Chem.*, 2017, **19**, 5559; (*c*) S. K. Tripathi, S. Sharma, H. B. Singh and R. J. Butcher, 2-Phenoxyethanol derived diselenide and related compounds; synthesis of a seven-membered seleninate ester, *Org. Biomol. Chem.*, 2011, **9**, 581; (*d*) E. J. Lenardão, C. Santi and L. Sancineto, *New Frontiers in Organoselenium Compounds*, Springer, Cham, Switzerland, 2018.

6 (*a*) D. Bartolini, L. Sancineto, A. F. de Bem, Q. D. Tew, C. Santi, R. Radi, P. Toquato and F. Galli, Selenocompounds in cancer therapy: an overview, *Adv. Cancer Res.*, 2017, **136**, 259; (*b*) M. Ibrahim, B. H. M. Mussulini, L. Moro, D. B. Rosemberg, D. L. Oliveira, J. Rocha, R. S. Schwab, A. M. Assis, D. Souza, E. P. Rico and P. H. Schneider, Anxiolytic effects of diphenyl diselenide on adult zebrafish in a novelty paradigma, *Prog. Neuro-Psychopharmacol. Biol. Psychiatry*, 2014, **54**, 187; (*c*) F. N. Victoria, D. M. Martinez, M. Castro, A. M. Casaril, D. Alves, E. J. Lenardão, H. D. Salles, P. H. Schneider and L. Savegnago, Antioxidant properties of (R)-Se-aryl thiazolidine-4-carboselenoate, *Chem.-Biol. Interact.*, 2013, **205**, 100; (*d*) G. K. Azad and R. S. Tomar, Ebselen: a promising antioxidant drug: mechanisms of action and targets of biological pathways, *Mol. Biol. Rep.*,

2014, **41**, 4865; (*e*) F. Martini, S. G. Rosa, I. P. Klann, B. C. W. Fulco, F. B. Carvalho, L. F. Rahmeier, M. C. Fernandes and C. W. Nogueira, A multifunctional compound ebselen reverses memory impairment, apoptosis and oxidative stress in a mouse model of sporadic Alzheimer's disease, *J. Psychiatr. Res.*, 2019, **109**, 107; (*f*) N. F. Pavin, F. Donato, F. W. Cibin, C. R. Jesse, P. H. Schneider, H. D. de Salles, L. A. Soares, D. Alves and L. Savegnago, Antinociceptive and anti-hypernociceptive effects of Se-phenyl thiazolidine-4-carboselenoate in mice, *Eur. J. Pharmacol.*, 2011, **668**, 169.

7 (*a*) G. Pandey, S. K. Tiwari, A. Budakoti and P. K. Sahani, Transition-metal-free photoredox intermolecular α-arylation of ketones, *Org. Chem. Front.*, 2018, **5**, 2610; (*b*) H. J. Reich, J. H. Renga and I. L. Reiche, Organoselenium chemistry: Conversion of ketones to enones by selenoxide syn elimination, *J. Am. Chem. Soc.*, 1975, **97**, 5434.

8 (*a*) F. S. S. Sousa, P. T. Birmann, R. Baldinotti, M. G. Fronza, R. Balaguez, D. Alves, C. A. Brüning and L. Savegnago, α-(phenylselanyl)acetophenone mitigates reserpine-induced pain–depression dyad: Behavioral, biochemical and molecular docking evidences, *Brain Res. Bull.*, 2018, **142**, 129; (*b*) F. S. S. Sousa, P. T. Birmann, S. R. Bampi, M. G. Fronza, R. Balaguez, D. Alves, M. R. Leite, C. W. Nogueira, C. A. Brüning and L. Savegnago, Lipopolysaccharide-induced depressive-like, anxiogenic-like and hyperalgesic behavior is attenuated by acute administration of α-(phenylselanyl) acetophenone in mice, *Neuropharmacology*, 2019, **146**, 128.

9 R. G. Mcleod, B. Johnston and M. Pinto, A generalized exo-anomeric effect: Substituent and solvent effects on the conformational equilibria of 2-(arylseleno)cyclohexanones, *Isr. J. Chem.*, 2000, **40**, 307.

10 (*a*) M. Iwaoka, *e-EROS Encycl. Reagents Org. Synth.*, 2005, **1**, 16; (*b*) M. H. Yang, H. S. Wang, Y. F. Zheng and C. J. Zhu, A simple protocol for the synthesis of α-substituted ketones, *Chin. J. Org. Chem.*, 2006, **9**, 1268; (*c*) J. Cossy and L. Furet, N-(Phenylseleno)Phthalimide: A Useful Reagent For The α-Selenylation Of Ketones And Aldehydes, *Tetrahedron Lett.*, 1993, **34**, 7755; (*d*) N. Miyoshi, T. Yamamoto, N. Kambe, S. Murai and N. Sonoda, A convenient method for the synthesis of α-phenylselenenyl carbonyl compounds, *Tetrahedron Lett.*, 1982, **23**, 4813; (*e*) B. Movassagh and A. Takallou, N,N,N-Triphenylselenylisocyanuric Acid (TPSCA): A New Versatile Reagent for α-Phenylselenenylation of Aldehydes and Ketones, *Synlett*, 2015, **26**, 2247.

11 H. J. Reich, M. L. Cohen and P. S. Peter, Reagents for synthesis of organoselenium compounds: diphenyl diselenide and benzeneselenenyl chloride, *Curr. Org. Synth.*, 1980, **59**, 141.

12 (*a*) N. Nazari and B. Movassagh, α-Phenylselenenylation of aldehydes and ketones with diphenyl diselenide mediated by KF/Al_2O_3, *Tetrahedron Lett.*, 2009, **50**, 1453; (*b*) F. N. Victoria, C. S. Radatz, M. Sachini, R. G. Jacob, G. Perin, W. P. da Silva and E. J. Lenardão, KF/Al_2O_3 and PEG-400 as a recyclable medium for the selective α-selenation of aldehydes and ketones: preparation of potential antimicrobial agents, *Tetrahedron Lett.*, 2009, **50**, 6761; (*c*) Y. Nishiyama, Y. Koguma, T. Tanaka and R. Umeda, Cesium carbonate-catalyzed α-phenylchalcogenation of carbonyl compounds with diphenyl dichalcogenide, *Molecules*, 2009, **14**, 3367.

13 (*a*) D. S. Rampon and P. H. Schneider, Palladium-catalyzed direct arylation of selenophene, *J. Org. Chem.*, 2014, **79**, 5987; (*b*) C. S. Radatz, D. Alves and P. H. Schneider, Direct synthesis of 2-aryl-1, 3-benzoselenazoles by reaction of bis(2-aminophenyl) diselenides with aryl aldehydes using sodium metabisulfite, *Tetrahedron*, 2013, **28**, 1316; (*c*) T. E. Frizon, D. S. Rampon, H. Gallardo, A. A. Merlo, P. H. Schneider, O. E. D. Rodrigues and A. L. Braga, Selenides and diselenides containing oxadiazoles: a new class of functionalised materials, *Liq. Cryst.*, 2012, **39**, 769; (*d*) D. S. Rampon, F. S. Rodembusch, R. Lourega, P. F. B. Gonçalves, A. A. Merlo and P. H. Schneider, An evaluation of the chalcogen atom effect on the mesomorphic and electronic properties in a new homologous series of chalcogeno esters, *J. Braz. Chem. Soc.*, 2010, **21**, 2100; (*e*) C. S. Radatz, D. S. Rampon, R. A. Balaguez, D. Alves and P. H. Schneider, Synthesis of 2-Substituted 1,3-Benzoselenazoles from Carboxylic Acids Promoted by Tributylphosphine, *Eur. J. Org. Chem.*, 2014, **31**, 6945.

14 Q. Teng, Y. Yao, W. Wei, H. Tang, J. Li and Y. Pan, Direct C–H sulfenylation of quinoxalinones with thiols under visible-light-induced photocatalyst-free conditions, *Green Chem.*, 2019, **21**, 6241.

15 S. Mitra, M. Ghosh, S. Mishra and A. Hajra, Metal-free thiocyanation of imidazoheterocycles through visible light photoredox catalysis, *J. Org. Chem.*, 2015, **80**, 8275.

16 G. Yan, J. A. Borah, L. Wang, Z. Pan, S. Chen, X. Shen and X. Wu, α-Arylchalcogenation of acetone with diaryl dichalcogenide *via* metal-free oxidative $C(sp^3)$–H bond functionalization, *Tetrahedron Lett.*, 2015, **56**, 4305.