RSC Advances



PAPER

View Article Online
View Journal | View Issue



Cite this: RSC Adv., 2023, 13, 13911

Synthesis of sulfur-containing benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-diones: blue light promoted radical cyclization process†

Feng Pan,‡^{ac} Haohu Li,‡^a Xiaohua Wang,‡^d Liwen Luo,^a Yanfei Lin,*^b Qingkai Yu,^a Wenlin Xie*^c and Lianpeng Zhang (D) *^a

The selective and controllable construction of spio-tricyclic skeletons through visible light promoted radical cyclization still remains challenging. Herein, a general and convenient protocol for the blue light-promoted radical-mediated cascade spiro-cyclization/Michael addition of *N*-arylpropiolamides with thiophenols under metal-free conditions was developed. In this protocol, commercially available hydrochloric acid was employed as the cheap promoter and air as the sustainable oxidant. In addition, many functional groups tolerate the reaction conditions and produce a series of sulfur-containing benzo[*b*]pyrrolo[2,1-*c*] [1,4]oxazine-3,9-diones.

Received 5th April 2023 Accepted 30th April 2023

DOI: 10.1039/d3ra02247a

rsc.li/rsc-advances

Introduction

It is well known that spirocyclic compounds can be used in photochromism,¹ organic optoelectronics,² and medicinal chemistry,³ and have also played an important role in organic synthesis.⁴ Antiobesity agent (I) is a selective histamine-3 receptor (H3R) modulator⁵ (Scheme 1). Among the spirocyclic compounds, N-containing spiro-products show important bioactivity as anticancer, antimicrobial and anti-inflammatory agents.⁶ In recent years, the Erythrina alkaloid cocculine II has attracted considerable attention because of its wide range of biological properties.⁵ Furthermore, some biologically active

Scheme 1 Biologically active spirocycles

^dTongji Zhejiang College, Jiaxing 314051, China

spirocycles with hypnotic, hypotensive, and CNS activity are found in numerous active molecules, such as the erythrina, aspidosperma, and strychnos families.⁸

Because of its unique properties, tremendous efforts have been made to construct the spirotricyclic derivatives in the past ten years. Among them, the dearomatization of arenes is an effective method for the synthesis of spiro compounds. In 2011, a catalytic enantioselective method for synthesizing fused spirotricyclic compounds has been developed. In this reaction, Gaunt and co-workers developed ICl-based electrophilic dearomatization of anisidine derivatives (Scheme 2a). In 2016, Srivastava and the co-workers reported a diastereo- and regioselective Ugi/ipso-cyclization/aza-michael cascade reaction to the synthesis of alkaloid-mimicking tricyclic skeletons (Scheme 2b). In the reaction, the use of H₂SO₄ played an important role in the dearomative cyclization.

On the other hand, transition metal promoted dearomatization has become one of the most popular reaction models with great achievements. In 2012, Li developed a general method for the synthesis of spiro[4,5]trienones by the intramolecular ipso-halocyclization of 4-(*p*-unsubstituted-aryl)-1-alkynes¹² (Scheme 2c). Subsequently, the azaquaternary tricyclic skeletons could be obtained *via* Pd-catalyzed intramolecular Heck reaction. In 2020, Reddy and the co-workers reported a Agcatalyzed oxidative ipso-cyclization *via* decarboxylative acylation/alkylation to construct pyrrolo-[2,1-*j*]-quinolone¹³ (Scheme 2d), which was a challenging framework found in tricyclic marine alkaloids.¹⁴

It is worth noting that Qiu and co-workers have paid more attention to the green and mild construction of spio-tricyclic skeletons over the past years. ¹⁵ Considering that our group's main research interest is the controllable synthesis of nitrogencontaining heterocycles based on the selective functionalization

[&]quot;Yunnan Provincial Key Laboratory of Wood Adhesives and Glued Products, Southwest Forestry University, Kunming 650224, Yunnan, China. E-mail: lpz@zju.edu.cn

^bCollege of Biological, Chemical Sciences and Engineering, Jiaxing University, Jiaxing 314001, Zhejiang, China. E-mail: 11219008@zju.edu.cn

School of Chemistry and Chemical Engineering, Hunan University of Science and Technology, Xiangtan 411201, Hunan, China. E-mail: xwl2000zsu@163.com

[†] Electronic supplementary information (ESI) available. CCDC 2203442. For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d3ra02247a

[‡] Equal contributions to this manuscript.

Scheme 2 Methods for the synthesis of spirotricyclic derivatives.

of alkynes.¹⁶ So, in this paper, we would like to share a blue light-promoted¹⁷ radical-mediated spiro-tricyclization of *N*-arylpropiolamides with thio(sele)phenols under metal-free conditions (Scheme 2e).

Results and discussion

At the initial stage of the investigations, the synthesized *N*-(2-hydroxyethyl)-*N*-(4-methoxyphenyl)-3-phenylpropiolamide **1a** and the purchased 4-methylbenzenethiol **2a** were chosen as model substrates to optimize the reaction conditions using blue LED as the light source (Table 1). Firstly, the influence of the blue LED power on the reaction is explored and 2.5 W was the most effective light power among the tested 1.5 W, 2.5 W, and 3.5 W (entries 1–3). To our delight, when the reaction temperature was raised to 50 °C, the expected product 1-phenyl-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4] oxazine-3,9-dione **3a** was obtained in 47% yield (entry 4, Table 1).

Further, the reaction temperature was increased to 60 °C and 70 °C, and it was found that the optimum temperature of this reaction was 60 °C with the desired product 3a obtained in 56% yield (entries 4–6). In order to further optimize the reaction results, the effect of the amount of 2a on the reaction was evaluated. As shown in entries 7–9, a better result was obtained by using 1.5 equiv of 2a, giving the desired product 3a in 62% yield. Changing the reaction solvent to MeOH, DMF, THF, or toluene has no good effect on the reaction (entries 11–14). When adding 0.15 mL 1.1 N HCl to this reaction, a 68% yield was achieved (entry 15, Table 1). Encouraged by this result, the effect of the additive HCl to this reaction was further explored. Replacing 1.1 N HCl to 2.0 N HCl or 3.0 N HCl, 2.0 N HCl was the

Table 1 Optimization of the reaction conditions^a

Entry	Blue LDE (x (W))	Solvent	Additive (y (mL))	T (°C)	Yield 3a ^b (%)
1	1.5	MeCN	_	r.t.	33
2	2.5	MeCN	_	r.t.	36
3	3.5	MeCN	_	r.t.	31
4	2.5	MeCN	_	50	47
5	2.5	MeCN	_	60	56
6	2.5	MeCN	_	70	49
7^c	2.5	MeCN	_	60	62
8^d	2.5	MeCN	_	60	40
9^e	2.5	MeCN	_	60	43
11^c	2.5	MeOH	_	60	16
12^c	2.5	DMF	_	60	12
13 ^c	2.5	THF	_	60	47
14^c	2.5	Toluene	_	60	51
15^c	2.5	MeCN	1.1 N HCl (0.15)	60	68
16 ^c	2.5	MeCN	2.0 N HCl (0.15)	60	76
17 ^c	2.5	MeCN	3.0 N HCl (0.15)	60	60
18 ^c	2.5	MeCN	2.0 N HCl (0.10)	60	65
19^{c}	2.5	MeCN	2.0 N HCl (0.20)	60	67
20^c	2.5	MeCN	2.0 N HCl (0.25)	60	70
21^c	2.5	MeCN	NaCl (1.0 equiv)	60	35
22^c	2.5	MeCN	2.0 N HCl (0.15)	r.t.	47

 $[^]a$ Standard conditions: **1a** (0.2 mmol), **2a** (0.4 mmol), air, in 2 mL of CH₃CN were stirred under blue LED, 12 h. b Isolated yield based on **1a**. c **2a** (1.5 equiv) was used. d **2a** (2.5 equiv) was used. e **2a** (1.0 equiv) was used.

optimal choice, leading to the desired product 3a in 76% yield (entries 15–17, Table 1). In addition, increasing or decreasing the amount of 2.0 N HCl led to a decrease in the 3a yield (entries 18–20, Table 1). When NaCl was used as the chlorine radical source, there was no significant increase in the yield of product 3a (entry 21). Next, with the addition of 0.15 mL of 2.0 N HCl, the reaction temperature was lowered to room temperature and the yield was found only 45% (entry 22). Finally, the standard reaction conditions were established as follows: a mixture of 1a (0.2 mmol), 2a (0.3 mmol), and 0.15 mL 2.0 N HCl in 2 mL MeCN were stirred under 2.5 W blue LED at 60 °C in air.

With the optimal conditions established, the general utilization of the photomediated spiro-tricyclization of N-hydroxylethyl-N-arylpropiolamides with thio(sele)phenols was probed. As shown in Table 2, diverse N-arylpropionamides with different substituents in the alkynyl moiety were all tolerated, and the yields of the corresponding products $3\mathbf{a}$ - \mathbf{d} were satisfactory (64–82% yields). In addition, the 1.0 mmol experiment of $1\mathbf{a}$ was carried out under standard conditions to obtain the desired product $3\mathbf{a}$ in 72% yield. Furthermore, the substituent R^1 could be replaced by 1-naphthyl, 2-thiophenyl, or 1,1'-biphenyl and the corresponding products $3\mathbf{e}$, $3\mathbf{f}$, and $3\mathbf{g}$ were observed in 70%, 46%, and 30% yields, respectively. Unfortunately, when R^1

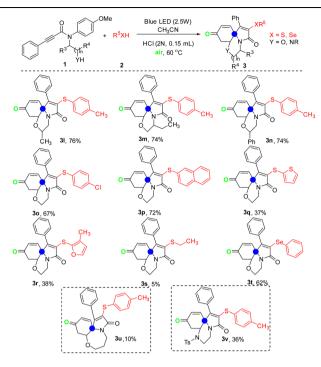
Table 2 Reaction scope using p-toluenethiophenol as the source of free radical^{a,t}

^a Standard conditions: 1 (0.2 mmol), 2a (0.3 mmol), HCl (2.0 N, 0.15 mL), air, in 2 mL of CH₃CN were stirred under blue LED (2.5 W) at 60 $^{\circ}$ C, 12 h. b Isolated yield based on 1. c 1.0 mmol scale experiment of 1a.

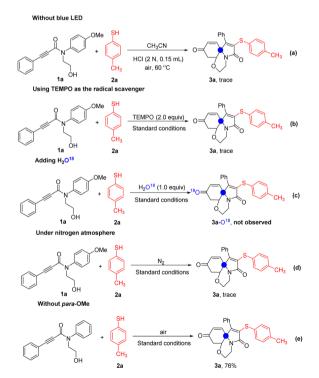
is methyl, the corresponding product 3h was obtained with only 30% yield. Next, the influence of phenyl substituents R^2 on the reaction of N-arylpropamides was studied. It can be seen from the results that substrates containing methyl, chlorine, or bromine substituted could react smoothly and give the corresponding products 3i-k in good yields. The structure of compound 3k (CCDC: 2203442†) was identified by X-ray singlecrystal diffraction (see the ESI† for details).

In order to extend the universality of the reaction substrates, the substrate with secondary alcohol or other primary alcohol was synthesized as the starting material (Table 3). The results showed that the substrate with secondary alcohol or other primary alcohol was also compatible for the reaction, leading to the corresponding products 31, 3m, and 3n in 76%, 74%, and 74% yields, respectively. Next, the influence of different thioalcohols on the reaction was investigated. Using 4-chlorobenzenethiol or naphthalene-2-thiol as the reaction substrate, the reaction proceeded smoothly and the corresponding products 30 and 3p were obtained in good yields. Unfortunately, using heterocyclic mercaptan and ethanethiol as the reaction substrates, the corresponding products could only be obtained in low yields of 5-38%. Happily, when phenylselenol was used as the substrate, the corresponding product 3t was obtained in 62% yield under standard conditions. Notably, the reaction using the substrate with 3-propanol was retarded, leading to the corresponding product 3u in only 10% yield. Finally, changing the primary alcohol to Ts protected amine, the reaction was still going on smoothly and the expected product 3v was achieved in 36% yield.

Table 3 Reaction scope for the synthesis of thio(sele)-containing spirotricycles^{a,b}



^a Standard conditions: 1 (0.2 mmol), 2 (0.3 mmol), HCl (2.0 N, 0.15 mL), air, in 2 mL of CH₃CN were stirred under blue LED (2.5 W) at 60 °C, 12 h. Isolated yield based on **1**.

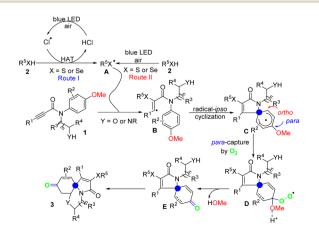


Scheme 3 Control experiments.

RSC Advances

In order to shed light on the mechanism of this reaction, some control experiments were carried out (Scheme 3). First of all, the reaction could not be carried out normally without the blue LED (Scheme 3a). Next, the expected product 3a could not be detected when 2.0 equiv of TEMPO (2,2,6,6-tetramethyl-1piperidinyloxy) was added to the reaction system (Scheme 3b). From this result, the reaction probably underwent a radical pathway. Furthermore, when adding 1.0 equiv of H₂O¹⁸ to the standard conditions, the O18 atom was not observed by LC-MS analysis in the product, which perhaps indicated that the oxygen of carbonyl was not derived from the water (Scheme 3c). Finally, the reaction did not work under N₂ atmosphere may be implied that the oxygen of carbonyl group came from the oxygen in the air (Scheme 3d). If the reaction was carried out with Nphenylproiolamides without a para-methoxy substituent on the N-substituted aryl moiety, the desired product 3a was still obtained in 76% yield, which indicated that oxygen of carbonyl was derived from the air (Scheme 3e).

Based on the control experiments aforementioned above and the previous reports, 15,18 a plausible mechanism was proposed in Scheme 4. Initially, ${}^{1}O_{2}$ (E=2.2 V) reacted with Cl⁻ (E=1.36V) producing chlorine radical in the presence of blue LED and air.18b Then chlorine radical undergoes HAT with thio(sele) phenol to give sulfur(selenium) radical A (route I).18a Of course, the sulfur(selenium) radical A could also be offered directly by the blue LED and air (route II). Intermediate B was formed through the α -addition of N-arylpropiolamides 1 to sulfur(selenium) radical A. Then, the key intermediate C was provided by radical ipso-cyclization. Next, the intermediate C was captured by molecular oxygen in para-site fashion to offer the intermediate **D**. Subsequently, under the action of proton acid, the key intermediate E was obtained through electron rearrangement, while releasing a molecule of methanol. When there was no methoxy group present in the reaction substrate, the required product 3a was still obtained in 76% yield (Scheme 3e), indicating that intermediate C could still be captured by molecular oxygen, leading to electron rearrangement to obtain intermediate E. Finally, assisted by the additives, the intermediate E undergoes an intramolecular Michael-addition reaction, thus providing the final products 3.



Scheme 4 Plausibe mechanism.

Conclusions

In conclusion, we have developed a general and convenient protocol for the blue LED-promoted chlorine radical-mediated spiro-tricyclization of N-arylpropiolamides with thiophenols under metal-free conditions. In this reaction, hydrochloric acid is used as the cheap promoter and air as the sustainable oxidant. Many functional groups tolerate the reaction conditions and produce a series of sulfur-containing benzo[b]pyrrolo [2,1-c][1,4]oxazine-3,9-diones with high efficiency and specific selectivity. Preliminary mechanistic studies indicated that the reaction undergoes LED-promoted chlorine radical-mediated spiro-cyclization and intramolecular Michael-addition reaction. Further studies on the visible light induced radical cyclization are currently ongoing.

Experimental

General methods and materials

Unless stated otherwise, reactions were conducted in dried glassware. Commercially available reagents and solvents were used as received. 300-400 mesh silica gel was used for flash column chromatography. Visualization on TLC was achieved by the use of UV light (254 nm). 400 MHz and 100 MHz were used to record the 1 H NMR and 13 C NMR spectra. Chemical shifts (δ ppm) were reported in parts per million, referring to either the internal standard of TMS or the residue of the deuterated solvents. The splitting pattern was described as follows: s for singlet, d for doublet, t for triplet, q for quartet, and m for multiplet. Coupling constants were reported in Hz. The highresolution mass spectrum (HRMS) was performed on waters Xevo G2-S QTof mass spectrometer. The crystal of 3k was measured on an Agilent Technologies Gemini single-crystal diffractometer and the solvent system for crystal growth is dichloromethane and petroleum ether.

Typical procedure for the synthesis of compound 3a

a test tube were added N-(2-hydroxyethyl)-N-(4methoxyphenyl)-3-phenylpropiolamide 1a (0.20 mmol), 4methylbenzenethiol 2a (0.30 mmol, 1.50 equiv), CH₃CN (2.00 mL), and then HCl (0.15 mL, 2.00 mol L⁻¹) was added to the mixture. Then the mixture was stirred under air at 60 °C under 2.5 W blue LED irradiation for 12 hours until the complete consumption of the substrate. The mixture was treated with saturated NaHCO₃ (2.0 mL) and extracted with EA (2.0 mL \times 3). The combined organic layer was dried with anhydrous Na₂SO₄. The solvent was removed under vacuum and the residue was purified by silica gel chromatography, using a mixture of petroleum ether/ethyl acetate to give the desired product 3a.

Characterization data

1-Phenyl-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b] pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3a). Yellow solid (61.3 mg, 76%); M.p. = 170–173 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.33–7.24 (m, 3H), 7.15 (d, J = 7.9 Hz, 2H), 7.08 (d, J = 7.5 Hz, 2H), 6.96 (dJ = 7.7 Hz, 2H, 6.41-6.34 (m, 2H), 4.26-4.23 (m, 1H), 3.90-3.85 Paper

 $\begin{array}{l} (m,1H), 3.72 \ (s,1H), 3.36-3.30 \ (m,1H), 3.17-3.11 \ (m,1H), 2.36-2.24 \ (m,1H), 2.24 \ (s,3H), 1.87-1.82 \ (m,1H); \ ^{13}C\{^{1}H\} NMR \ (100 \ MHz, CDCl_3) \ \delta \ 194.4, 166.1, 153.5, 142.6, 137.8, 134.0, 133.7, 131.9, 129.7, 129.4, 128.7, 128.3, 127.5, 79.1, 66.2, 41.3, 38.8, 21.1; IR (KBr): 2950, 1688, 1640, 1495, 1070, 1044, 1020, 739, 621 cm \ ^{-1}; HRMS (ESI-TOF) \ m/z: \ [M + H] \ ^+ \ calcd \ for \ C_{24}H_{21}NO_3-NaS \ 426.1140; \ found: 426.1137. \\ \end{array}$

1-(*p*-Tolyl)-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*] pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3b). Yellow solid (53.4 mg, 64%); M.p. = 144–147 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.12 (m, 4H), 6.97 (s, 4H), 6.37–6.34 (m, 2H), 4.24–4.23 (m, 1H), 3.86–3.84 (m, 1H), 3.69 (m, 1H), 3.33–3.28 (m, 1H), 3.14–3.08 (m, 1H), 2.35 (s, 1H), 2.31 (s, 3H), 2.24 (s, 3H), 1.93–1.89 (m, 1H); ¹³C{1H}NMR (100 MHz, CDCl₃) δ 194.5, 166.2, 154.1, 142.7, 139.7, 137.7, 134.0, 133.1, 131.7, 129.8, 129.5, 129.0, 128.1, 127.8, 79.2, 66.1, 41.3, 38.7, 21.3, 21.1; IR (KBr): 2917, 1493, 1273, 1170, 1060, 1013, 788, 765, 755, 662 cm⁻¹; HRMS (ESI-TOF) *m/z*: [M + H]⁺ calcd for C₂₅H₂₃NO₃NaS 440.1296; found: 440.1290.

1-(4-Chlorophenyl)-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3c). Yellow solid (62.1 mg, 71%); M.p. = 175–178 °C; 1H NMR (400 MHz,CDCl₃) δ 7.20 (d, J = 8.0 Hz, 2H), 7.11 (d, J = 6.4 Hz, 2H), 6.96 (d, J = 8.8 Hz, 4H), 6.35 (s, 2H), 4.26–4.22 (m, 1H), 3.88–3.85 (m, 1H), 3.70 (s, 1H), 3.34–3.28 (m, 1H), 3.12–3.10 (m, 1H), 2.39–2.34 (m, 1H), 2.25 (s, 3H), 1.88–1.84 (m, 1H); 13 C{ 1H }NMR (100 MHz, CDCl₃) δ 194.0, 165.8, 150.7, 142.5, 138.3, 135.6, 134.7, 134.1, 132.5, 130.2, 129.7, 128.9, 126.5, 79.0, 66.2, 66.1, 41.3, 38.8, 21.1; IR (KBr): 2924, 1693, 1488, 1398, 1384, 1071, 1012, 804, 760, 661 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^+$ calcd for $C_{24}H_{20}NO_3$ -NaSCl 460.0750; found: 460.0751.

1-(4-Bromophenyl)-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3d). Yellow solid (79.1 mg, 82%); M.p. = 167–170 °C; 1 H NMR (400 MHz, CDCl₃) δ 7.35 (d, J = 7.7 Hz, 2H), 7.11 (d, J = 7.5 Hz, 2H), 6.93 (d, J = 7.6 Hz, 2H), 6.89 (d, J = 7.7 Hz, 2H), 6.35 (s, 2H), 4.26–4.22 (m, 1H), 3.88–3.85 (m, 1H), 3.70 (s, 1H), 3.34–3.28 (m, 1H), 3.16–3.10 (m, 1H), 2.39–2.35 (m, 1H), 2.25 (s, 3H), 1.89–1.85 (m, 1H); 13 C { 1 H}NMR (100 MHz, CDCl₃) δ 194.0, 165.8, 150.4, 142.5, 138.4, 134.7, 134.1, 132.5, 131.8, 130.7, 129.9, 129.7, 126.4, 123.8, 79.0, 66.1, 41.3, 38.8, 21.2; IR (KBr): 2916, 1693, 1398, 1385, 1107, 1067, 1012, 805, 787, 688, 660 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^+$ calcd for $C_{24}H_{20}NO_3NaSBr$ 504.0245; found: 504.0243.

1-(Naphthalen-1-yl)-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3e). Yellow solid (63.5 mg, 70%); M.p. = 206–209 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.77 (d,J = 5.7 Hz, 2H), 7.68 (d,J = 7.9 Hz, 1H), 7.61 (d,J = 8.9 Hz, 1H), 7.52 (s, 2H), 7.21 (m, 1H), 6.96 (d,J = 7.1 Hz, 1H), 6.82 (d,J = 7.5 Hz, 2H), 6.61 (m, 2H), 6.41 (d,J = 10.1 Hz, 1H), 6.32 (d,J = 9.8 Hz, 1H), 4.36 (m, 1H), 3.97–3.86 (m, 2H), 3.46–3.41 (m, 1H), 3.24–3.21 (m, 1H), 2.10 (s, 3H), 2.07 (s, 1H), 1.39–1.35 (m, 1H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.2, 165.9, 146.9, 142.9, 138.1, 136.3, 133.7, 133.3, 130.3, 129.2, 129.0, 128.8, 128.7, 128.3, 127.5, 127.2, 126.4, 124.4, 124.3, 78.8, 67.5, 66.2, 41.0, 38.9, 20.9; IR (KBr): 2973, 2861, 1685, 1490, 1442, 1385, 1103, 1064, 1052, 1016, 811, 792, 761, 649 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C_{28} H $_{23}$ NO $_{3}$ NaS 476.1296; found: 476.1298.

1-(Thiophen-2-yl)-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3f). Yellow solid (37.7 mg, 46%); M.p. = 115–118 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.40 (s, 1H), 7.20 (s, 2H), 7.07 (s, 1H), 7.01 (s, 3H), 6.46 (s, 1H), 6.41 (s, 1H), 4.23–4.20 (m, 1H), 3.86–3.83 (m, 1H), 3.67 (s, 1H), 3.32–3.26 (m, 1H), 3.13–3.07 (m, 1H), 2.46–2.42 (m, 1H), 2.26 (s, 3H), 2.18–2.14 (m, 1H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.6, 165.8, 146.3, 141.8, 137.9, 135.4, 133.6, 131.6, 131.5, 130.0, 129.7, 129.16, 127.6, 79.6, 66.0, 65.8, 41.3, 38.8, 21.2; IR (KBr): 2970, 2920, 1683, 1487, 1397, 1384, 1281, 1101, 1060, 797, 760, 709, 700, 649 cm⁻¹; HRMS (ESI-TOF) *m/z*: [M + H]⁺ calcd for C₂₂H₁₉NO₃NaS₂ 432.0704; found: 432.0697.

1-[[1,1'-Biphenyl]-4-yl)-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3g). Yellow solid (28.8 mg, 30%); M.p. = 91–94 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.52 (d, J = 17.6 Hz, 5H), 7.45 (s, 2H), 7.38 (s, 1H), 7.18 (s, 3H), 6.96 (s, 2H), 6.43 (s, 2H), 4.30–4.27 (m, 1H), 3.91–3.87 (m, 1H), 3.77 (s, 1H), 3.37–3.33 (m, 1H), 3.20–3.14 (m, 1H), 2.42–2.38 (m, 1H), 2.23 (s, 3H), 2.02–1.98 (m, 1H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) 194.4, 166.2, 152.6, 142.7, 142.3, 139.7, 137.9, 134.1, 133.9, 132.1, 130.8, 129.7, 128.9, 127.8, 127.2, 127.0, 79.2, 66.2, 41.4, 38.8, 21.1; IR (KBr): 2975, 2918, 1686, 1487, 1437, 1385, 1277, 1098, 1061, 760, 730, 730, 693 cm $^{-1}$; HRMS (ESITOF) m/z: [M + H] $^{+}$ calcd for C₃₀H₂₅NO₃NaS 502.1453; found: 502.1448.

1-Methyl-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*] pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3h). Yellow solid (20.5 mg, 30%); M.p. = 160–163 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.25 (d, *J* = 6.6 Hz, 2H), 7.08 (d, *J* = 7.1 Hz, 2H), 6.35 (d, *J* = 10.0 Hz, 1H), 6.18 (d, *J* = 9.9 Hz, 1H), 4.21–4.18 (m, 1H), 3.88–3.86 (s, 1H), 3.64 (m, 1H), 3.32–3.26 (m, 1H), 3.13–3.07 (m, 1H), 2.87–2.75 (m, 2H), 2.29 (s, 3H), 2.07 (s, 3H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.2, 166.6, 154.8, 144.7, 137.5, 133.1, 132.1, 130.7, 129.9, 128.8, 78.5, 66.3, 66.0, 41.9, 38.5, 21.1, 13.8; IR (KBr): 2918, 2816, 1691, 1601, 1490, 1398, 1283, 1105, 1062, 801, 744 cm⁻¹; HRMS (ESI-TOF) *m/z*: [M + H]⁺ calcd for C₁₉H₁₉NO₃NaS 364.0983; found: 364.0984.

11-Methyl-1-phenyl-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3i). Yellow solid (66.0 mg, 79%); M.p. = 141–143 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.29 (m, 3H), 7.13 (d,J = 7.3 Hz, 2H), 6.97 (m, 4H), 6.27 (s, 1H), 4.26–4.23 (m, 1H), 3.85–3.82 (m, 1H), 3.66 (s, 1H), 3.35–3.29 (m, 1H), 2.92–2.86 (m, 1H), 2.33–2.28 (m, 1H), 2.23 (s, 3H), 1.85 (s, 3H), 1.79 (s, 1H); ¹³C{¹H}NMR (100 MHz, CDCl₃) δ 194.2, 166.6, 153.7 150.5, 137.8, 134.0, 132.6, 131.9, 131.8, 129.7, 129.6, 128.7, 127.9, 79.6, 68.6, 65.9, 41.3, 38.6, 21.1, 18.2; IR (KBr): 2877, 2915, 1705,1676, 1493, 1436, 1385, 1346, 1276, 1103, 1065, 870, 813, 778, 769, 723, 710, 647 cm⁻¹; HRMS (ESI-TOF) m/z: [M + H]⁺ calcd for C₂₅H₂₃NO₃NaS 440.1296; found: 440.1291.

10-Chloro-1-phenyl-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3j). Yellow solid (64.8 mg, 74%); M.p. = 165–168 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.30 (d, J = 7.7 Hz, 3H), 7.15 (d, J = 6.8 Hz, 2H), 7.03 (d, J = 6.5 Hz, 2H), 6.95 (d, J = 7.1 Hz, 2H), 6.58 (s, 1H), 4.27–4.24 (m, 1H), 3.89–3.87 (m, 1H), 3.70 (m, 1H), 3.36–3.30 (m, 1H), 3.21–3.16 (m, 1H), 2.54–2.49 (m, 1H), 2.24 (s, 3H), 1.91–1.86 (m,

1H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 192.17, 166.90, 155.67, 142.1, 135.1, 134.0, 133.0, 132.4, 131.0, 129.4, 129.1, 129.0, 128.7, 128.1, 127.9, 127.8, 126.8, 82.1, 72.8, 68.1, 52.5, 44.7, 17.8; IR (KBr): 2912, 2859, 1694, 1489, 1440, 1398, 1385, 1098, 1063, 802, 605 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C₂₄-H₂₀NO₃NaSCl 460.0750; found: 460.0742.

10-Bromo-1-phenyl-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3k). Yellow solid (70.4 mg, 73%); M.p. = 183–185 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.29 (d, J = 6.8 Hz, 3H), 7.14 (d, J = 5.1 Hz, 2H), 7.03 (s, 2H), 6.94 (d, J = 5.7 Hz, 2H), 6.85 (s, 1H), 4.26–3.23 (m, 1H), 3.89–3.86 (m, 1H), 3.71 (s, 1H), 3.34–3.29 (m, 1H), 3.21–3.15 (m, 1H), 2.56–2.52 (m, 1H), 2.23 (s, 3H), 1.91–1.87 (m, 1H); ¹³C{¹H} NMR (100 MHz, CDCl₃) δ 186.4, 165.8, 151.8, 142.8, 138.1, 134.2, 132.3, 131.5,129.7, 129.6, 128.9, 128.2, 127.9, 126.9, 78.9, 68.2, 66.1, 41.0, 38.8, 21.1; IR (KBr): 2960, 2854, 1697, 1492, 1439, 1384, 1339,1275, 1127, 1097, 1062, 1011, 997, 805, 775, 711, 687 cm⁻¹; HRMS (ESI-TOF) m/z: [M + H]⁺ calcd for C₂₄H₂₀NO₃-NaS 504.0245; found: 504.0240.

10-Bromo-1-phenyl-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3l). Yellow solid (63.5 mg, 76%); M.p. = 173–175 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.14 (d,J = 7.5 Hz, 2H), 7.07 (d,J = 6.9 Hz, 2H), 6.95 (d,J = 7.4 Hz, 2H), 6.37 (d,J = 10.4 Hz, 1H), 6.33 (d,J = 10.5 Hz, 1H), 4.4–4.21 (m, 1H), 3.77 (s, 1H), 3.46–3.35 (m, 1H), 2.75–2.69 (m, 1H), 2.35–2.31 (m, 1H), 2.23 (s, 3H), 1.85–1.81 (m, 1H), 1.13 (d,J = 5.9 Hz, 3H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.5, 166.1, 153.7, 142.6, 137.7, 134.0, 133.5,132.0, 131.9, 129.6, 129.4, 128.6, 128.3, 127.6, 78.7, 72.3, 65.7, 44.6, 41.3, 21.1, 17.9; IR (KBr): 2973, 2900, 2875, 1700, 1635, 1490, 1439, 1385, 1272, 1109, 1045, 1014, 791, 753 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C₂₅H₂₃NO₃NaS 440.1296; found: 440.1292.

5-Ethyl-1-phenyl-2-(p-tolylthio)-5,6,7a,8-tetrahydro-3H,9H-benzo[b]pyrrolo[2,1-c][1,4]oxazine-3,9-dione (3m). Yellow solid (61.2 mg, 74%); M.p. = 166–169 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.26 (m, 3H), 7.13 (d, J = 7.1 Hz, 2H), 7.00 (d, J = 6.4 Hz, 2H), 6.92 (d, J = 6.9 Hz, 2H), 6.43 (d, J = 9.8 Hz, 1H), 6.23 (d, J = 10.0 Hz, 1H), 4.25–4.15 (m, 1H), 3.85–3.82 (m, 1H), 3.71 (s, 1H), 3.43–3.41 (m, 1H), 2.36–2.32 (m, 1H), 2.22 (s, 3H), 1.85–1.81 (m, 1H), 1.70–1.69 (m, 2H), 0.95 (t, J = 6.5 Hz, 3H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.2, 167.3, 153.4 (s), 143.9, 137.8, 133.6, 132.1, 131.9, 129.6, 129.2, 128.6, 128.3, 127.3, 79.3, 68.7, 65.8, 51.7, 41.3, 24.7, 21.1, 11.0; IR (KBr): 3053, 2965, 2917, 2875, 1706, 1685, 1490, 1384, 1318, 1269, 1118, 1077, 1044, 1032, 1010, 809, 764, 678, 703 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for $C_{26}H_{25}NO_{3}NaS$ 454.1453; found: 454.1446.

1,6-Diphenyl-2-(*p*-tolylthio)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo [*b*] pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3n). Yellow solid (70.9 mg, 74%); M.p. = 90–93 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.32 (d, J = 5.1 Hz, 10H), 7.21 (d, J = 6.4 Hz, 1H), 7.15 (s, 2H), 7.00 (s, 1H), 6.46 (s, 2H), 4.48–4.39 (m, 2H), 4.00 (s, 1H), 3.03–2.93 (m, 1H), 2.49–2.45 (m, 1H), 2.27 (s, 3H), 1.96–1.92 (m, 1H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.4, 166.1, 153.4, 142.6, 137.9, 137.5, 134.2, 133.7, 132.0, 131.9, 129.7, 129.5, 128.7, 128.6, 128.4, 128.3, 127.4, 125.8, 79.0, 77.7, 65.7, 44.9, 41.3, 21.2; IR (KBr): 2919, 2854, 1686, 1493, 1392, 1063, 1013, 752,

698 cm⁻¹; HRMS (ESI-TOF) m/z: [M + H]⁺ calcd for C₃₀H₂₅NO₃-NaS 502.1453; found: 502.1453.

2-((4-Chlorophenyl)thio)-1-phenyl-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (30). Yellow solid (56.8 mg, 67%); M.p. = 176–179 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.44–7.24 (m, 4H), 7.15 (s, 2H), 7.11 (s, 2H), 7.06 (d, *J* = 6.1 Hz, 2H), 6.36 (s, 2H), 4.23–4.21 (m, 1H), 3.87–3.84 (m, 1H), 3.71 (s, 1H), 3.33–3.28 (m 1H), 3.16–3.10 (m, 1H), 2.34–2.31 (m, 1H), 1.85–1.80 (m, 1H). 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.1, 165.8, 154.7, 142.2, 134.2, 133.8, 132.9, 132.8, 131.7,129.8, 129.7, 129.0, 128.8, 128.2, 79.0, 66.4, 66.1, 41.2, 38.8; IR (KBr): 3062, 2927, 2853, 1689, 1475, 1401, 1383, 1105, 1069, 1013, 818, 755, 698, 660 cm $^{-1}$; HRMS (ESI-TOF) *m/z*: [M + H]⁺ calcd for C₂₃H₁₈NO₃NaSCl 446.0594; found: 446.0584.

2-(Naphthalen-2-ylthio)-1-phenyl-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3p). Yellow solid (63.3 mg, 72%); M.p. = 167–169 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.73 (s, 2H), 7.64 (s, 2H), 7.43 (s, 2H), 7.32 (s, 1H), 7.20 (s, 3H), 7.09 (s, 2H), 6.40 (s, 2H), 4.26 (m, 1H), 3.88 (m, 1H), 3.76 (s, 1H), 3.34 (m, 1H), 3.15 (m, 1H), 2.35 (m, 1H), 1.83 (m, 1H); ¹³C{¹H} NMR (100 MHz, CDCl₃) δ 194.3, 166.1, 154.5, 142.5, 134.1, 133.3, 132.4, 131.8, 131.0, 129.5, 128.6, 128.5 128.2, 127.6, 127.4, 126.5, 126.4, 79.1, 66.4, 66.2, 41.3, 38.8; IR (KBr): 2327, 2313, 1712, 1679, 1384, 1098, 1065, 1010, 824, 752, 703 cm⁻¹; HRMS (ESITOF) *m/z*: [M + H]⁺ calcd for C₂₇H₂₁NO₃NaS 462.1104; found: 462.1135.

2-((3-Methylfuran-2-yl)thio)-1-phenyl-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*]pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3r). Yellow solid (29.9 mg, 38%); M.p. = 161–163 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.35–7.26 (m, 3H), 7.03 (d, *J* = 6.6 Hz, 3H), 6.36–6.24 (m, 2H), 6.18–6.10 (m, 1H), 4.28–4.25 (d, *J* = 13.3 Hz, 1H), 3.90–3.87 (m, 1H), 3.74–3.69 (m, 1H), 3.37–3.31 (m, 1H), 3.18–3.11 (m, 1H), 2.34–2.30 (m, 1H), 2.12 (s, 3H), 1.83–1.78 (m, 1H). ¹³C {¹H}NMR (100 MHz, CDCl₃) δ 194.3, 166.2, 156.1, 150.8, 142.6, 140.4, 133.9, 133.6, 131.7, 129.3, 128.5, 128.1, 115.2, 105.1, 78.9, 66.2, 66.1, 41.3, 38.7, 11.8; IR (KBr): 2925, 2865, 2322, 1690, 1384, 1275, 1179, 1275, 1179, 1095, 1052, 801, 754, 707 cm⁻¹; HRMS (ESI-TOF) *m/z*: [M + H]⁺ calcd for C₂₂H₁₉NO₃NaS 416.0932; found: 416.0934.

2-(Ethylthio)-1-phenyl-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo[*b*] pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3s). Yellow solid (3.4 mg, 5%); M.p. = 106–109 °C; 1 H NMR (400 MHz, CDCl₃) δ 7.40 (d, J = 1.7 Hz, 3H), 7.18 (m, 2H), 6.37 (s, 2H), 4.30 (m, 1H), 3.91 (m, 1H), 3.71 (s, 1H), 3.35 (m, 1H), 3.17 (m, 1H), 2.99 (m, 2H), 2.36 (m, 1H), 1.87 (m, 1H), 1.16 (t, J = 6.1 Hz, 3H); 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.4, 151.1, 142.8, 133.9, 133.3, 132.5, 129.6, 128.9, 128.3, 79.2, 66.1, 66.0, 41.3, 38.6, 25.1, 15.1; IR (KBr): 2968, 2920, 2319, 1689, 1385, 1098, 1070, 848, 766, 728, 710 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C₁₉H₁₉NO₃-NaS 364.0983; found: 364.0988.

1-Phenyl-2-(phenylselanyl)-5,6,7a,8-tetrahydro-3*H*,9*H*-benzo [*b*] pyrrolo[2,1-*c*][1,4]oxazine-3,9-dione (3t). Yellow solid (54.1 mg, 62%); M.p. = 155–158 °C; ¹H NMR (400 MHz,CDCl₃) δ 7.32 (d, J = 6.8 Hz, 2H), 7.27 (d, J = 6.6 Hz, 1H), 7.23 (d, J = 6.9 Hz, 2H), 7.14 (d, J = 6.5 Hz, 1H), 7.08 (d, J = 6.9 Hz, 2H), 7.00 (d, J = 6.5 Hz, 2H), 6.47–6.19 (m, 2H), 4.28–4.24 (m, 1H), 3.88–3.85 (m, 1H), 3.72 (s, 1H), 3.35–3.30 (m, 1H), 3.18–3.11 (m, 1H),

Paper

2.34–2.29 (m, 1H), 1.83–1.78 (m, 1H); $^{13}\text{C}\{^1\text{H}\}\text{NMR}$ (100 MHz, CDCl₃) δ 194.3, 167.0, 156.2, 142.5, 134.0, 133.9, 132.5, 129.4, 129.0, 128.7, 128.0, 127.9, 126.9, 78.9, 67.4, 66.2, 41.2, 38.9; IR (KBr): 1712, 1698, 1385, 1093, 1060, 742, 656 cm $^{-1}$; HRMS (ESITOF) m/z: [M + H] $^+$ calcd for $\text{C}_{23}\text{H}_{19}\text{NO}_3\text{NaSe}$ 460.0428; found: 460.0427.

1-Phenyl-2-(*p*-tolylthio)-6,7,8a,9-tetrahydro-3*H*,5*H*,10*H*-benzo[*b*] pyrrolo[2,1-*c*][1,4]oxazepine-3,10-dione (3u). Yellow solid (8.4 mg, 10%); M.p. = 154–158 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.35–7.25 (m, 3H), 7.15 (d, J = 8.0 Hz, 2H), 7.08 (d, J = 6.9 Hz, 2H), 6.95 (d, J = 7.9 Hz, 2H), 6.41–6.39 (m, 1H), 6.35–6.32 (m, 1H), 4.21–4.18 (m, 2H), 3.78 (d, J = 2.3 Hz, 1H), 3.52–3.45 (m, 1H), 3.23–3.16 (m, 1H), 2.38–2.33 (m, 1H), 2.25 (s, 3H), 2.11–2.02 (m, 1H), 1.94–1.85 (m, 1H), 1.78–1.72 (m, 1H). 13 C{ 1 H}NMR (100 MHz, CDCl₃) δ 194.6, 167.4, 153.4, 143.2, 137.8, 134.5, 132.6, 132.0, 129.6, 129.4, 128.7, 128.1, 127.6, 85.8, 71.6, 70.3, 42.7, 37.4, 27.1, 21.1; IR (KBr): 2946, 1695, 1682, 1492, 1433, 1405, 1338, 1308, 1193, 1107, 1013, 950, 811, 747, 624, 652 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C₂₅H₂₃NO₃NaS 440.1296; found: 440.1298.

1-Phenyl-2-(*p*-tolylthio)-7-tosyl-6,7,7a,8-tetrahydro-3*H*-pyrrolo [1,2-*d*]quinoxaline-3,9(5*H*)-dione (3*v*). Yellow solid (40.1 mg, 36%), M.p. = 216–220 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.59 (d, J = 8.0 Hz, 2H), 7.37–7.25 (m, 5H), 7.12 (d, J = 7.8 Hz, 2H), 7.07 (d, J = 7.4 Hz, 2H), 6.94 (d, J = 7.8 Hz, 2H), 6.45 (d, J = 10.1 Hz, 1H), 6.37 (d, J = 10.1 Hz, 1H), 4.37–4.32 (m, 1H), 3.91–3.86 (m, 1H), 3.80–3.70 (m, 1H), 3.51–3.44 (m, 1H), 3.14–3.08 (m, 1H), 2.71–2.66 (m, 1H), 2.46 (s, 3H), 2.24 (s, 3H), 2.05–2.00 (m, 1H). 13 C{ 1 H}NMR (100 MHz, CDCl $_{3}$) δ 193.9, 166.6, 154.2, 144.9, 144.6, 138.0, 135.9, 133.5, 132.9, 132.3, 131.1, 130.3, 129.6, 128.8, 128.2, 126.9, 126.8, 64.2, 57.0, 41.7, 40.5, 37.4, 21.7, 21.1; IR (KBr): 2326, 1741, 1641, 1385, 1170, 1166, 1093, 818, 665 cm $^{-1}$; HRMS (ESI-TOF) m/z: [M + H] $^{+}$ calcd for C₃₁H₂₈N₂-O₄NaS₂ 579.1388; found: 579.1392.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work is supported by the Natural Science Foundation of China (22161043 and 21801096), Yunnan Fundamental Research Project (202201AU070071 and 202301AT070224), "High-level Talent Introduction Program" Project of Yunnan Province (YNQR-QNRC-2019-065), Department of Education of Zhejiang Province (Y202147909), the Scientific Research Foundation of Hunan Provincial Education Department (22A0348), and the Start up Funding of Southwest Forestry University (112126), also Supported by the 111 Project (D21027).

Notes and references

1 For selected examples, see:(a) C. Tonnelé and F. Castet, *Photochem. Photobiol. Sci.*, 2019, **18**, 2759; (b) T. H.-C. Fung, C.-L. Wong, W.-K. Tang, M.-Y. Leung, K.-H. Low and V. W.-W. Yam, *Chem. Commun.*, 2022, **58**, 4231; (c) J. Liu,

- A. K.-W. Chan, M. Ng, E. Y.-H. Hong, N. M.-W. Wu, L. Wu and V. W.-W. Yam, *Organometallics*, 2019, **38**, 3542; (*d*) A. V. Chernyshev, N. A. Voloshin, I. A. Rostovtseva, O. P. Demidov, K. E. Shepelenko, E. V. Solov'eva, E. B. Gaeva and A. V. Metelitsa, *Dyes Pigm.*, 2020, **178**, 108337; (*e*) J. Karpiuk, P. Gawryś, E. Karpiuk and K. Suwińska, *Chem. Commun.*, 2019, 55, 8414.
- 2 For selected examples:(a) T. P. I. Saragi, T. Spehr, A. Siebert, T. Fuhrmann-Lieker and J. Salbeck, *Chem. Rev.*, 2007, **107**, 1011; (b) R. O. Al-Kaysi, I. Gallardo and G. Guirado, *Molecules*, 2008, **13**, 1282; (c) C.-Y. Chank, Y.-C. Wong, M.-Y. Chan, S.-H. Cheung, S.-K. So and V. W.-W. Yam, *ACS Appl. Mater. Interfaces*, 2016, **8**, 24782; (d) Q. Wang, X. Jiao, C. Liu, K. Huang, S. He, L. Zhao and X. Zeng, *Org. Biomol. Chem.*, 2018, **16**, 7609.
- 3 (a) Y.-J. Zheng and C. M. Tice, Expert Opin. Drug Discovery, 2016, 11, 831; (b) K. Hiesinger, D. Dafin, E. Proschak and M. Krasavin, J. Med. Chem., 2021, 64, 150; (c) M. Benabdallah, O. Talhi, F. Nouali, N. Choukchou-Braham, K. Bachari and A. M. S. Silva, Curr. Med. Chem., 2018, 25, 3748; (d) A. A. Kirichok, I. O. Shton, I. M. Pishel, S. A. Zozulya, P. O. Borysko, V. Kubyshkin, O. A. Zaporozhets, A. A. Tolmachev and P. K. Mykhailiuk, Chem.-Eur. J., 2018, 24, 5444.
- 4 (a) R. Saruengkhanphasit, D. Collier and I. Coldham, J. Org. Chem., 2017, 82, 6489; (b) M. Luo, R. Yuan, X. Liu, L. Yu and W. Wei, Chem.-Eur. J., 2016, 22, 9797; (c) Y.-C. Wang, J.-B. Liu, H. W. Zhou, W. Xie, P. Rojsitthisak and G. Qiu, J. Org. Chem., 2020, 85, 1906; (d) N. Lv, Y. Liu, C. Xiong, Z. Liu and Y. Zhang, Org. Lett., 2017, 19, 4640; (e) A. Ren, B. Lang, J. Lin, P. Lu and Y. Wang, J. Org. Chem., 2017, 82, 10953; (f) Y. Yu, Y. Chen, W. Huang, W. Wu and H. Jiang, J. Org. Chem., 2017, 82, 9479.
- 5 (a) A. Ghoshal, A. Kumar, D. Yugandhar, C. Sona, S. Kuriakose, K. Nagesh, M. Rashid, S. K. Singh, M. Wahajuddin, P. N. Yadav and A. K. Srivastava, Eur. J. Med. Chem., 2018, 152, 148; (b) T. Honda and H. Shigehisa, Org. Lett., 2006, 8, 657; (c) H. Shigehisa, J. Takayama and T. Honda, Tetrahedron Lett., 2006, 47, 7301.
- 6 (a) Y.-T. Yang, J.-F. Zhu, G. Liao, H.-J. Xu and B. Yu, Curr. Med. Chem., 2018, 25, 2233; (b) E. Rajaranendar, K. Ramakrishna, K. Govardhan Reddy, D. Nagaraju and N. Y. Reddy, Bioorg. Med. Chem. Lett., 2013, 23, 3954; (c) G. Bhaskar, Y. Arun, C. Balachandran, C. Salikumar and P. T. Perumal, Eur. J. Med. Chem., 2012, 51, 79; (d) Y. Arun, G. Bhaskar, C. Balachandran, S. Ignachimuthu and P. T. Perumal, Bioorg. Med. Chem. Lett., 2013, 23, 1839.
- 7 A. F. Parsons and D. A. J. Williams, *Tetrahedron*, 2000, 56, 7217.
- 8 (a) K. Sakamoto, E. Tsujii, F. Abe, T. Nakanishi, M. Yamashita, N. Shigematsu, S. Izumi and M. Okuhara, J. Antibiot., 1996, 49, 37; (b) A. J. Blackman, C. Li, D. C. R. Hockless, B. W. Skelton and A. H. White, Tetrahedron, 1993, 49, 8645; (c) J. Y. Cha, Y. Huang and T. R. R. Pettus, Angew. Chem., Int. Ed., 2009, 48, 9519.
- 9 (a) C. R. Reddy, D. H. Kolgave, U. Ajaykumar and R. Ramesh, Org. Biomol. Chem., 2022, 20, 6879; (b) D. Yugandhar and

A. K. Srivastava, ACS Comb. Sci., 2015, 17, 474; (c) Y. He, L. Song, C. Liu, D. Wu, Z. Li, L. V. Meervelt and E. V. V. Eycken, J. Org. Chem., 2020, 85, 15092; (d) X.-H. Ouyang, R.-J. Song, Y. Li, B. Liu and J.-H. Li, J. Org. Chem., 2014, 79, 4582; (e) W.-T. Wei, R.-J. Song, X.-H. Ouyang, Y. Li, H.-B. Li and J.-H. Li, Org. Chem. Front., 2014, 1, 484; (f) X.-H. Yang, X.-H. Ouyang, W.-T. Wei, R.-J. Song and J.-H. Li, Adv. Synth. Catal., 2015, 357, 1161; (g) X.-H. Ouyang, R.-J. Song, B. Liu and J.-H. Li, Chem. Commun., 2016, 52, 2573; (h) M. Li, R.-J. Song and J.-H. Li, Chin. J. Chem., 2017, 35, 299.

- 10 R. Leon, A. Jawalekar, T. Redert and M. J. Gaunt, *Chem. Sci.*, 2011, 2, 1487.
- 11 D. Yugandhar, S. Kuriakose, J. B. Nanubolu and A. K. Srivastava, *Org. Lett.*, 2016, **18**, 1040.
- 12 B.-X. Tang, Y.-H. Zhang, R.-J. Song, D.-J. Tang, G.-B. Deng, Z.-Q. Wang, Y.-X. Xie, Y.-Z. Xia and J.-H. Li, *J. Org. Chem.*, 2012, 77, 2837.
- 13 C. R. Reddy, D. H. Kolgave, M. Subbarao, M. Aila and S. K. Prajapti, *Org. Lett.*, 2020, 22, 5342.
- 14 E. Vessally, M. Babazadeh, K. Didehban, A. Hosseinian and L. Edjlali, *Curr. Org. Chem.*, 2018, 22, 286.
- For selective examples:(a) Y.-C. Wang, K.-K. Huang, X. Lai,
 Z. Shi, J.-B. Liu and G. Qiu, Org. Biomol. Chem., 2021, 19,
 1940; (b) S. F. Ren, Y.-C. Wang, J.-B. Liu and G. Qiu, Chin.
 J. Org. Chem., 2021, 41, 3652; (c) Y.-C. Wang, J.-B. Liu,
 G. Qiu, Y. Yang and H. Zhou, Chin. J. Org. Chem., 2021, 41,

- 4798; (*d*) F. Pan, H. Xie, W. Xie, Y.-C. Wang, J.-B. Liu and G. Qiu, *Synthesis*, 2022, **54**, 3105; (*e*) S. Guo, Z. Zhang, Y. Zhu, Z. Wei, X. Zhang and X. Fan, *Org. Chem. Front.*, 2022, **9**, 6598; (*f*) K. Huang, J.-N. Li, G. Qiu, W. Xie and J.-B. Liu, *RSC Adv.*, 2019, **9**, 33460; (*g*) G. Qiu, Z.-F. Chen, W. Xie and H. Zhou, *Eur. J. Org. Chem.*, 2019, **2019**, 4327.
- 16 (a) Y. Zhang, T. Liu, L. Liu, H. Guo, H. Zeng, W. Bi, G. Qiu, W. Gao, X. Ran, L. Yang, G. Du and L. Zhang, J. Org. Chem., 2022, 87, 8515; (b) Y. Zhang, W. Lai, L. Zhang, X. Gao, G. Qiu and H. Zhou, Org. Biomol. Chem., 2021, 19, 1827; (c) X. Wang, H. Zeng, W. Zhang, H. Guo, T. Jin, S. Shi, X. Jin, N. Qu, L. Liu and L. Zhang, Org. Biomol. Chem., 2022, 20, 7949; (d) H. Diao, L. Liu, J. Wang, Y. Lin, X. Zhao, H. Zeng, S. Shi, W. Gao, L. Yang, G. Du and L. Zhang, Eur. J. Org. Chem., 2022, 2022, e202200811.
- 17 (a) F.-L. Zeng, X.-L. Chen, K. Sun, H.-L. Zhu, X.-Y. Yuan,
 Y. Liu, L.-B. Qu, Y.-F. Zhao and B. Yu, Org. Chem. Front.,
 2021, 8, 760; (b) W.-C. Yang, M.-M. Zhang and J.-G. Feng,
 Adv. Synth. Catal., 2020, 362, 4446; (c) C.-H. Ma, L. Zhao,
 X. He, Y.-Q. Jiang and B. Yu, Org. Chem. Front., 2022, 9, 1445.
- 18 (a) L. Ding, K. Niu, Y. Liu and Q. Wang, ChemSusChem, 2022,
 15, e202200367; (b) K. Niu, X. Shi, L. Ding, Y. Liu, H. Song and Q. Wang, ChemSusChem, 2022,
 15, e202102326; (c)
 M. Yang, J. Hua, H. Wang, T. Ma, C. Liu, W. He, N. Zhu, Y. Hu, Z. Fang and K. Guo, J. Org. Chem., 2022,
 87, 8445; (d) T. Liu, Y. Li, L. Jiang, J. Wang, K. Jin, R. Zhang and C. Duan, Org. Biomol. Chem., 2020,
 18, 1933.