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Yi-Wei Liu,[†] Satpal Singh Badsara,[†] Yi-Chen Liu, and Chin-Fa Lee*

Abstract

$K_2S_2O_8/I_2$ promoted C-S coupling reaction of *β*-diketone with disulfide has been described. The resulting α-thio-β-diketones compounds were obtained in good to excellent yields. Both diaryl and dialkyl disulfides are coupled well with a variety of *β*-diketones under under metal-free and solvent-free conditions.

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ARTICLE TYPE

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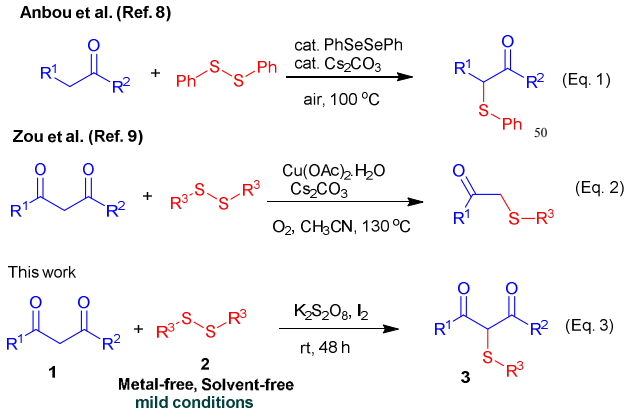
Introduction

Due to their versatile synthetic applications as intermediates in many organic transformations, the preparation of thioaryl carbonyl compounds has recently gained much attention.[1] α-Thio-β-dicarbonyl compounds such as, α-arylthiodialkyl malonates are useful synthons for the syntheses of a number of heterocyclic frameworks like coumarins and α-pyrones etc.[2] Meanwhile, α-thio-β-diketones have also shown to represent interesting examples of strong intramolecular hydrogen bonding.[3]

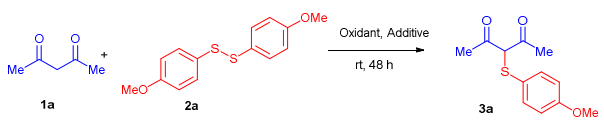
Various synthetic methods have been reported in the literatures for the preparation of thioaryl carbonyl compounds including: (1) the sulfenylation of enolates with various sulfenylating agents such as sulphenyl halides,[4] disulfides,[5] (2) nucleophilic substitution of α-halogenated ketones with sulphur surrogates,[6] (3) *via* transition-metal catalyzed C-S bond formation.[7] A cesium carbonate and diphenyl diselenide promoted direct α-phenylthiolation of carbonyl compounds using diaryl disulfides has been also reported by Nishiyama and co-workers (Eq. 1).[8] Bolm and co-workers[9] have reported an interesting $Cu(OAc)_2$-H_2O catalyzed C-S coupling of *β*-diketones with diaryl disulfide to afford α-thioaryl carbonyl compounds (Eq. 2). Recently, oxidant-promoted C-C, C-heteroatom bond forming reactions emerged as an interesting class of synthetic methodology.[10] As our ongoing research on C-S coupling reactions,[10a-b, 11] we herein report a novel transition metal-free and solvent-free $K_2S_2O_8/I_2$ promoted synthesis of α-thio-β-dicarbonyl compounds *via* the C-S coupling between *β*-diketones and disulfides at room temperature (Eq. 3).



Results and discussion

Accordingly, first we have carried out the oxidative C-S coupling reaction between acetylacetone (**1a**) and bis(4-methoxyphenyl)disulfide (**2a**) under the influence of I_2 at room temperature. Which after 48 h provided the corresponding α-thio-β-diketones compound **3a** in 27% isolated yield (Table 1, entry 1). To our delight, a 88% yield of product was obtained when H_2O_2 was used as an oxidant (Table 1, entry 2). Other oxidants were screened to obtained optimal reaction conditions (Table 1, entries 3-8). $K_2S_2O_8$ is the best of these oxidants, providing product **3a** in 99% isolated yield (Table 1, entry 6). Decreasing the amount of I_2 (Table 1, entry 9), $K_2S_2O_8$ (Table 1, entry 10) and reaction time (Table 1, entry 11) diminished the yield of **3a.** A 96 % yield of **3a** was obtained when NIS was used as additive instead of I_2 (Table 1, entry 12)

Table 1. Optimization of reaction conditions[a]



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Electronic Supplementary Information (ESI) available: For 1H and 13C spectra of componunds **3** and **4** See DOI: 10.1039/b000000x//

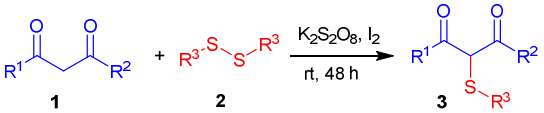
Entry	Oxidant (equiv)	Additive	Yield (%)[b]
1	-	I_2	27
2	H_2O_2 (5)	I_2	88
3	DTBP (5)	I_2	53
4	TBHP (5)	I_2	58
5	BPO (5)	I_2	24
6	$K_2S_2O_8$ (5)	I_2	99
7	AcOOH (5)	I_2	36
8	TBPB (5)	I_2	84
9[c]	$K_2S_2O_8$ (5)	I_2	49
10[d]	$K_2S_2O_8$ (5)	I_2	73
11	$K_2S_2O_8$ (4)	I_2	58
12	$K_2S_2O_8$ (5)	NIS	96

[a] Reaction conditions: 2,4-Pentanedione **1a** (1.0 mL), bis(4-methoxyphenyl)disulfide **2a** (0.5 mmol), $K_2S_2O_8$ (5.0 eq.), I_2 (0.3 mmol), at room temperature for 48 h. [b] Isolated yield. [c] I_2 (0.2 mmol). [d] 36 h (TBHP = *tert*-butyl hydroperoxide, BPO = benzoyl peroxide, AcOOH = peracetic acid, DTBP = di-*tert*-butyl peroxide)

To generalize and expand the scope of this methodology, we have carried out this $K_2S_2O_8/I_2$ promoted oxidative C-S coupling reaction between variety of dicarbonyl compound **1a-1d** and diaryl disulfides **2a-2g** under optimized reaction conditions which provided the resulting α-thio-β-diketones compounds **3b-3u** in good to excellent yields (Table 2). This system shows good functional group tolerance, functional groups including fluoro (Table 2, entries 3, 10 and 16), choloro (Table 2, entries 4, 11 and 17), bromo (Table 2, entries 5, 12 and 18), trifluoromethyl (Table 2, entries 2, 9 and 15) are all tolerated under the reaction conditions employed. Disulfides containing both the electron donating (Table 2, entry 7) and electron withdrawing group (Table 2, entries 2, 9 and 15) coupled well with dicarbonyl compounds, providing the products in good to excellent yields.

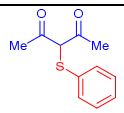
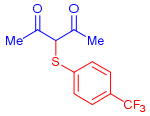
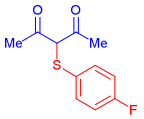
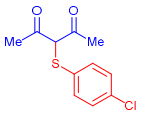
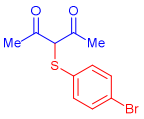
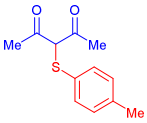
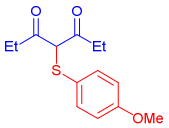
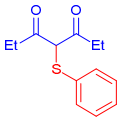
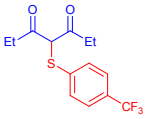
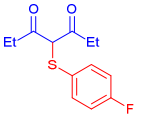
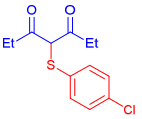
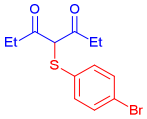
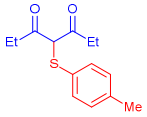
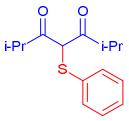
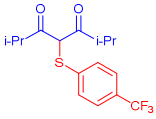
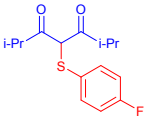
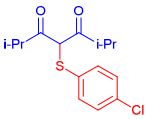
Dialkyl disulfides could also be used as the coupling partners for the oxidative C-S coupling reaction as shown in Table 2 (entries 21-24). Dialkyl disulfides **4a** & **4b** underwent oxidative C-S coupling reaction with dicarbonyl compound **1a-1c** under the influence of $K_2S_2O_8/I_2$ at 70 °C, provided the products **3v-3y** in 51-92 % yields.

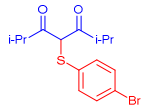
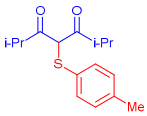
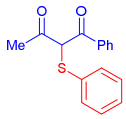
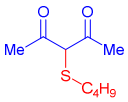
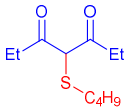
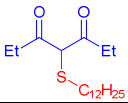
Table 2. Reactions of various 1,3-diketones **1** with disulfides **2**



1 **2** **3**

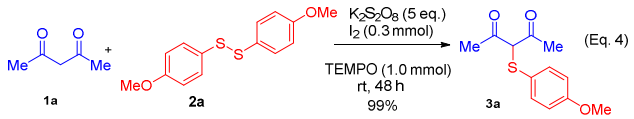
$R^1 = R^2$ = Me (**1a**); $R^1 = R^2$ = Et (**1b**)
$R^1 = R^2$ = *i*-Pr (**1c**); R^1 = Me, R^2 = Ph (**1d**)

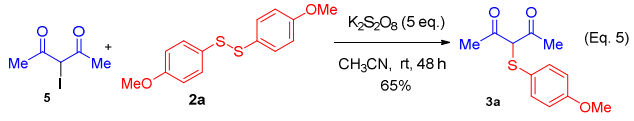
Entry	**1**	R^3	Product		Yield (%)[b]
1	**1a**	Ph (**2b**)		**3b**	72
2	**1a**	4-CF_3Ph (**2c**)		**3c**	64
3	**1a**	4-FPh (**2d**)		**3d**	76
4	**1a**	4-ClPh (**2e**)		**3e**	95
5	**1a**	4-BrPh (**2f**)		**3f**	91
6	**1a**	4-MePh (**2g**)		**3g**	58
7	**1b**	**2a**		**3h**	95
8	**1b**	**2b**		**3i**	89
9	**1b**	**2c**		**3j**	83
10	**1b**	**2d**		**3k**	85
11	**1b**	**2e**		**3l**	94
12	**1b**	**2f**		**3m**	83
13	**1b**	**2g**		**3n**	90
14	**1c**	**2b**		**3o**	90
15	**1c**	**2c**		**3p**	86
16	**1c**	**2d**		**3q**	84
17	**1c**	**2e**		**3r**	67

18	**1c**	**2f**		**3s**	83
19	**1c**	**2g**		**3t**	93
20	**1d**	**2b**		**3u**	0[c]
21	**1a**	*n*-C_4H_9 **(2h)**		**3v**	71
22	**1a**	*n*-$C_{12}H_{25}$ **(2i)**		**3w**	92
23	**1b**	**2h**		**3x**	51
24	**1b**	**2i**		**3y**	71

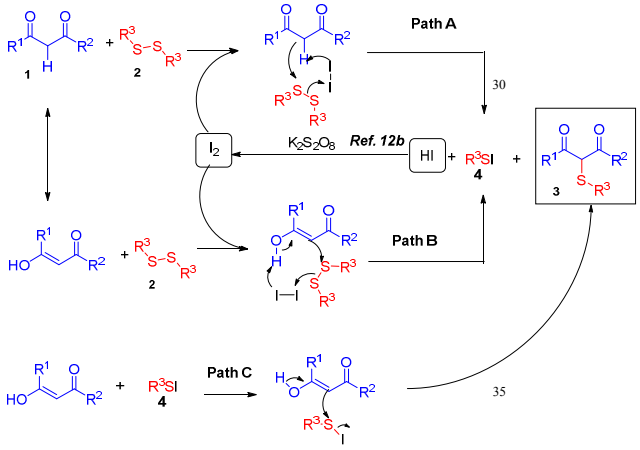
[a] Reaction conditions: various 1,3-diketones (1.0 mL), disulfides (0.5 mmol), $K_2S_2O_8$ (5.0 eq.), I_2 (0.3 mmol), at room temperature for 48 h. [b] Isolated yield. [c] 1,3-diketones (5.0 mmol) and CH_3CN (1.5 mL) was used as solvent.

To check the possibility of radical mechanism, we have carried out the reaction of **1a** with **2a** under optimized conditions using $K_2S_2O_8$-I_2 in presence of TEMPO and found that there was no effect on the product formation, hence the radical mechanism is ruled out (Eq 4). Next, we have treated 3-iodopentane-2,4-dione (**5**) with disulphide **2a** using oxidant $K_2S_2O_8$ under optimized conditions, provided the desired product **3a** in 65% yield (Eq. 5).[12a] Based on these experiments, we proposed plausible mechanism for this transformation as shown in Scheme 1. Initially, in presence of I_2, disulfide **2** can attack on dicarbonyl compounds **1** to provide the desired product **3** along with the formation of HI and R^3SI (**4**) as shown in Path A. Alternatively, the enol form of dicarbonyl compounds **1** can also undergo a similar kind of reaction to generate product **3** along with HI and R^3SI (**4**) (Path B). It is known that in presence of oxidant HI can reoxidize into molecular iodine.[12b] Since the R^3SI (**4**) is very reactive species, the enol form of dicarbonyl compounds **1** can react with **4** to provide the desired product **3** according to path C.





Scheme 1. Plausible mechanism.



Conclusions

In conclusion, we have developed an interesting transition metal free $K_2S_2O_8/I_2$ promoted syntheses of α-thio-β-dicarbonyl compounds *via* the oxidative C-S coupling reaction between *β*-diketones **1** and disulfide **2** at room temperature under solvent free conditions. The resulting α-thio-β-diketones compounds **3** were obtained in good to excellent yields. The system shows good functional group tolerance as the functional groups such as fluoro, choloro, bromo, trifluoromethyl and methoxy are all tolerated by the reaction conditions employed.

Experimental

General information

All chemicals were purchased from commercial suppliers and used without further purification. Flash chromatography was performed on Merck silica gel 60 (230-400 mesh). NMR spectra were recorded on a Varian Unity Inova-600 or a Varian Mercury-400 instrument using $CDCl_3$ as solvent. Chemical shifts are reported in parts per million (ppm) and referenced to the residual solvent resonance. Coupling constant (J) are reported in hertz (Hz). Standard abbreviations indicating multiplicity were used as follows: s = singlet, d = doublet, t = triplet, dd = double of doublet, q = quartet, m = multiplet, b = broad. Melting points (m.p.) were determined using a Büchi 535 apparatus and are reported uncorrected. GC-MS analyses were performed on a GC-MS analysis on HP 5890 GC equipped with HP 5972 MS. High-resolution mass spectra were carried out on a Jeol JMS-HX 110 spectrometer by the services at the National Chung Hsing University.

General procedure and representative example for Table 1: 3-((4-methoxyphenyl)thio) pentane-2,4-dione (entry 6, 3a):[1d]

A sealed vial equipped with a magnetic stir bar was charged with pentane-2,4-dione **1a** (1.0 mL), 1,2-bis(4-methoxyphenyl)disulfane **2a** (0.5 mmol, 139 mg), oxidant (5.0 equiv.) and additive (0.3 mmol) and then the reaction mixture was stirred for 48 h at room temperature. The resulting solution was directly filtered through a pad of silica gel then washed with ethyl acetate (3 x 10 mL) and concentrated to give the crude material which was then purified by flash silica gel column chromatography (eluent: hexane) to afford the desired product **3a** as a yellow solid (236

mg, 99% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.35 (s, 6 H), 3.77 (s, 3 H), 6.83 (d, J = 8.8 Hz, 2 H), 7.04 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.4, 55.3, 103.0, 114.9, 126.8, 128.3, 157.9, 198.0.

General procedure for Table 2.

A sealed vial equipped with a magnetic stir bar was charged with 1,3-diketone **1** (1.0 mL), disulfide **2** (0.5 mmol), $K_2S_2O_8$ (5.0 mmol) and I_2 (0.3 mmol) and then the reaction mixture was stirred for 48 h at room temperature. The resulting solution was then directly filtered through a pad of silica gel then washed with ethyl acetate (3x 10 mL) and concentrated to give the crude material which was then purified by column chromatography (SiO_2, hexane) to yield **3**.

3-(Phenylthio) pentane-2,4-dione 3b (Table 2, entry 1):[1d] The tittle compound was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), diphenyl disulfide (0.109 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3b** as a yellow liquid (150 mg, 72% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.33 (s, 6 H), 7.08-7.14 (m, 3 H), 7.27 (t, J = 7.6 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.3, 101.5, 124.6, 125.2, 129.0, 129.2, 134.8, 137.7, 198.3.

3-{(4-(Trifluoromethyl)phenyl)thio}pentane-2,4-dione 3c (Table 2, entry 2): The tittle compound was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), 1,2-bis(4-(trifluoromethyl)phenyl)disulfane (0.1772 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3c** as a yellow liquid (177 mg, 64% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.32 (s, 6 H), 7.19 (d, J = 8.0 Hz, 2 H), 7.52 (d, J = 8.0 Hz, 2 H); ^{13}C NMR (150 MHz, $CDCl_3$): δ 24.2 (d, J = 12.9 Hz), 100.3 (d, J = 2.0 Hz), 124.1 (q, J = 270.2 Hz), 124.3, 126.0 (q, J = 3.8 Hz), 127.4 (q, J = 32.6 Hz), 142.9, 198.4; ^{19}F NMR (376 MHz, $CDCl_3$): δ -63.9 (s); HRMS-EI calcd. for $C_{12}H_{11}F_3O_2S$: 276.0432, found: 276.0434.

3-{(4-Fluorophenyl)thio}pentane-2,4-dione 3d (Table 2, entry 3): The tittle compound was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), 1,2-bis(4-fluorophenyl)disulfane (0.0942 mL, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3d** as a yellow liquid (172 mg, 76% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.34 (s, 6 H), 6.97-7.02 (m, 2 H), 7.05-7.08 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.3, 102.1, 116.2 (d, J = 21.9 Hz), 126.5 (d, J = 8.1 Hz), 132.7 (d, J = 3.6 Hz), 159.8, 162.2, 198.1; ^{19}F NMR (376 MHz, $CDCl_3$): δ -119.0 (s); HRMS-EI calcd. for $C_{11}H_{11}FO_2S$: 226.0464, found: 226.0456.

3-{(4-Chlorophenyl)thio}pentane-2,4-dione 3e (Table 2, entry 4): The tittle compound was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), 1,2-bis(4-chlorophenyl)disulfane (0.160 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3e** as a white solid (230 mg, 95% yield). M.P. = 68-69 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.33 (s, 6H), 7.02 (d, J = 8.8 Hz, 2 H), 7.25 (d, J = 8.8 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.2, 101.2, 125.8, 129.2, 131.0, 136.3, 198.2; HRMS-EI calcd. for $C_{11}H_{11}ClO_2S$: 242.0168, found: 242.0160.

3-{(4-bromophenyl)thio}pentane-2,4-dione 3f (Table 2, entry 5): The tittle compounds was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), 1,2-bis(4-bromophenyl)disulfane (0.1881 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3f** as a white solid (261 mg, 91% yield). M.P. = 70-71 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.33 (s, 6 H), 6.96 (d, J = 8.4 Hz, 2 H), 7.40 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.2, 101.0, 118.7, 126.1, 132.1, 136.9, 198.1; HRMS-EI calcd. for $C_{11}H_{11}BrO_2S$: 285.9663, found: 285.9659.

3-(*p*-Tolylthio)pentane-2,4-dione 3g (Table 2, entry 6): The tittle compounds was prepared following the general procedure for Table 2 using pentane-2,4-dione (1.0 mL), 1,2-di-*p*-tolyldisulfane (0.123 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3g** as a yellow liquid (129 mg, 58% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.31 (s, 3 H), 2.34 (s, 6 H), 6.99 (d, J = 8.4 Hz, 2 H), 7.10 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.8, 24.3, 102.0, 124.8, 129.9, 134.1, 135.0, 198.1; HRMS-EI calcd. for $C_{12}H_{14}O_2S$: 222.0715, found: 222.0719.

4-{(4-Methoxyphenyl)thio}heptane-3,5-dione 3h (Table 2, entry 7): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), 1,2-bis(4-methoxyphenyl)disulfane (0.1435 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3h** as a colorless liquid (253 mg, 95% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.10 (t, J = 7.4 Hz, 6 H), 2.74 (q, J = 7.3 Hz, 4 H), 3.77 (s, 3 H), 6.83 (d, J = 6.8 Hz, 2 H), 7.02 (d, J = 6.6 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.5, 29.9, 55.3, 101.4, 114.9, 126.5, 128.9, 157.8, 201.0; HRMS-EI calcd. for $C_{14}H_{18}O_3S$: 266.0977, found: 266.0973.

4-(Phenylthio)heptane-3,5-dione 3i (Table 2, entry 8): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), diphenyl disulfide (0.109 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3i** as a yellow liquid (210 mg, 89% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.09 (t, J = 7.3 Hz, 6 H), 2.60-2.90 (m, 4 H), 7.02-7.13 (m, 3 H), 7.26 (t, J = 7.6 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.4, 29.8, 99.9, 124.4, 125.0, 129.0, 138.2, 201.2; HRMS-EI calcd. for $C_{13}H_{16}O_2S$: 236.0871, found: 236.0875.

4-{(4-(Trifluoromethyl)phenyl)thio}heptane-3,5-dione 3j (Table 2, entry 9): The tittle compounds was prepared following the general procedure for Table 2, heptane-3,5-dione (1.0 mL), 1,2-bis(4-(trifluoromethyl)phenyl)disulfane (0.1772 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3j** as a yellow liquid (252 mg, 83% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.12 (t, J = 7.2 Hz, 6 H), 2.40-3.10 (m, 4 H), 7.20 (d, J = 8.4 Hz, 2 H), 7.52 (d, J = 8.0 Hz, 2 H);^{13}C NMR (150 MHz, $CDCl_3$): δ 9.4, 29.9, 98.8, 124.1 (q, J = 270.1 Hz), 124.2, 126.0 (q, J = 3.8 Hz), 127.2 (q, J = 38.9 Hz), 143.5, 201.4; ^{19}F NMR (376 MHz, $CDCl_3$): δ -63.9 (s); HRMS-EI calcd. for $C_{14}H_{15}F_3O_2S$: 304.0745, found: 304.0741.

4-{(4-Fluorophenyl)thio}heptane-3,5-dione 3k (Table 2, entry 10): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), 1,2-bis(4-fluorophenyl)disulfane (0.0942 mL, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3k** as a yellow liquid (216 mg, 85% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.10 (t, J = 7.2 Hz, 6 H), 2.50-2.90 (m, 4 H), 6.96-7.07 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.4, 29.8, 100.5, 116.2 (d, J = 21.9 Hz), 126.2 (d, J = 7.3 Hz), 133.2, 159.7, 162.1, 201.1; ^{19}F NMR (376 MHz, $CDCl_3$): δ -119.2 (s); HRMS-EI calcd. for $C_{13}H_{15}FO_2S$: 254.0777, found: 254.0770.

4-{(4-Chlorophenyl)thio}heptane-3,5-dione 3l (Table 2, entry 11): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), 1,2-bis(4-chlorophenyl)disulfane (0.160 g, 0.5 mmol, 1.0 equiv), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3l** as a yellow liquid (254mg, 94% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ1.09 (t, J = 7.4 Hz, 6 H), 2.60-2.90 (m, 4 H), 7.01 (d, J = 8.8 Hz, 2 H), 7.23 (d, J = 8.8 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ9.4, 29.8, 99.6, 125.6, 129.1, 130.8, 136.8, 201.1; HRMS-EI calcd. for $C_{13}H_{15}ClO_2S$: 270.0481, found: 270.0485.

4-{(4-bromophenyl)thio}heptane-3,5-dione 3m (Table 2, entry 12): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), 1,2-bis(4-bromophenyl)disulfane (0.1881 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3m** as a yellow liquid (284 mg, 83% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.09 (t, J = 7.1 Hz, 6 H), 2.60-2.90 (m, 4 H), 6.95 (d, J = 8.2 Hz, 2 H), 7.37 (d, J = 8.0 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.4, 29.8, 99.5, 118.5, 125.9, 132.0, 137.5, 201.1; HRMS-EI calcd. for $C_{13}H_{15}BrO_2S$: 313.9976, found: 313.9968.

4-(*p*-Tolylthio)heptane-3,5-dione 3n (Table 2, entry 13): The tittle compounds was prepared following the general procedure for Table 2 using heptane-3,5-dione (1.0 mL), 1,2-di-*p*-tolyldisulfane (0.123 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3n** as a yellow liquid (225 mg, 90% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.09 (t, J = 7.4 Hz, 6 H), 2.28 (s, 3 H), 2.60-2.90 (m, 4 H), 6.97 (d, J = 8.0 Hz, 2 H), 7.07 (d, J = 8.0 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.4, 20.7, 29.8, 100.4, 124.6, 129.8, 134.6, 134.7, 201.1; HRMS-EI calcd. for $C_{14}H_{18}O_2S$: 250.1028, found: 250.1019.

2,6-Dimethyl-4-(phenylthio)heptane-3,5-dione 3o (Table 2, entry 14): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), diphenyl disulfide (0.109 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3o** as a white liquid (238 mg, 90% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.93 (d, J = 6.8 Hz, 12 H), 3.41-3.51 (m, 2 H), 7.06-7.14 (m, 3 H), 7.25-7.29 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.4, 33.7, 98.1, 124.3, 124.9, 129.0, 139.0, 205.5; HRMS-EI calcd. for $C_{15}H_{20}O_2S$: 264.1184, found: 264.1189.

2,6-Dimethyl-4-{(4-(trifluoromethyl)phenyl)thio}heptane-3,5-dione 3p (Table 2, entry 15): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), 1,2-bis(4-(trifluoromethyl)phenyl)disulfane (0.1772 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3p** as a yellow solid (286 mg, 86% yield). M.P. = 41-42 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.93-1.27 (m, 12 H), 3.35-3.45 (m, 2 H), 7.19 (d, J = 8.4 Hz, 2 H), 7.52 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (150 MHz, $CDCl_3$): δ 19.4 (d, J = 178.1 Hz), 33.8 (d, J = 17.6 Hz), 96.9, 124.1 (q, J = 270.1 Hz), 124.1, 125.9 (q, J = 3.7 Hz), 127.2 (q, J = 32.5 Hz), 144.3, 205.7; ^{19}F NMR (376 MHz, $CDCl_3$): δ -63.8 (s); HRMS-EI calcd. for $C_{16}H_{19}F_3O_2S$: 332.1058, found: 332.1060.

4-{(4-Fluorophenyl)thio}-2,6-dimethylheptane-3,5-dione 3q (Table 2, entry 16): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), 1,2-bis(4-fluorophenyl)disulfane (0.0942 mL, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3q** as a yellow solid (237 mg, 84% yield). M.P. = 48-49 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.08 (d, J = 6.4 Hz, 6 H), 1.14 (d, J = 6.8 Hz, 6 H), 3.42-3.52 (m, 2 H), 6.95-7.07 (m, 5 H);^{13}C NMR (100 MHz, $CDCl_3$): δ 19.4, 33.8, 98.6, 116.1 (d, J = 21.9 Hz), 126.0 (d, J = 7.3 Hz), 134.1, 159.7, 162.1, 205.5; ^{19}F NMR (376 MHz, $CDCl_3$): δ -119.4 (s); HRMS-EI calcd. for $C_{15}H_{19}FO_2S$: 282.1090, found: 282.1085.

4-{(4-Chlorophenyl)thio}-2,6-dimethylheptane-3,5-dione 3r (Table 2, entry 17): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), 1,2-bis(4-chlorophenyl)disulfane (0.160 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3r** as a yellow solid (200 mg, 67% yield). M.P. = 41-42 ^{o}C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.80-1.40 (m, 12 H), 3.37-3.47 (m, 2 H), 7.01 (d, J = 8.4 Hz, 2 H), 7.24 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.5, 33.8, 97.8, 125.5, 129.1, 130.8, 137.7, 205.5; HRMS-EI calcd. for $C_{15}H_{19}ClO_2S$: 298.0794, found: 298.0797.

4-{(4-Bromophenyl)thio}-2,6-dimethylheptane-3,5-dione 3s (Table 2, entry 18): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), 1,2-bis(4-bromophenyl)disulfane (0.1881 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3s** as a yellow liquid (285 mg, 83% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.80-1.35 (m, 12 H), 3.35-3.46 (m, 2 H), 6.94 (d, J = 8.8 Hz, 2 H), 7.38 (d, J = 9.0 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.5, 33.8, 97.7, 118.5, 125.9, 132.0, 138.4, 205.6; HRMS-EI calcd. for $C_{15}H_{19}BrO_2S$: 342.0289, found: 342.0284.

2,6-Dimethyl-4-(*p*-tolylthio)heptane-3,5-dione 3t (Table 2, entry 19): The tittle compounds was prepared following the general procedure for Table 2 using 2,6-dimethylheptane-3,5-dione (1.0 mL), 1,2-di-*p*-tolyldisulfane (0.123 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3t** as a yellow liquid (259 mg, 93% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07 (d, J = 6.4 Hz, 12 H), 2.28 (s, 3 H), 3.42-3.52 (m, 2 H), 6.96 (d, J = 8.4 Hz, 2 H), 7.07 (d, J = 8.4 Hz, 2 H);^{13}C NMR

(100 MHz, $CDCl_3$): δ 19.5, 20.7, 33.7, 98.4, 124.4, 129.8, 134.6, 135.4, 205.4; HRMS-EI calcd. for $C_{16}H_{22}O_2S$: 278.1341, found: 278.1349.

1-Phenyl-2-(phenylthio)butane-1,3-dione 3u (Table 2, entry 20): A sealed vial equipped with a magnetic stir bar was charged with 1-phenylbutane-1,3-dione (0.743 g, 5.0 mmol), diphenyl disulfide (0.109 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol) and CH_3CN (1.5 mL). After being stirred for 48 hours at room temperature, the resulting solution was directly filtered through a pad of silica gel then washed with ethyl acetate (3 x10 mL) and concentrated to give the crude material which was then purified by flash silica gel column chromatography (eluent: hexane) to afford the desired product **3u** as a yellow solid. (216 mg, 80% yield). M.P. = 57-58 ºC; ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.42 (s, 3 H), 7.11-7.15 (m, 3 H), 7.24-7.34 (m, 4 H), 7.40-7.44 (m, 1 H), 7.63 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.7, 100.7, 124.8, 125.2, 127.7, 128.4, 129.2, 131.1, 135.6, 138.6, 190.6, 203.3; HRMS-EI calcd. for $C_{16}H_{14}O_2S$: 270.0715, found: 270.0713.

General procedure for Compounds 3v-3y.
A sealed vial equipped with a magnetic stir bar was charged with 1,3-diketone (1.0 mL), dialkyl disulfide (0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol). The reaction mixture was then stirred for 48 hours at 70 ºC. The resulting solution was directly filtered through a pad of silica gel then washed with ethyl acetate (3x 10 mL) and concentrated to give the crude material which was then purified by column chromatography (SiO_2, hexane) to yield **3**.

3-(Butylthio)pentane-2,4-dione 3v (Table 2, entry 21): The tittle compounds was prepared following the general procedure for compounds **3v-3y** using pentane-2,4-dione (1.0 mL), 1,2-dibutyldisulfane (0.098 mL, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **3v** as a colorless liquid (133 mg, 71% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (t, J = 7.3 Hz, 3 H), 1.37-1.46 (m, 2 H), 1.49-1.57 (m, 2 H), 2.44 (s, 6 H), 2.50 (t, J = 7.0 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.7, 22.0, 24.5, 31.2, 36.5, 104.7, 197.4; HRMS-EI calcd. for $C_9H_{16}O_2S$: 188.0871, found: 188.0870.

3-(Dodecylthio)pentane-2,4-dione 3w (Table 2, entry 22): The tittle compounds was prepared following the general procedure for compounds **3v-3y** using pentane-2,4-dione (1.0 mL), 1,2-didodecyldisulfane (0.2014 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **5b** as a yellow liquid (276 mg, 92% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, J = 7.2 Hz, 3 H), 1.26-1.38 (m, 18 H), 1.50-1.57 (m, 2 H), 2.43 (s, 6 H), 2.48 (t, J = 7.6 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1, 22.7, 24.5, 28.9, 29.2, 29.3, 29.3, 29.5, 29.6, 29.6, 31.9, 36.9, 104.7, 197.4; HRMS-EI calcd. for $C_{17}H_{32}O_2S$: 300.2123, found: 300.2124.

4-(Butylthio)heptane-3,5-dione 3x (Table 2, entry 23): The tittle compounds was prepared following the general procedure for compounds **3v-3y** heptane-3,5-dione (1.0 mL), 1,2-dibutyldisulfane (0.098 mL, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **5c** as a yellow liquid (110 mg, 51% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (t, J = 7.2 Hz, 3 H), 1.16 (t, J = 7.4 Hz, 6 H), 1.36-1.45 (m, 2 H), 1.49-1.56 (m, 2 H), 2.49 (t, J = 7.4 Hz, 2 H), 2.85 (q, J = 7.2 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.7, 13.6, 22.0, 29.9, 31.2, 37.0, 103.4, 200.4; HRMS-EI calcd. for $C_{11}H_{20}O_2S$: 216.1184, found: 216.1180.

4-(Dodecylthio)heptane-3,5-dione 3y (Table 2, entry 24): The tittle compounds was prepared following the general procedure for compounds **3v-3y** heptane-3,5-dione (1.0 mL), 1,2-didodecyldisulfane (0.2014 g, 0.5 mmol), $K_2S_2O_8$ (1.3653 g, 5.0 mmol) and I_2 (76 mg, 0.3 mmol), then purified by column chromatography (SiO_2, hexane) to provide **5d** as a yellow liquid (233 mg, 71% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.87 (t, J = 6.8 Hz, 3 H), 1.15 (t, J = 7.6 Hz, 6 H), 1.26-1.38 (m, 18 H), 1.49-1.57 (m, 2 H), 2.47 (t, J = 7.6 Hz, 2 H), 2.85 (q, J = 7.6 Hz, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.6, 14.0, 22.6, 28.9, 29.1, 29.2, 29.3, 29.4, 29.5, 29.6, 29.9, 31.8, 33.7, 37.3, 103.4, 200.3; HRMS-EI calcd. for $C_{19}H_{36}O_2S$: 328.2436, found: 328.2437.

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