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Facile synthesis of benzo[*b*]thiophenes *via* metal-free radical-triggered intramolecular C-S bond formation

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A facile synthesis of benzo[*b*]thiophenes with good to excellent yields *via* metal-free intramolecular C-S bond formation has been developed by utilizing I_2 as the catalyst and O_2 from air as the oxidant (20 Examples). Notable features such as catalytic I_2, intramolecular C-S bond formation, short reaction times, and broad functional group tolerance make this strategy highly attractive. The purification of products only needs to be washed by solvents, thereby avoiding traditional chromatography and recrystallization, which belongs to group-assisted purification (GAP) chemistry.

Introduction

Among diverse heterocycles, benzo[*b*]thiophenes commonly exist in a myriad of bioactive compounds, represented by benocyclidine, zileuton, sertaconazole[1] (Figure 1), which have been found to show a broad range of biological activities such as anti-fungal,[2] anti-tumor,[3] anti-inflammatory.[4] Therefore, these derivatives have attracted special attention in organic and medicinal fields. As a result, many approaches toward benzo[*b*]thiophenes have been developed.[5] However, these reactions still have some inherent limitations such as moisture sensitivity, costly metal catalysts, and environmental toxicity.

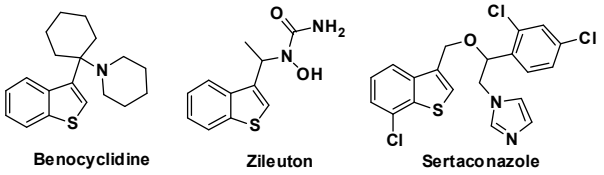
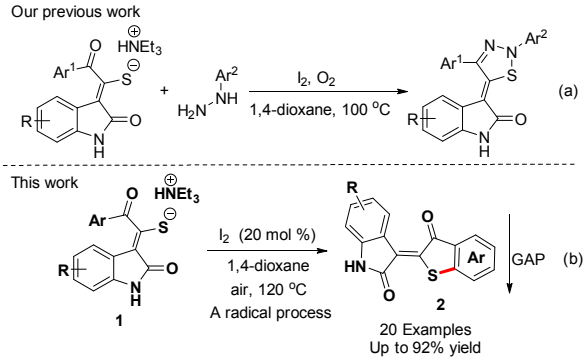


Figure 1. Several representative benzo[*b*]thiophenes

On the other hand, metal-free catalyzed carbon-heteroatom bond formation has drawn considerable interests over the past several decades due to its wide range of practical applications in constructing organic molecules as well as in the pharmaceutical industry and process development.[6] The formation of C-S bonds is one of the most useful and fundamental reactions since it represents a key step in the synthesis of complex molecules.[7] Despite the aforementioned success of C-S coupling reactions, however, metal-free catalyzed intramolecular C-S bond formation still provides a great challenge in modern organic synthesis. Recently, our groups have been heavily involved in the development of C-S forming reaction.[8] For example, we have established an I_2/O_2-enabled intermolecular N-S bond-formation to access functionalized 1,2,3-thiadiazoles *via* a formal [3 + 2] annulation of triethylammonium thiolates with aryl hydrazines under metal-free condition (Scheme 1a).[9] As a continuation of our project, we found that radical-enabled intramolecular C-S bond formation *via* C(sp^2)-H functionalization could be realized, providing a new and straightforward cyclization approach to benzo[*b*]thiophenes (Scheme 1b). Under air conditions the preformed triethylammonium thiolates **1** preferentially reacts with I_2 to form S-I bond, followed by its homolysis to give S-radical, which is trapped by phenyl ring to generate benzo[*b*]thiophenes **2** due to the combination of I_2/O_2 could serve as an efficient radical catalytic system.[10] Notably, the synthesis followed the group-assisted purification (GAP) chemistry/technology, in which pure benzo[*b*]thiophenes **2** could be readily isolated by washing the crude products with common 95% EtOH.



Scheme 1 Metal-free synthesis of benzo[*b*]thiophenes

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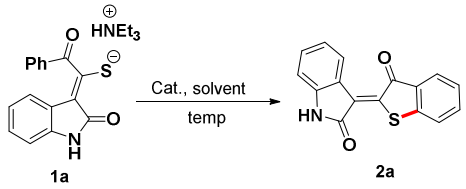
Results and discussion

Initially, we carried out the tentative reaction of triethylammonium thiolate **1a** in MeCN at 100 °C using 20 mol% of I_2 as a catalyst under air conditions. This transformation hardly proceeded, giving a trace amount of the expected product **2a** which failed to be isolated (entry 1). Similar inferior outcomes were observed when both 1,2-dichloroethane (DCE) and ethyl acetate (EA) served as reaction media (entries 2-3) whereas the reaction did not work in EtOH and the starting materials remained completely unconsumed (entry 4). To our delight, exchanging EtOH for tetrahydrofuran (THF) led to an 80% yield of product **2a** (entry 5). The higher yield (83%) was obtained using 1,4-dioxane as a solvent (entry 6). It was found that the reaction temperature affected the reaction efficiency (entries 6-7). The increase of reaction temperature to 120 °C resulted in a higher 91% yield (entry 7). However, the higher reaction temperature (130 °C) was adverse to the improvement of chemical yield of **2a** (entry 8). Afterward, we turned our attention to investigate the loading of I_2-catalyst. Decreasing the loading of I_2 lowered the yield of **2a** (entry 9) whereas the yield leveled off when the loading of I_2 was increased to 30 mol% (entry 10). Without I_2 catalyst, the desired product **2a** was not observed (entry 11), confirming that I_2 is essential for the success of this transformation. The identical performed under O_2 conditions resulted in a flat yield as compared with air conditions (entry 12), suggestion that O_2 from air as a green oxidant could thoroughly oxidize this reaction process to complete the construction of C-S bond.

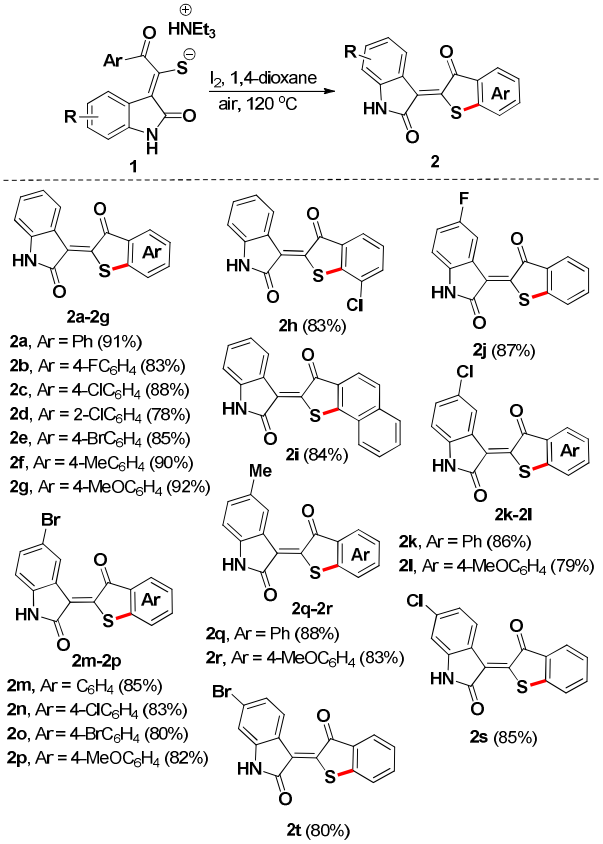
Table 1. Optimization of reaction conditions for forming **2a**[a]



entry	cat. (mol%)	solvent	*t* (°C)	yield (%)[b]
1	I_2 (20)	MeCN	100	trace
2	I_2 (20)	DCE	100	trace
3	I_2 (20)	EA	100	trace
4	I_2 (20)	EtOH	100	ND[c]
5	I_2 (20)	THF	100	80
6	I_2 (20)	1,4-dioxane	100	83
7	I_2 (20)	1,4-dioxane	120	91
8	I_2 (20)	1,4-dioxane	130	80
9	I_2 (10)	1,4-dioxane	120	82
10	I_2 (30)	1,4-dioxane	120	90
11	-	1,4-dioxane	120	ND[c]
12	I_2 (20)	1,4-dioxane	120	91[d]

[a]Reaction conditions: all the reactions were performed with **1a** (1.0 mmol), solvent (2.0 mL) in the sealed reaction tube under microwave conditions for 30 min. [b]Isolated yield. [c]ND (Not Detected). [d]Under O_2 (1.0 atm) conditions.

With the established optimal conditions, we then set out to explore the scope of this transformation by employing a variety of structurally diverse triethylammonium thiolate **1**. The results are summarized in Scheme 2. Firstly, the influence of substituents in the phenyl ring (Ar moiety) of triethylammonium thiolate **1** was investigated. The variants of substituents bearing both electron-donating and electron-withdrawing groups under the optimized conditions did not hamper the reaction process. Substituents resided at different positions on the phenyl ring (Ar), such as Cl, Br, Me, and MeO, were compatible. For instance, more sterically demanding 2-chloro-substituent was well-suited for this present transformation, delivering the corresponding product **2d** in 78% isolated yield. It is worth mentioning that both 3-chlorophenyl and 2-naphthyl counterparts enabled their regioselective C-S coupling to access product **2h** and **2i** in 83% and 84% yields, respectively. After the successful utilization of various substituents in the phenyl ring (Ar moiety), we next extended our investigation to the electronic properties of indolin-2-one moiety (R). Functional groups like fluoride, chloride, bromide and methyl situated in 5- or 6-position of indolin-2-one ring were well tolerated, affording the corresponding benzo[*b*]thiophenes **2j**-**2t** in excellent yields (79%-88%). The structural elucidation of the products was determined from its IR, ^{1}H, ^{13}C NMR, and HRMS spectra. In the case of **2d**, its structure was unequivocally confirmed by X-ray analysis (Figure 2).



Scheme 2 Substrate scope for synthesis of **2.** Reaction conditions: all the reactions were performed with **1** (1.0 mmol), I_2 (0.2 mmol), and 1,4-dioxane (2.0 mL) in the sealed reaction tube at 120 °C under air conditions for 30 min. [b]Isolated yield.

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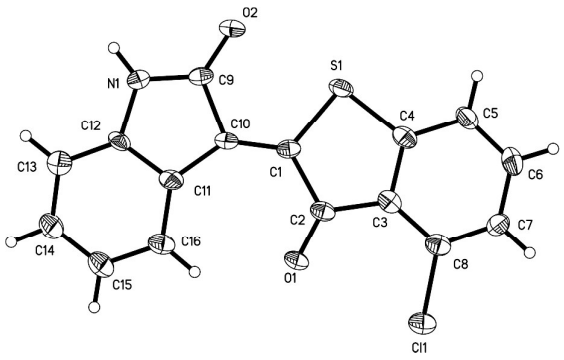
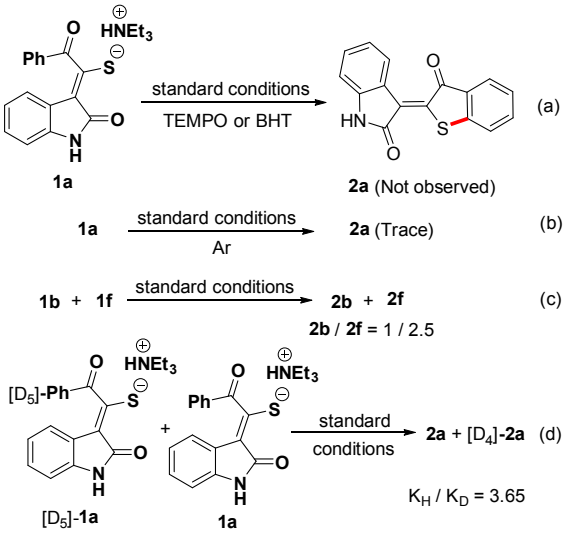


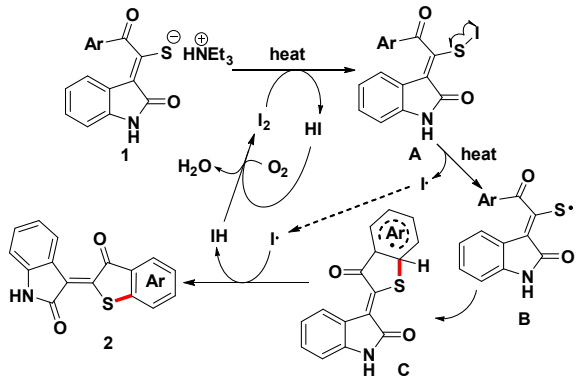
Figure 2. The ORTEP Drawing of **2d**

To understand the mechanism, several control experiments were conducted (Scheme 3). Substrate **1a** was treated with 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) or butylhydroxytoluene (BHT) (2.0 equiv.) under the standard conditions (Scheme 3a), and a complex mixture was detected without observation of **2a**, suggesting a possible radical process. The reaction of **1a** under Ar conditions gave a trace amount of **2a** (Scheme 3b), indicating that O_2 play a key role in the success of this reaction. An intermolecular competitive experiment between **1b** and **1f** revealed that electron-rich group of phenyl ring (Ar) is beneficial to the transformation (Scheme 3c). A significant primary kinetic isotope effect was observed (K_H / K_D = 3.65), showing that the cleavage of C-H bond is a rate-limiting step (Scheme 3d).



Scheme 3 Control Experiments

On the basis of the above analysis and literature survey[9], a reasonable mechanism is outlined in Scheme 4. Substrate **1** undergoes an S-I bond formation to generate intermediate **A**, followed by homolysis of S-I bond to yield radical intermediate **B**. The intramolecular radical coupling/cyclization between S-radical and C(sp^2)-H of Ar attached by carbonyls occurs, allowing a single-electron transfer (SET) process to access the final benzo[*b*]thiophenes **2** *via* deprotonation. I_2 is regenerated by reacting with iodine anion and molecular O_2.



Scheme 4 Proposed mechanisms for forming products **2**

Conclusions

In summary, we have developed a new metal-free intramolecular C-S bond formation that offers a facile synthesis of benzo[*b*]thiophenes. The reaction pathway involved a radical coupling/SET sequence, allowing us to access blocks of benzo[*b*]thiophenes with a wide diversity of substituents. Eco-friendly oxidant, flexible structural modification and broad functional group compatibility as well as mild reaction conditions make this strategy highly viable for future applications. Besides, the purification of products could avoid traditional chromatography and recrystallization, which provide a valuable complement for group-assisted purification (GAP) chemistry.

Experiment

General Information

Melting points were determined in open capillaries and were uncorrected. IR spectra were taken on a FT-IR-Tensor 27 spectrometer in KBr pellets and reported in cm^{-1}. ^1H NMR (^{13}C NMR) spectra were measured on a Bruker DPX 400 MHz spectrometer in DMSO-d_6 or DMF-d_7 with chemical shift (δ) given in ppm relative to TMS as internal standard [(s = singlet, d = doublet, t = triplet, brs = broad singlet, m = multiplet), coupling constant (Hz)]. HRMS (ESI) was determined by using microTOF-Q Ⅱ HRMS/MS instrument (BRUKER). X-Ray crystallographic analysis was performed with a Siemens SMART CCD and a Siemens P4 diffractometer.

General Procedure for the Synthesis of Products 1.

Example for the synthesis of **1a**: Indoline-2,3-dione (10.0 mmol, 1.47 g) and 1-phenyl-2-thiocyanatoethanones (10.0 mmol, 1.77 g) were introduced into a 50-mL reaction flask, ethyl acetate (10.0 ml) and triethylamine (12.0 mmol, 1.22 g) were then successively added into this reaction mixture. The reaction system was stirred at room temperature for

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overnight. After the completion of the reaction (monitored by TLC), triethylamine and ethyl acetate were removed under vacuum. The crude solid was purified by recrystallization from 95% ethanol to afford the pure triethylammonium thiolates **1a**.

General Procedure for the Synthesis of Products 2.

Example for the synthesis of **2a**: In a typical experiment procedure, triethylammonium (*Z*)-2-oxo-1-(2-oxoindolin-3-ylidene)-2-phenylethanethiolate (**1a**, 1.0 mmol, 382 mg), and I_2 (0.2 mmol, 50.8 mg) were introduced into a 10-mL reaction vial. Then 1,4-dioxane (2.0 mL) were successively added, and the mixture stirred at 120 °C under microwave conditions for 30 min. After completion of the reaction (monitored by TLC), the reaction mixture was down to room temperature. The solid product was collected by Büchner filtration to give almost pure product **2a**.

(*Z*)-3-(3-Oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2a)

A red solid; 254 mg; 91% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3160, 1698, 1648, 1617, 1587, 1460, 1450, 1338, 1298; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.12 (s, 1H, NH), 9.00 (d, 1H, *J* = 7.6 Hz, ArH), 7.84 (d, 1H, *J* = 7.6 Hz, ArH), 7.75-7.70 (m, 2H, ArH), 7.42-7.37 (m, 2H, ArH), 7.09-7.05 (m, 1H, ArH), 6.94 (d, 1H, *J* = 7.6 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.5, 169.6, 147.5, 144.1, 138.5, 136.9, 133.2, 129.3, 127.9, 126.9, 126.8, 125.0, 122.3, 121.2, 110.8; HRMS (ESI): m/z calcd for: $C_{16}H_8NO_2S$, 278.0276 $[M-H]^-$; found: 278.0285.

(*Z*)-3-(6-Fluoro-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2b)

A red solid; 247 mg; 83% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3187, 1711, 1662, 1610, 1538, 1495, 1433, 1418, 1401, 1343; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.16 (s, 1H, NH), 9.01 (d, 1H, *J* = 6.8 Hz, ArH), 7.94 (t, 1H, *J* = 5.2 Hz, ArH), 7.74 (d, 1H, *J* = 8.4 Hz, ArH), 7.42 (t, 1H, *J* = 6.8 Hz, ArH), 7.25 (t, 1H, *J* = 6.8 Hz, ArH), 7.09 (t, 1H, *J* = 7.2 Hz, ArH), 6.96 (d, 1H, *J* = 7.6 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6+DMF-d_7) (δ, ppm): 188.7, 169.5, 144.3, 138.2, 133.2, 129.4 ($^4J_{CF}$ = 1.6 Hz), 129.3, 128.0 ($^2J_{CF}$ = 11.3 Hz), 126.2 ($^3J_{CF}$ = 1.7 Hz), 122.2, 121.1, 114.7, 114.5, 114.3 ($^5J_{CF}$ = 1.2 Hz), 111.9 ($^1J_{CF}$ = 25.8 Hz), 110.7;HRMS (ESI): m/z calcd for: $C_{16}H_7FNO_2S$, 296.0182 $[M-H]^-$; found: 296.0190.

(*Z*)-3-(6-Chloro-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2c)

A red-brown solid; 275 mg; 88% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3179, 1702, 1675, 1616, 1590, 1459, 1394, 1340, 1302; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.15 (s, 1H, NH), 9.00 (d, 1H, *J* = 8.0 Hz, ArH), 7.96 (d, 1H, *J* = 1.6 Hz, ArH), 7.85 (d, 1H, *J* = 8.4 Hz, ArH), 7.46-7.40 (m, 2H, ArH), 7.08 (t, 1H, *J* = 8.0 Hz, ArH), 6.95 (d, 1H, *J* = 7.6 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 189.2, 169.5, 149.5, 144.3, 141.7, 138.1, 133.4, 128.4, 128.2, 128.1, 128.0, 127.1, 124.8, 122.4, 121.2, 110.8;

HRMS (ESI): m/z calcd for: $C_{16}H_7ClNO_2S$, 311.9886 $[M-H]^-$; found: 311.9893.

(*Z*)-3-(4-Chloro-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2d)

A red solid; 244 mg; 78% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3191, 1702, 1672, 1611, 1583, 1481, 1459, 1433, 1403, 1334; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.15 (s, 1H, NH), 8.98 (d, 1H, *J* = 8.0 Hz, ArH), 7.72 (d, 1H, *J* = 7.6 Hz, ArH), 7.67 (t, 1H, *J* = 7.6 Hz, ArH), 7.43-7.39 (m, 2H, ArH), 7.09 (t, 1H, *J* = 8.0 Hz, ArH), 6.95 (d, 1H, *J* = 7.6 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 187.9, 169.7, 150.5, 144.2, 138.2, 137.1, 134.3, 133.3, 128.6, 128.0, 127.7, 124.6, 124.0, 122.4, 121.1, 110.8; HRMS (ESI): m/z calcd for: $C_{16}H_7ClNO_2S$, 311.9886 $[M-H]^-$; found: 311.9892.

(*Z*)-3-(6-Bromo-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2e)

A red-brown solid; 303 mg; 85% yield; Mp: 297-298 °C; IR (KBr, ν, cm^{-1}): 3179, 1705, 1675, 1616, 1585, 1458, 1389, 1340, 1301;

^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.16 (s, 1H, NH), 9.00 (d, 1H, *J* = 8.4 Hz, ArH), 8.12 (d, 1H, *J* = 1.2 Hz, ArH), 7.77 (d, 1H, *J* = 8.4 Hz, ArH), 7.61-7.58 (m, 1H, ArH), 7.43 (t, 1H, *J* = 8.0 Hz, ArH), 7.09 (t, 1H, *J* = 8.0 Hz, ArH), 6.96 (d, 1H, *J* = 7.6 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 189.5, 169.6, 149.6, 144.3, 138.1, 133.4, 131.0, 129.9, 128.5, 128.4, 128.2, 128.0, 127.7, 122.4, 121.2, 110.8; HRMS (ESI): m/z calcd for: $C_{16}H_7BrNO_2S$, 355.9381 $[M-H]^-$; found: 355.9374.

(*Z*)-3-(6-Methyl-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2f)

A red solid; 264 mg; 90% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3166, 1703, 1676, 1654, 1618, 1597, 1461, 1399, 1339; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.12 (s, 1H, NH), 9.03 (d, 1H, *J* = 7.6 Hz, ArH), 7.76 (d, 1H, *J* = 7.6 Hz, ArH), 7.57 (s, 1H, ArH), 7.41 (t, 1H, *J* = 7.6 Hz, ArH), 7.23 (d, 1H, *J* = 7.6 Hz, ArH), 7.08 (t, 1H, *J* = 7.6 Hz, ArH), 6.95 (d, 1H, *J* = 7.6 Hz, ArH), 2.43 (s, 3H, CH_3); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 189.9, 169.6, 148.3, 147.8, 144.0, 139.0, 133.0, 127.9(5), 127.8(9), 127.7, 127.2, 126.7, 125.0, 122.2, 121.2, 110.7, 22.2; HRMS (ESI): m/z calcd for: $C_{17}H_{10}NO_2S$, 292.0432 $[M-H]^-$; found: 292.0426.

(*Z*)-3-(6-Methoxy-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2g)

A red solid; 284 mg; 92% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3186, 1702, 1667, 1617, 1593, 1488, 1461, 1414, 1336; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.08 (s, 1H, NH), 9.02 (d, 1H, *J* = 8.0 Hz, ArH), 7.76 (d, 1H, *J* = 8.4 Hz, ArH), 7.40-7.36 (m, 1H, ArH), 7.31 (d, 1H, *J* = 2.4 Hz, ArH), 7.08-7.04 (m, 1H, ArH), 6.94-6.89 (m, 2H, ArH), 3.90 (s, 3H, OCH_3); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 188.3, 169.5, 166.5, 150.6, 143.9, 139.5, 132.7, 128.5, 128.0, 127.1, 122.7, 122.1, 121.2, 114.3, 110.5, 108.7, 56.6; HRMS (ESI): m/z calcd for: $C_{17}H_{10}NO_3S$, 308.0382 $[M-H]^-$; found: 308.0377.

(*Z*)-3-(7-Chloro-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2h)

A red-brown solid; 260 mg; 83% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3231, 1702, 1674, 1617, 1585, 1459, 1413, 1385, 1340;

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^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.23 (s, 1H, NH), 9.01 (d, 1H, *J* = 7.6 Hz, ArH), 7.89-7.86 (m, 2H, ArH), 7.49-7.42 (m, 2H, ArH), 7.11 (t, 1H, *J* = 8.0 Hz, ArH), 6.97 (d, 1H, *J* = 8.0 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 189.7, 169.5, 146.0, 144.5, 137.4, 136.1, 133.7, 131.6, 129.0, 128.9, 128.5, 128.1, 125.5, 122.4, 121.1, 111.0; HRMS (ESI): m/z calcd for: $C_{16}H_7ClNO_2S$, 311.9886 [M-H]$^-$; found: 311.9896.

(*Z*)-3-(3-Oxonaphtho[1,2-*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2i)

A red solid; 276 mg; 84% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3204, 1690, 1667, 1590, 1573, 1513, 1459, 1435, 1358; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.21 (s, 1H, NH), 9.11 (d, 1H, *J* = 8.0 Hz, ArH), 8.13 (d, 2H, *J* = 8.4 Hz, ArH), 7.90 (d, 1H, *J* = 8.8 Hz, ArH), 7.83 (t, 2H, *J* = 6.4 Hz, ArH), 7.76 (t, 1H, *J* = 7.2 Hz, ArH), 7.44 (t, 1H, *J* = 7.6 Hz, ArH), 7.11 (t, 1H, *J* = 8.0 Hz, ArH), 6.97 (d, 1H, *J* = 8.0 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.3, 169.6, 149.8, 144.5, 137.6, 137.0, 133.6, 131.3, 129.7, 128.9, 128.5, 128.3, 128.0, 127.1, 126.6, 124.6, 122.4, 121.5, 121.2, 110.8; HRMS (ESI): m/z calcd for: $C_{20}H_{10}NO_2S$, 328.0432 [M-H]$^-$; found: 328.0443.

(*Z*)-5-Fluoro-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2j)

A red solid; 258 mg; 87% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3170, 1694, 1677, 1648, 1587, 1490, 1469, 1451, 1312, 1284; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.16 (s, 1H, NH), 8.84-8.81 (m, 1H, ArH), 7.89 (d, 1H, *J* = 7.6 Hz, ArH), 7.79-7.74 (m, 2H, ArH), 7.45-7.41 (m, 1H, ArH), 7.31-7.26 (m, 1H, ArH), 6.97-6.94 (m, 1H, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.7, 169.5, 157.8 ($^1J_{CF}$ = 233.0 Hz), 147.3, 140.5, 140.1, 137.1, 129.1, 127.3 ($^6J_{CF}$ = 3.0 Hz), 127.0 ($^5J_{CF}$ = 5.3 Hz), 125.0, 121.7 ($^3J_{CF}$ = 10.2 Hz), 119.5, 119.3, 114.4 ($^2J_{CF}$ = 27.5 Hz), 111.4 ($^4J_{CF}$ = 8.3 Hz); HRMS (ESI): m/z calcd for: $C_{16}H_7FNO_2S$, 296.0182 [M-H]$^-$; found: 296.0188.

(*Z*)-5-Chloro-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2k)

A red solid; 269 mg; 86% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3180, 1694, 1678, 1645, 1616, 1586, 1458, 1450, 1307; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.25 (s, 1H, NH), 9.05 (d, 1H, *J* = 2.0 Hz, ArH), 7.88 (d, 1H, *J* = 7.6 Hz, ArH), 7.62-7.50 (m, 2H, ArH), 7.47-7.40 (m, 2H, ArH), 6.96 (d, 1H, *J* = 8.4 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.7, 169.3, 147.2, 142.7, 140.4, 137.2, 132.3, 129.1, 127.2, 127.0, 126.9(9), 126.6, 126.0, 125.1, 122.4, 112.1; HRMS (ESI): m/z calcd for: $C_{16}H_7ClNO_2S$, 311.9886 [M-H]$^-$; found: 311.9872.

(*Z*)-5-Chloro-3-(6-methoxy-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2l)

A red solid; 271 mg; 79% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3199, 1695, 1671, 1655, 1584, 1476, 1467, 1426, 1385, 1326; ^{1}H NMR (400 MHz, DMF-d_7) (δ, ppm): 11.24 (s, 1H, NH), 9.22 (d, 1H, *J* = 2.0 Hz, ArH), 7.89 (d, 1H, *J* = 8.8 Hz, ArH), 7.52-7.49 (m, 1H, ArH), 7.39 (d, 1H, *J* = 2.4 Hz, ArH), 7.09 (d, 1H, *J* = 8.4 Hz, ArH), 7.03-7.00 (m, 1H, ArH), 4.03 (s, 3H, OCH_3); ^{13}C NMR (100 MHz, DMSO-d_6+DMF-d_7) (δ, ppm): 188.5, 169.3, 167.0, 150.6, 142.7, 141.5, 131.7, 128.6, 127.3, 126.1, 125.9, 122.6, 122.4, 114.3, 111.8, 108.8, 56.4; HRMS (ESI): m/z calcd for: $C_{17}H_9ClNO_3S$, 341.9992 [M-H]$^-$; found: 341.9988.

(*Z*)-5-Bromo-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2m)

A red solid; 303 mg; 85% yield; Mp: 295-296 °C; IR (KBr, ν, cm^{-1}): 3175, 1702, 1676, 1615, 1585, 1451, 1382, 1316, 1284; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.27 (s, 1H, NH), 9.20 (d, 1H, *J* = 2.0 Hz, ArH), 7.89 (d, 1H, *J* = 7.6 Hz, ArH), 7.77-7.74 (m, 2H, ArH), 7.60-7.57 (m, 1H, ArH), 7.45-7.41 (m, 1H, ArH), 6.93 (d, 1H, *J* = 8.4 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.7, 169.2, 147.2, 143.1, 140.4, 137.2, 135.1, 129.9, 129.1, 127.1, 127.0, 126.5, 125.1, 122.9, 113.8, 112.6; HRMS (ESI): m/z calcd for: $C_{16}H_7BrNO_2S$, 355.9381 [M-H]$^-$; found: 355.9374.

(*Z*)-5-Bromo-3-(6-chloro-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2n)

A red solid; 324 mg; 83% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3179, 1702, 1675, 1655, 1615, 1585, 1453, 1402, 1385; ^{1}H NMR (400 MHz, DMF-d_7) (δ, ppm): 11.49 (s, 1H, NH), 9.46 (d, 1H, *J* = 2.0 Hz, ArH), 8.16 (d, 1H, *J* = 1.6 Hz, ArH), 8.12 (d, 1H, *J* = 8.4 Hz, ArH), 7.83-7.81 (m, 1H, ArH), 7.71-7.68 (m, 1H, ArH), 7.22 (d, 1H, *J* = 8.4 Hz, ArH); ^{13}C NMR (100 MHz, DMF-d_7) (δ, ppm): 189.4, 169.2, 149.6, 143.5, 142.2, 140.0, 135.2, 130.2, 128.2, 128.1, 127.2, 127.0, 124.7, 123.0, 113.9, 112.5; HRMS (ESI): m/z calcd for: $C_{16}H_6BrClNO_2S$, 389.8991 [M-H]$^-$; found: 389.8985.

(*Z*)-5-Bromo-3-(6-bromo-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2o)

A red solid; 350 mg; 80% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3171, 1701, 1675, 1615, 1583, 1452, 1388, 1315, 1267; ^{1}H NMR (400 MHz, DMSO-d_6+DMF-d_7) (δ, ppm): 11.37 (s, 1H, NH), 9.28 (d, 1H, *J* = 2.0 Hz, ArH), 8.17 (d, 1H, *J* = 1.6 Hz, ArH), 7.87 (d, 1H, *J* = 8.4 Hz, ArH), 7.70-7.65 (m, 2H, ArH), 7.04 (d, 1H, *J* = 8.4 Hz, ArH); ^{13}C NMR (100 MHz, DMSO-d_6+DMF-d_7) (δ, ppm): 189.7, 169.3, 149.6, 143.5, 140.0, 135.3, 131.3, 130.2, 130.1, 128.5, 128.2, 127.7, 127.1, 123.0, 113.9, 112.6; HRMS (ESI): m/z calcd for: $C_{16}H_6Br_2NO_2S$, 435.8466 [M-H]$^-$; found: 435.8477.

(*Z*)-5-Bromo-3-(6-methoxy-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2p)

A red solid; 317 mg; 82% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3176, 1698, 1673, 1650, 1616, 1594, 1486, 1452, 1402, 1317; ^{1}H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.24 (s, 1H, NH), 9.23 (s, 1H, ArH), 7.82 (d, 1H, *J* = 8.4 Hz, ArH), 7.57 (d, 1H, *J* = 6.8 Hz, ArH), 7.37 (s, 1H, ArH), 6.97-6.91 (m, 2H, ArH), 3.93 (s, 3H, OCH_3); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 188.5, 169.2, 166.8, 150.5, 142.9, 141.5, 134.7, 130.1, 128.9, 125.8, 122.8, 122.6, 114.6, 113.7, 112.5, 109.1, 56.8; HRMS (ESI): m/z calcd for: $C_{17}H_9BrNO_3S$, 385.9487 [M-H]$^-$; found: 385.9479.

(*Z*)-5-Methyl-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2q)

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A red solid; 256 mg; 88% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3179, 1694, 1672, 1619, 1586, 1472, 1451, 1408, 1322; ^1H NMR (400 MHz, DMSO-d_6) (δ, ppm): 11.02 (s, 1H, NH), 8.87 (s, 1H, ArH), 7.86 (d, 1H, *J* = 7.6 Hz, ArH), 7.76-7.73 (m, 2H, ArH), 7.43-7.39 (m, 1H, ArH), 7.23-7.21 (m, 1H, ArH), 6.83 (d, 1H, *J* = 7.6 Hz, ArH), 2.34 (s, 3H, CH_3); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 190.5, 169.6, 147.5, 142.0, 138.2, 136.8, 133.7, 130.9, 129.4, 128.3, 128.2, 126.8, 126.7(6), 125.0, 121.3, 110.5, 21.4; HRMS (ESI): m/z calcd for: $C_{17}H_{10}NO_2S$, 292.0432 $[M-H]^-$; found: 292.0443.

(*Z*)-3-(6-Methoxy-3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)-5-methylindolin-2-one(2r)

A red solid; 268 mg; 83% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3174, 1702, 1675, 1589, 1468, 1397, 1316, 1269; ^1H NMR (400 MHz, DMSO-d_6) (δ, ppm): 10.99 (s, 1H, NH), 8.89 (s, 1H, ArH), 7.79 (d, 1H, *J* = 8.8 Hz, ArH), 7.34 (d, 1H, *J* = 2.0 Hz, ArH), 7.22-7.20 (m, 1H, ArH), 6.95-6.93 (m, 1H, ArH), 6.83 (d, 1H, *J* = 8.0 Hz, ArH), 3.91 (s, 3H, OCH_3), 2.34 (s, 3H, CH_3); ^{13}C NMR (100 MHz, DMSO-d_6) (δ, ppm): 188.5, 169.7, 166.6, 150.7, 141.7, 139.3, 133.3, 130.9, 128.7, 128.4, 127.5, 122.8, 121.3, 114.5, 110.4, 108.8, 56.7, 21.4; HRMS (ESI): m/z calcd for: $C_{18}H_{12}NO_3S$, 322.0538 $[M-H]^-$; found: 322.0543.

(*Z*)-6-Chloro-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2s)

A red solid; 266 mg; 85% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3164, 1707, 1657, 1623, 1588, 1442, 1378, 1310, 1276; ^1H NMR (400 MHz, DMF-d_7) (δ, ppm): 11.45 (s, 1H, NH), 9.27 (d, 1H, *J* = 8.8 Hz, ArH), 8.10 (d, 1H, *J* = 7.6 Hz, ArH), 7.96-7.95 (m, 2H, ArH), 7.65-7.62 (m, 1H, ArH), 7.37-7.35 (m, 1H, ArH), 7.25 (d, 1H, *J* = 2.0 Hz, ArH); ^{13}C NMR (100 MHz, DMF-d_7) (δ, ppm): 190.4, 169.5, 147.4, 145.4, 139.1, 137.0, 136.6, 129.3, 129.0, 126.5, 126.5, 124.6, 121.8, 120.2, 110.5; HRMS (ESI): m/z calcd for: $C_{16}H_7ClNO_2S$, 311.9886 $[M-H]^-$; found: 311.9890.

(*Z*)-6-Bromo-3-(3-oxobenzo[*b*]thiophen-2(3*H*)-ylidene)indolin-2-one (2t)

A red solid; 286 mg; 80% yield; Mp: >300 °C; IR (KBr, ν, cm^{-1}): 3175, 1696, 1667, 1617, 1587, 1572, 1472, 1452, 1356; ^1H NMR (400 MHz, DMF-d_7) (δ, ppm): 11.30 (s, 1H, NH), 9.05 (d, 1H, *J* = 8.4 Hz, ArH), 7.95 (d, 1H, *J* = 7.6 Hz, ArH), 7.82-7.80 (m, 2H, ArH), 7.50-7.46 (m, 1H, ArH), 7.38-7.36 (m, 1H, ArH), 7.25 (d, 1H, *J* = 1.6 Hz, ArH); ^{13}C NMR (100 MHz, DMF-d_7) (δ, ppm): 190.4, 169.3, 147.4, 145.4, 139.3, 136.5, 129.2, 129.1, 126.5(4), 126.5(2), 126.4(7), 125.6, 124.7, 124.5, 120.5, 113.3; HRMS (ESI): m/z calcd for: $C_{16}H_7BrNO_2S$, 355.9381 $[M-H]^-$; found: 355.9376.

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Facile synthesis of benzo[*b*]thiophenes via metal-free radical-triggered intramolecular C-S bond formation

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