JOC The Journal of Organic Chemistry

Phenyliodine(III) Bis(trifluoroacetate) (PIFA)-Mediated Synthesis of Aryl Sulfides in Water

Qingyuan Feng, Dengfeng Chen, Mei Hong, Fei Wang, and Shenlin Huang

J. Org. Chem., **Just Accepted Manuscript** • DOI: 10.1021/acs.joc.8b00435 • Publication Date (Web): 17 Apr 2018

Just Accepted

ACS Publications

is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

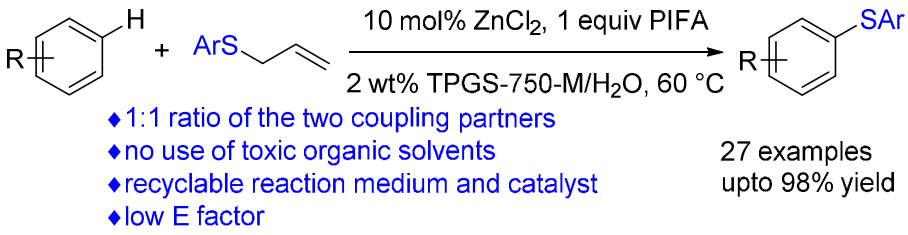
Phenyliodine(III) Bis(trifluoroacetate) (PIFA)-Mediated Synthesis of Aryl Sulfides in Water

Qingyuan Feng,[†] Dengfeng Chen,[†] Mei Hong,[†] Fei Wang,[†,‡] Shenlin Huang*[,†,‡]

[†]Jiangsu Provincial Key Lab for the Chemistry and Utilization of Agro-Forest Biomass, College of Chemical Engineering, Nanjing Forestry University, Nanjing, 210037, P. R. China

[‡]Jiangsu Key Lab of Biomass-Based Green Fuels and Chemicals, Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing Forestry University, Nanjing, 210037, P. R. China

Supporting Information Placeholder

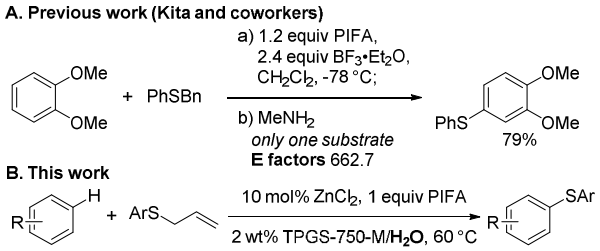


ABSTRACT: An environmentally benign method for the synthesis of aryl sulfides in water under mild conditions has been realized, in which arenes are coupled with equal stoichiometry of allyl sulfides. This arylthiolation is enabled by the presence of the Lipshutz surfactant, TPGS-750-M, using water as the recyclable reaction medium.

Aryl sulfides are key constituents of pharmaceuticals,[1] ligands,[2] and organic materials[3] and are useful intermediates[4] in modern organic chemistry. Accordingly, a wide variety of approaches to aryl sulfides have been developed. One of the most common methods involves the transition metal-catalyzed coupling of aryl halides or pseudohalides with thiols or other sulfur based partners,[5] which typically require prefunctionalized arenes (e.g. aryl halides). The direct C–H arythiolation of arenes mediated by transition metals[6] offers improved reaction efficiency; however, these reactions often require expensive and sometimes toxic transition metals, raising issues of metal contamination especially in the pharmaceutical industry. More recently, direct C–H arylthiolation for the synthesis of aryl sulfides under metal-free conditions[7] has emerged. Various electrophilic sulfur reagents and precursors including thiols,[8] disulfides,[9] sulfonyl chlorides,[10] sulfonyl hydrazines,[11] N-(thio)succinicmides,[12] sodium sulfonates,[13] and others[14] have been employed. While these represent powerful transformations, the vast majority of current synthetic approaches suffer from limitations

including: the use of bad odor, air-sensitive thiol substrates, strongly basic media, inert atmosphere, excess oxidants, high reaction temperature, and toxic organic solvents. Therefore, the development of new sustainable protocols for the synthesis of aryl sulfides in green solvents, such as water,[15] under mild conditions is still highly desirable for sustainable organic synthesis.

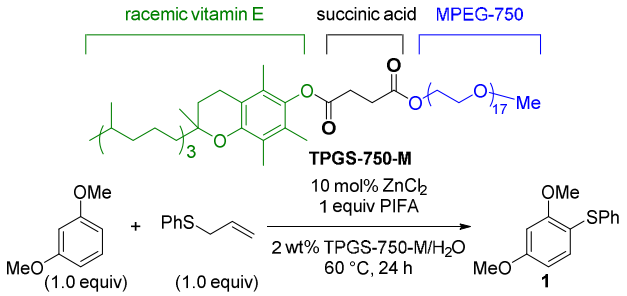
Scheme 1. PIFA-Mediated Direct C–H arylthiolation



The arylthiolation of arenes with benzyl phenyl sulfide in the presence of phenyliodine(III) bis(trifluoroacetate) (PIFA) was first reported by Kita et al.[16] in 1996 and involved a one-pot two-step procedure at -78 °C (Scheme 1A). Given PIFA, which belongs to one of the most important classes of hypervalent iodine(III) reagents,[17] is easy accessible and low toxic, this transformation is potentially useful. However, only one substrate, *o*-dimethoxybenzene was reported using halogenated solvent CH_2Cl_2, which is environmentally egregious.[18] In addition, the E Factor[19] from Kita's procedure is very high. As our continuing efforts exploring organosulfur chemistry in water,[20] we report herein an environmentally benign method for the synthesis of aryl sulfides via C–H functionalization of electron-rich arenes in water (Scheme 1B). This new method offers some advantages, including a benign reaction solvent, a 1:1 ratio of the two coupling partners, catalytic use of $ZnCl_2$ under micellar conditions,[21] and recyclable reaction medium and catalyst.

Our optimization studies focused on the reaction between *m*-dimethoxybenzene and commercially available allyl phenyl sulfide (Table 1). To our delight, the desired arylthiolation product **1** was obtained in 70% yield after a 24 h reaction that employed 10 mol% $ZnCl_2$ as the catalyst, 1 equiv PIFA as the oxidant, and 2 wt% TPGS-750-M/H_2O as the solvent (Table 1, entry 1). In order to shed light on the role of each reagent, several control experiments were subsequently conducted. Reaction efficiency was dramatically affected upon removing $ZnCl_2$ from the reaction (Table 1, entry 2), which suggested that the reactivity of PIFA might be further enhanced by Lewis acid $ZnCl_2$.[22] Attempts to replace $ZnCl_2$ with other Lewis acids, such as LiCl and BF_3•Et_2O, resulted in a much lower yield (Table 1, entries 3 and 4). Inferior reaction performance was also observed when a variety of alternative solvents such as toluene, THF, MeCN, CH_2Cl_2, toluene/water, CH_2Cl_2/water, or pure water were used (Table 1, entries 5–11). This confirmed that TPGS-750-M, developed by Lipshutz,[23] might be playing a significant role in the micellar catalysis.

Table 1. Optimization of the Reaction Conditions

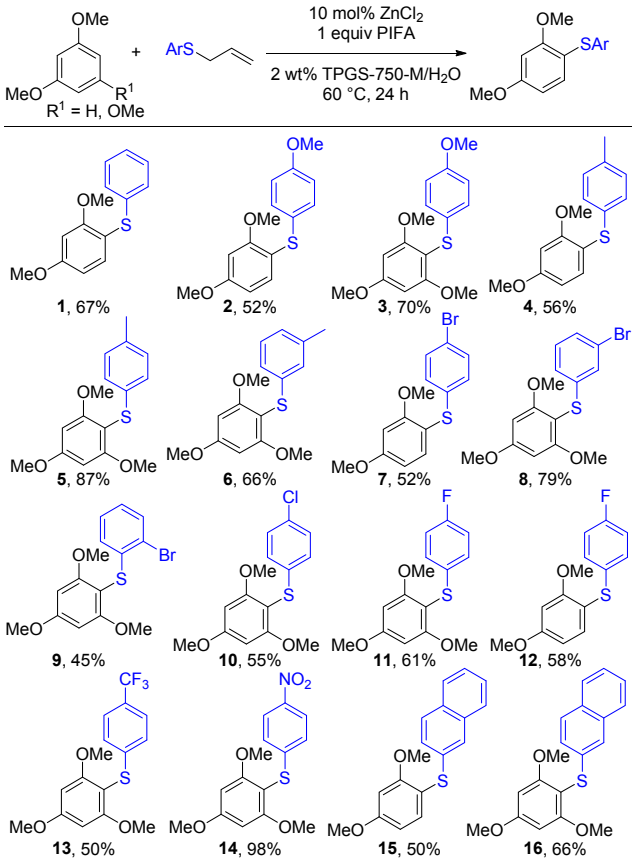


entry	variation from the standard condition	yield[b]
1	none	70
2	without $ZnCl_2$	42
3	LiCl instead of $ZnCl_2$	46
4	BF_3•Et_2O instead of $ZnCl_2$	37
5	in toluene	32
6	in THF	8
7	in MeCN	27
8	in CH_2Cl_2	24
9	in toluene/water	50
10	in CH_2Cl_2/water	56
11	in H_2O	61

[a]Conditions: *m*-dimethoxybenzene (0.24 mmol), allyl phenyl sulfide (0.24 mmol), $ZnCl_2$ (0.024 mmol), PIFA (0.24 mmol), solvent (0.6 M) at 60 °C for 24 h. [b]Yields were determined by HPLC analysis with 1-nitro naphthalene as an internal standard.

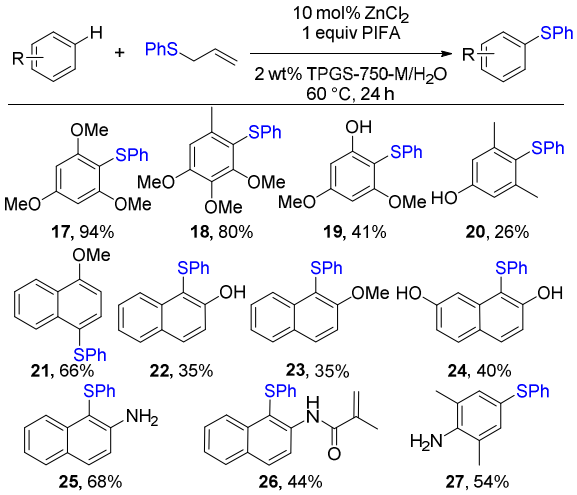
Using the standard conditions described in Table 1, we next explored the scope of this transformation. With respect to ally sulfides, diverse ally aryl sulfides served as effective cross-coupling partners with *m*-dimethoxybenzene or 1,3,5-trimethoxybenzene (Scheme 2). Product **1** was isolated in 67% yield. Arylthiolation products were obtained in moderate to excellent yields (45%–98%) with allyl sulfides containing electron-donating (**2**–**6**) and electron-withdrawing (**7**–**14**) functional groups. It is worth highlighting that versatile bromo, chloro, and fluoro substituents were well tolerated, which could be potentially further functionalized. While electronic effects had no significant influence on the process (**3**, **5**, and **14**), steric effects resulted in noticeable differences in reactivity (**5** *vs* **6**, and **8** *vs* **9**). Naphthyl-substituted substrates were also competent in the reaction conditions, delivering desired sulfides (**15** and **16**) in good yields.

Scheme 2. Scope of ally sulfides



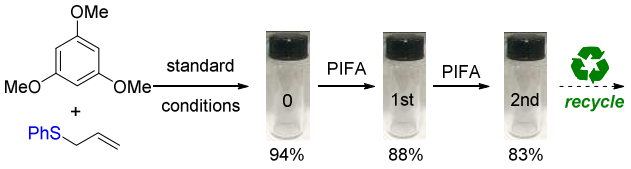
We next evaluated the scope with regards to the arene coupling partner (Scheme 3). Various electron-rich arenes were successfully coupled to allyl phenyl sulfide. Alkoxybenzenes proceeded well under the standard conditions, giving the corresponding products in high yields (**17** and **18**). Phenols also underwent smooth C–H arylthiolation, albeit in lower yields (**19** and **20**). In addition, extended aromatics were successfully applied (**21**–**26**). Finally, this coupling reaction is compatible with free hydroxyl (**19**, **20**, **22** and **24**), amine (**25** and **27**), and amide (**26**) groups. With respect to limitatioins, this method is unsuccessful with arenes like simple phenol, anisole, and toluene, or arenes with electron-withdrawing groups.

Scheme 3. Scope of arenes



To further demonstrate the sustainability of this micelle-enabled coupling, we performed recycling of the aqueous medium containing the surfactant TPGS-750-M and $ZnCl_2$ catalyst (Scheme 4). Once an arylthiolation was complete, the reaction solution was extracted with a minimum volume of ethyl acetate, providing the desired coupling product. To the remaining aqueous mixture, was then introduced 1,3,5-trimethoxybenzene (1 equiv), allyl phenyl sulfide (1 equiv), and PIFA (1 equiv), leading to another arylthiolation. As shown in scheme 4, the arylthiolation proceeded efficiently without significant loss of yields and with a low E factor for each recycle. The E factor can be reduced dramatically compared to Kita's reaction conditions (Scheme 1a).

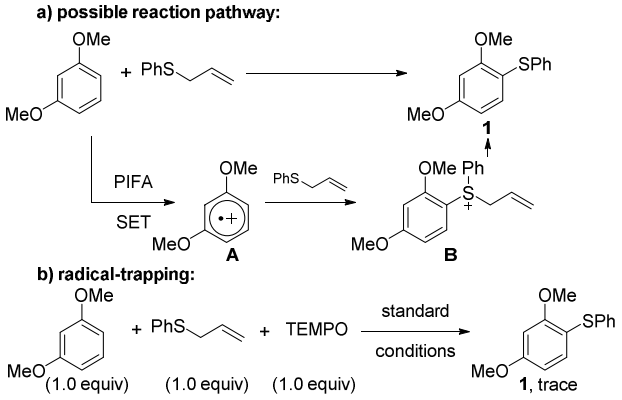
Scheme 4. Recycle Studies



Based on	E Factor reaction	1 st recycle	2nd recycle
Yield(%)	94%	88%	83%
Total organic solvent	6.5	6.9	7.3
Aqueous waste included	12.9	6.9	7.3

Lastly, a hypothetical mechanism for the arylthiolation is outlined in Scheme 5a. We propose that the first step is the formation of radical cation intermediate **A**, via a single electron transfer (SET) process.[8d] Subsequent nucleophilic attack of radical cation **B** by the sulfide would give rise to the sulfonium salt **B**. Following deallylation[7b] would liberate the desired aryl sulfide product **1**. Importantly, it has been shown that PIFA is an excellent SET oxidant.[17, 24] Moreover, the addition of radical scavenger TEMPO prevented formation of sulfide **1**, suggesting that radical intermediates might be involved in the transformation.

Scheme 5. Proposed Reaction mechanism



In summary, we have demonstrated an environmentally benign method for the synthesis of diaryl sulfides under micellar conditions. The C–H arylthiolation process was enabled by the presence of the Lipshutz surfactant, TPGS-750-M. Most notably, this reaction proceeded in an aqueous reaction medium that avoids organic solvent and allows for the recycling of the water, surfactant, and the catalyst.

ASSOCIATED CONTENT

EXPERIMENTAL SECTION

General Experimental.

General Information: All glassware was oven dried and all solvents were distilled prior to use, unless otherwise noted. Unless otherwise noted, all reactions were performed under an atmosphere of argon. Optimization and substrate screens were performed in 2-mL and 4-mL vials. All reagents were used as received from commercial suppliers unless otherwise indicated. TPGS-750-M was prepared according to the literature.[23d] The 2 wt% TPGS-750-M/H_2O solution was prepared by dissolving TPGS-750-M in water. Allyl phenyl sulfide were prepared according to the procedures reported in the literature[25]. Thin-layer chromatography (TLC) was carried out on Merck silica gel plates (60F-254) and compounds were visualized using UV light absorbance and/or Vanillin reagent, and High Performance Liquid Chromatography (HPLC) with UV detection at 254 nm. For HPLC yields, UV response factors relative to an internal standard (1-Nitronaphthalene). Flash column chromatography was performed using silica gel 60 (230-400 mesh). High resolution mass spectra were acquired by Agilent 6500 QTOFMS (ESI). All ^{1}H NMR, ^{13}C NMR spectra were recorded on Bruker DRX-600 or AMX-400 instruments. Chemical shifts were given in parts per million (ppm, δ), referenced to the solvent peak of $CDCl_3$, defined at δ = 7.26 (^{1}H NMR), defined at δ = 77.16 (^{13}C NMR). Coupling constants were quoted in Hz (J). ^{1}H NMR Spectroscopy splitting patterns were designated as singlet (s), doublet (d), triplet (t), quartet (q). Splitting patterns that could not be interpreted or easily visualized were designated as multiplet (m) or broad (br).

General Procedure for the Preparation of aryl sulfides: An oven-dried 4 mL vial was charged with $ZnCl_2$ (0.024 mmol, 10 mol%), arene (0.24 mmol, 1 eq), 2 wt% TPGS-750-M/H_2O (0.4 mL, 0.6 M) and allyl sulfide (0.24 mmol, 1 eq) sequentially. The

mixture was stirred for about 1 min until a homogeneous solution appeared. PIFA (0.24 mmol, 1 eq) was added and the solution was heated at 60 °C for 24 hours. After the completion monitored by TLC, the reaction was cooled to RT and extracted by EtOAc (3×0.4 mL), the organic phases was dried over anhydrous Na_2SO_4 and concentrated in vacuo. The crude was purified by flash column chromatography (petroleum ether /EtOAc = 50/1 to petroleum ether /EtOAc = 20/1) to afford desired aryl sulfides.

(2,4-Dimethoxyphenyl)(phenyl)sulfane (1).[26] The product was obtained as a colorless oil (39.5 mg, 0.161 mmol, 67% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.34 (d, *J* = 8.4 Hz, 1H), 7.22 (m, 2H), 7.12 (m, 3H), 6.53 (d, *J* = 2.5 Hz, 1H), 6.50 (dd, *J* = 8.4, 2.5 Hz, 1H), 3.84 (s, 3H), 3.81 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 162.0, 160.5, 137.9, 136.9, 128.9, 127.9, 125.6, 112.3, 105.5, 99.4, 56.1, 55.6.

(2,4-Dimethoxyphenyl)(4-methoxyphenyl)sulfane (2).[9d] The product was obtained as a colorless oil (34.5 mg, 0.125 mmol, 52% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29 – 7.24 (m, 2H), 7.07 (d, *J* = 8.5 Hz, 1H), 6.86 – 6.80 (m, 2H), 6.48 (d, *J* = 2.5 Hz, 1H), 6.42 (dd, *J* = 8.5, 2.5 Hz, 1H), 3.84 (s, 3H), 3.79 (s, 3H), 3.79 (s, 3H).

(4-Methoxyphenyl)(2,4,6-trimethoxyphenyl)sulfane (3).[7c] The product was obtained as a white solid (51.4 mg, 0.168 mmol, 70% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09 – 7.04 (m, 2H), 6.76 – 6.71 (m, 2H), 6.19 (s, 2H), 3.85 (s, 3H), 3.81 (s, 6H), 3.74 (s, 3H).

(2,4-Dimethoxyphenyl)(p-tolyl)sulfane (4).[9d] The product was obtained as a colorless oil (35.0 mg, 0.134 mmol, 56% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.24 (d, *J* = 8.4 Hz, 1H), 7.12 – 7.08 (m, 2H), 7.05 (d, *J* = 8.4 Hz, 2H), 6.51 (d, *J* = 2.5 Hz, 1H), 6.47 (dd, *J* = 8.4, 2.5 Hz, 1H), 3.821 (s, 3H), 3.818 (s, 3H) 2.30 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.5, 159.9, 135.9, 135.6, 133.5, 129.8, 129.2, 113.8, 105.4, 99.4, 56.1, 55.6, 21.1

p-Tolyl(2,4,6-trimethoxyphenyl)sulfane (5).[26] The product was obtained as a white solid (60.6mg, 0.209 mmol, 87% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.99 – 6.93 (m, 4H), 6.21 (s, 2H), 3.87 (s, 3H), 3.81 (s, 6H), 2.25 (s, 3H).

m-Tolyl(2,4,6-trimethoxyphenyl)sulfane (6). The product was obtained as a white solid (46.0 mg, 0.158 mmol, 66% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ7.03 (t, *J* = 7.7 Hz, 1H), 6.88 (s, 1H), 6.84 (d, *J* = 7.5 Hz, 1H), 6.77 (d, *J* = 7.9 Hz, 1H), 6.22 (s, 2H), 3.88 (s, 3H), 3.81 (s, 6H), 2.24 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.0, 162.7, 138.6, 138.3, 128.5, 126.5, 125.5, 122.8, 91.4, 56.5, 55.6, 21.5. HRMS-ESI (*m/z*) $[M+H]^+$ calculated for $C_{16}H_{19}O_3S$ 291.1049, found 291.1056. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{16}H_{18}KO_3S$ 329.0608, found 329.0609.

(4-Bromophenyl)(2,4-dimethoxyphenyl)sulfane (7).[27] The product was obtained as a colorless oil (40.4 mg, 0.125 mmol, 52% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (dd, *J* = 8.1, 0.5 Hz, 1H), 7.34 – 7.28 (m, 2H), 6.99 – 6.94 (m, 2H), 6.55 – 6.48 (m, 2H), 3.84 (s, 3H), 3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.4, 160.7, 137.6, 137.4, 131.8, 129.0, 119.0, 111.4, 105.6, 99.6, 56.1, 55.7.

(3-Bromophenyl)(2,4,6-trimethoxyphenyl)sulfane (8). The product was obtained as a white solid (67.3 mg, 0.190 mmol, 79% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.15 (ddd, *J* = 7.7, 1.8, 1.2 Hz, 1H), 7.09 (t, *J* = 1.7 Hz, 1H), 7.01 (t, *J* = 7.8 Hz, 1H), 6.98 –

6.93 (m, 1H), 6.22 (s, 2H), 3.88 (s, 3H), 3.81 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 162.6, 159.6, 156.7, 141.5, 129.9, 128.1, 127.5, 124.3, 122.8, 91.8, 91.5, 56.4, 55.7, 55.6. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{15}H_{15}BrKO_3S$ 392.9557, found 392.9570.

(2-Bromophenyl)(2,4,6-trimethoxyphenyl)sulfane (9).[26] The product was obtained as a white solid (38.2 mg, 0.108 mmol, 45% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (dd, *J* = 7.9, 1.3 Hz, 1H), 7.06 – 6.99 (m, 1H), 6.92 – 6.85 (m, 1H), 6.51 (dd, *J* = 8.0, 1.5 Hz, 1H), 6.23 (s, 2H), 3.88 (s, 3H), 3.80 (s, 6H).

(4-Chlorophenyl)(2,4,6-trimethoxyphenyl)sulfane (10).[26] The product was obtained as a white solid (40.9 mg, 0.132 mmol, 55% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13 – 7.09 (m, 2H), 6.97 – 6.92 (m, 2H), 6.21 (s, 2H), 3.87 (s, 3H), 3.81 (s, 6H).

(4-Fluorophenyl)(2,4,6-trimethoxyphenyl)sulfane (11).[26] The product was obtained as a white solid (43.1 mg, 0.146 mmol, 61% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.06 – 6.99 (m, 2H), 6.89 – 6.83 (m, 2H), 6.20 (s, 2H), 3.86 (s, 3H), 3.81 (s, 6H).

(2,4-Dimethoxyphenyl)(4-fluorophenyl)sulfane (12). The product was obtained as a colorless oil (36.8 mg, 0.139 mmol, 58% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27 (d, *J* = 8.6 Hz, 1H), 7.19 – 7.13 (m, 2H), 6.98 – 6.90 (m, 2H), 6.53 – 6.46 (m, 2H), 3.82 (s, 3H), 3.81 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 161.9, 161.6 (d, *J* = 245.3 Hz), 160.1, 135.96, 132.5 (d, *J* = 3.1 Hz), 130.7 (d, *J* = 7.9 Hz), 116.0 (d, *J* = 22.0 Hz), 113.4, 105.6, 99.5, 56.1, 55.6. HRMS-ESI (*m/z*) $[M+H]^+$ calculated for $C_{14}H_{14}FO_2S$ 265.0693, found 265.0681.

(4-(Trifluoromethyl)phenyl)(2,4,6-trimethoxyphenyl)sulfane (13). The product was obtained as a colorless oil (41.3 mg, 0.120 mmol, 50% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.38 (d, *J* = 8.3 Hz, 1H), 7.06 (d, *J* = 8.3 Hz, 1H), 6.23 (s, 1H), 3.89 (s, 3H), 3.81 (s, 6H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 163.6, 162.7, 144.4, 126.4 (q, *J* = 32.4 Hz), 125.4 (q, *J* = 7.5 Hz), 125.2, 124.6 (q, *J* = 271.5 Hz), 91.8, 91.4, 56.4, 55.6. HRMS-ESI (*m/z*) $[M+H]^+$ calculated for $C_{16}H_{16}F_3O_3S$ 345.0767, found 345.0769. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{16}H_{15}F_3KO_3S$ 383.0326, found 383.0323.

(4-Nitrophenyl)(2,4,6-trimethoxyphenyl)sulfane (14).[26] The product was obtained as a yellow solid (75.5 mg, 0.235 mmol, 98% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 (d, *J* = 8.9 Hz, 2H), 7.05 (d, *J* = 8.9 Hz, 2H), 6.24 (s, 2H), 3.90 (s, 3H), 3.81 (s, 6H).

(2,4-Dimethoxyphenyl)(naphthalen-2-yl)sulfane (15). The product was obtained as a colorless oil (35.5 mg, 0.120 mmol, 50% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ7.76 (d, *J* = 7.9 Hz, 1H), 7.69 (d, *J* = 8.6 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.55 (d, *J* = 1.1 Hz, 1H), 7.45 – 7.36 (m, 3H), 7.28 (dd, *J* = 8.6, 1.8 Hz, 1H), 6.56 (d, *J* = 2.5 Hz, 1H), 6.52 (dd, *J* = 8.5, 2.5 Hz, 1H), 3.85 (s, 3H), 3.81 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ162.0, 160.5, 136.8, 135.4, 134.0, 131.8, 128.4, 127.8, 127.2, 126.5, 126.5, 125.9, 125.5, 112.4, 105.6, 99.5, 56.1, 55.7. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{18}H_{16}KO_2S$ 335.0503, found 335.0500.

Naphthalen-2-yl(2,4,6-trimethoxyphenyl)sulfane (16).[26] The product was obtained as a white solid (51.7 mg, 0.158 mmol, 66% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, *J* = 7.8 Hz, 1H), 7.62 (dd, *J* = 13.8, 8.4 Hz, 2H), 7.42 – 7.30 (m, 3H), 7.21 (dd, *J* = 8.6, 1.9 Hz, 1H), 6.25 (s, 2H), 3.90 (s, 3H), 3.81 (s, 6H).

Phenyl(2,4,6-trimethoxyphenyl)sulfane (17).[26] The product was obtained as a white solid (62.3 mg, 0.226 mmol, 94% yield). ^{1}H NMR (600 MHz, $CDCl_3$): δ 7.15 (m, 2H), 7.03 (m, 3H), 6.22 (s, 2H), 3.87 (s, 3H), 3.81 (s, 6H).

Phenyl(2,3,4-trimethoxy-6-methylphenyl)sulfane (18). The product was obtained as a white solid (55.7 mg, 0.192 mmol, 80% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.18 (t, *J* = 7.8 Hz, 2H), 7.06 (t, *J* = 7.4 Hz, 1H), 7.00 (d, *J* = 7.4 Hz, 2H), 6.67 (s, 1H), 3.90 (s, 3H), 3.87 (s, 3H), 3.78 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 156.0, 154.6, 141.1, 139.8, 139.0, 128.9, 126.0, 124.8, 116.8, 109.6, 61.6, 61.1, 56.1, 21.5. HRMS-ESI (*m/z*) $[M+H]^+$ calculated for $C_{16}H_{19}O_3S$ 291.1049, found 291.1054. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{16}H_{18}KO_3S$ 329.0608, found 329.0618.

3,5-Dimethoxy-2-(phenylthio)phenol (19).[28] The product was obtained as a colorless oil (25.8 mg, 0.098 mmol, 41% yield). ^{1}H NMR (600 MHz, $CDCl_3$): δ 7.21 (t, *J* = 7.7 Hz, 2H), 7.12 (t, *J* = 7.3 Hz, 1H), 7.06 (d, *J* = 7.4 Hz, 2H), 6.92 (s, 1H), 6.30 (d, *J* = 2.6 Hz, 1H), 6.14 (d, *J* = 2.5 Hz, 1H), 3.83 (s, 3H), 3.79 (s, 3H).

3,5-Dimethyl-4-(phenylthio)phenol (20).[13b] The product was obtained as an orange oil (14.4 mg, 0.062 mmol, 26% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.17 (t, *J* = 7.7 Hz, 2H), 7.05 (t, *J* = 7.3 Hz, 1H), 6.91 (d, *J* = 7.5 Hz, 2H), 6.69 (s, 2H), 2.38 (s, 6H).

(4-Methoxynaphthalen-1-yl)(phenyl)sulfane (21).[24b] The product was obtained as a white solid (42.1 mg, 0.158 mmol, 66% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.35 – 8.30 (m, 2H), 7.80 (d, *J* = 8.0 Hz, 1H), 7.55 – 7.47 (m, 2H), 7.15 (t, *J* = 7.7 Hz, 2H), 7.08 – 7.01 (m, 3H), 6.84 (d, *J* = 8.0 Hz, 1H), 4.05 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 157.3, 139.2, 135.9, 135.4, 129.0, 127.8, 126.8, 126.8, 126.1, 125.9, 125.2, 122.7, 120.3, 104.2, 55.8.

1-(Phenylthio)naphthalen-2-ol (22).[13b] The product was obtained as a white solid (21.2 mg, 0.084 mmol, 35% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.24 (d, *J* = 8.4 Hz, 1H), 7.92 (d, *J* = 8.9 Hz, 1H), 7.83 (d, *J* = 8.0 Hz, 1H), 7.53 – 7.48 (m, 1H), 7.41 – 7.37 (m, 1H), 7.36 (d, *J* = 8.9 Hz, 1H), 7.22 – 7.16 (m, 3H), 7.11 (m, 1H), 7.07 – 7.02 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.1, 135.6, 135.5, 133.0, 129.6, 129.3, 128.7, 128.1, 126.5, 126.0, 124.8, 124.0, 117.0, 108.2.

(2-Methoxynaphthalen-1-yl)(phenyl)sulfane (23).[13b] The product was obtained as a colorless oil (22.4 mg, 0.084 mmol, 35% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.46 (d, *J* = 8.6 Hz, 1H), 7.98 (d, *J* = 9.1 Hz, 1H), 7.83 (d, *J* = 8.1 Hz, 1H), 7.50 (t, *J* = 7.6 Hz, 1H), 7.39 (t, *J* = 8.3 Hz, 2H), 7.13 (t, *J* = 7.6 Hz, 2H), 7.07 – 6.97 (m, 3H), 3.97 (s, 3H).

1-(Phenylthio)naphthalene-2,7-diol (24).[13b] The product was obtained as a white solid (25.7 mg, 0.096 mmol, 40% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.82 (d, *J* = 8.8 Hz, 1H), 7.72 (d, *J* = 8.8 Hz, 1H), 7.52 (d, *J* = 2.5 Hz, 1H), 7.21 – 7.09 (m, 6H), 7.01 (dd, *J* = 7.3, 1.8 Hz, 2H), 6.97 (dd, *J* = 8.7, 2.5 Hz, 1H).

1-(Phenylthio)naphthalen-2-amine (25).[11b] The product was obtained as a brown solid (41.0 mg, 0.163 mmol, 68% yield). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.28 (d, *J* = 8.5 Hz, 1H), 7.77 (d, *J* = 8.8 Hz, 1H), 7.73 (d, *J* = 8.0 Hz, 1H), 7.44 (t, *J* = 7.7 Hz, 1H), 7.30 – 7.26 (m, 1H), 7.16 (t, *J* = 7.7 Hz, 2H), 7.09 – 7.05 (m, 2H), 7.03 (d, *J* = 8.4 Hz, 2H), 4.73 (br, 2H).

N-(1-(phenylthio) naphthalen-2-yl)methacrylamide (26). The product was obtained as a brown oil (33.7 mg, 0.106 mmol, 44% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.33 (s, 1H), 8.85 (d, *J* = 9.0 Hz, 1H), 8.44 (d, *J* = 8.5 Hz, 1H), 8.01 (d, *J* = 9.1 Hz, 1H), 7.86

(d, J = 8.1 Hz, 1H), 7.52 (t, J = 7.7 Hz, 1H), 7.45 (t, J = 7.4 Hz, 1H), 7.18 (t, J = 7.4 Hz, 2H), 7.11 (t, J = 7.3 Hz, 1H), 7.00 (d, J = 7.8 Hz, 2H), 5.75 (s, 1H), 5.43 (s, 1H), 2.01 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.4, 140.8, 140.6, 135.5, 135.5, 131.8, 131.3, 129.5, 128.6, 128.0, 126.4, 126.1, 125.9, 125.3, 121.1, 119.7, 113.8, 18.6. HRMS-ESI (*m/z*) $[M+H]^+$ calculated for $C_{20}H_{18}NOS$ 320.1104, found 320.1101. HRMS-ESI (*m/z*) $[M+K]^+$ calculated for $C_{20}H_{17}KNOS$ 358.0662, found 358.0664.

2,6-Dimethyl-4-(phenylthio)aniline (27).[29] The product was obtained as a brown oil (29.7 mg, 0.130 mmol, 54% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.20 (t, J = 7.6 Hz, 2H), 7.16 – 7.07 (m, 5H), 3.74 (s, 2H), 2.17 (s, 6H).

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Further experimental details and copies of ^{1}H and ^{13}C NMR Spectra (PDF)

AUTHOR INFORMATION

Corresponding Author

*E-mail: shuang@njfu.edu.cn.

ACKNOWLEDGMENT

Financial support provided by the Natural Science Foundation of China (21502094), the Natural Science Key Project of the Jiangsu Higher Education Institutions (17KJA220003), and the Natural Science Foundation of Jiangsu Province (BK20140969) is warmly acknowledged. We are also grateful for support by the Top-notch Academic Programs Project of Jiangsu Higher Education Institutions (TAPP), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and advanced analysis and testing center of Nanjing Forestry University.

REFERENCES

(1) (a) Damani, L. A. *Sulphur-Containing Drugs and Related Organic Compounds*; Wiley, 1989. (b) Feng, M.; Tang, B.; Liang, S.; Jiang, X. Sulfur Containing Scaffolds in Drugs: Synthesis and Application in Medicinal Chemistry. *Curr. Top. Med. Chem.* **2016**, *16*, 1200-1216. (c) Ilardi, E. A.; Vitaku, E.; Njardarson, J. T. Data-Mining for Sulfur and Fluorine: An Evaluation of Pharmaceuti-cals To Reveal Opportunities for Drug Design and Discovery. *J. Med. Chem.* **2014**, *57*, 2832-2842.

(2) (a) Mellah, M.; Voituriez, A.; Schulz, E. Chiral Sulfur Ligands for Asymmetric Catalysis. *Chem. Rev*. **2007**, *107*, 5133-5209. (b) Arrayás, R. G.; Carretero, J. C. Chiral thioether-based catalysts in asymmetric synthesis: recent advances. *Chem. Commun.* **2011**, *47*, 2207-2211. (c) Bao, D.-H.; Wu, H.-L.; Liu, C.-L.; Xie, J.-H.; Zhou, Q.-L. Development of Chiral Spiro P-N-S Ligands for Iridium-Catalyzed Asymmetric Hydrogenation of β-Alkyl-β-Ketoesters. *Angew. Chem., Int. Ed*. **2015**, *54*, 8791-8794. (d) Wei, Y.; Lu, L.-Q.; Li, T.-R.; Feng, B.; Wang, Q.; Xiao, W.-J.; Alper, H.

P,S Ligands for the Asymmetric Construction of Quaternary Stereo-centers in Palladium-Catalyzed Decarboxylative [4+2] Cycloaddi-tions. *Angew. Chem., Int. Ed*. **2016**, *55*, 2200-2204.

(3) (a) Boyd, D. A. Sulfur and Its Role In Modern Materials Science. *Angew. Chem., Int. Ed.* **2016**, *55*, 15486-15502. (b) Iino, H.; Usui, T.; Hanna, J.-i. Liquid crystals for organic thin-film transistors. *Nat. Commun.* **2015**, *6*, 6828.

(4) (a) Wang, L.; He, W.; Yu, Z. K. Transition-metal mediated carbon–sulfur bond activation and transformations. *Chem. Soc. Rev.* **2013**, *42*, 599-621. (b) Lian, Z.; Bhawal, B. N.; Morandi, B. Palladium-catalyzed carbon-sulfur or carbon-phosphorus bond metathesis by reversible arylation. *Science* **2017**, *356*, 1059-1063.

(5) For selected reviews and examples, see: (a) Beletskaya, I. P.; Ananikov, V. P. Transition-Metal-Catalyzed C−S, C−Se, and C−Te Bond Formation via Cross-Coupling and Atom-Economic Addition Reactions. *Chem. Rev.* **2011**, *111*, 1596-1636. (b) Bichler, P.; Love, J. A. Organometallic Approaches to Carbon–Sulfur Bond Formation. *Top. Organomet. Chem.* **2010**, *31*, 39-64. (c) Mao, J.; Jia, T.; Frensch, G.; Walsh, P. J. Palladium-Catalyzed Debenzylative Cross-Coupling of Aryl Benzyl Sulfides with Aryl Bromides: Synthesis of Diaryl Sulfides. *Org. Lett.* **2014**, *16*, 5304-5307. (d) Johnson, M. W.; Hannoun, K. I.; Tan, Y.; Fu, G. C.; Peters, J. C. A mechanistic investigation of the photoinduced, copper-mediated cross-coupling of an aryl thiol with an aryl halide. *Chem. Sci.*, **2016**, *7*, 4091-4100. (e) Sun, F.-G.; Li, M.; He, C.-F.; Wang, B.; Li, B.; Sui, X.-W.; Gu, Z.-H. Cleavage of the C(O)–S Bond of Thioesters by Palladium/Norbornene/Copper Cooperative Catalysis: An Efficient Synthesis of 2-(Arylthio)aryl Ketones. *J. Am. Chem. Soc*. **2016**, *138*, 7456-7459.

(6) (a) Shen, C.; Zhang, P.; Sun, Q.; Bai, S.; Hor, T. S. A.; Liu, X. Recent advances in C–S bond formation via C–H bond functionalization and decarboxylation. *Chem. Soc. Rev.* **2015**, *44*, 291-314. (b) Lee, C.-F.; Liu Y.-C.; Badsara, S. S. Transition-Metal-Catalyzed C-S Bond Coupling Reaction. *Chem. –Asian J.* **2014**, *9*, 706-722. (c) Eichman, C. C.; Stambuli, J. P. Transition Metal Catalyzed Synthesis of Aryl Sulfides. *Molecules*, **2011**, *16*, 590-608.

(7) (a) Liu, B.; lim, C.-H.; Miyake, G. M. Visible-Light-Promoted C–S Cross-Coupling via Intermolecular Charge Transfer. *J. Am. Chem. Soc.* **2017**, *139*, 13616-13619. (b) Song, S.; Zhang, Y.; Yeerlan, A.; Zhu, B.; Liu, J.; Jiao, N. Cs_2CO_3-Catalyzed Aerobic Oxidative Cross-Dehydrogenative Coupling of Thiols with Phosphonates and Arenes. *Angew. Chem., Int. Ed.* **2017**, *56*, 2487-2491. (c) Fernández-Salas, J. A.; Pulis, A. P.; Procter, D. J. Metal-free C–H thioarylation of arenes using sulfoxides: a direct, general diaryl sulfide synthesis. *Chem. Commun*. **2016**, *52*, 12364-12367. (d) Wagner, A. M.; Sanford, M. S. Transition-Metal-Free Acid-Mediated Synthesis of Aryl Sulfides from Thiols and Thioethers. *J. Org. Chem.* **2014**, *79*, 2263-2267.

(8) For examples: (a) Parumala, S. K. R.; Peddinti, R. K. Iodine catalyzed cross-dehydrogenative C–S coupling by $C(sp^2)$–H bond activation: direct access to aryl sulfides from aryl thiols. *Green Chem.* **2015**, *17*, 4068-4072. (b) Liao, Y.; Jiang, P.; Chen, S.; Qia H.; Deng, G.-J. Iodine-catalyzed efficient 2-arylsulfanylphenol formation from thiols and cyclohexanones. *Green Chem.* **2013**, *15*, 3302-3306. (c) Ravi, C.; Mohan, D. C.; Adimurthy, S. *N*-Chlorosuccinimide-Promoted Regioselective Sulfenylation of Imidazoheterocycles at Room Temperature. *Org. Lett.* **2014**, *16*, 2978-2981. (d) Huang, Z.; Zhang, D.; Qi, X.; Yan, Z.; Wang, M.; Yan, H.; Lei, A. Radical–Radical Cross-Coupling for C–S Bond Formation. *Org. Lett.* **2016**, *18*, 2351-2354.

(9) For examples: (a) Ge, W; Wei, Y. Iodine-catalyzed oxidative system for 3-sulfenylation of indoles with disulfides using DMSO as oxidant under ambient conditions in dimethyl carbonate. *Green Chem.* **2012**, *14*, 2066-2070. (b) Zou, L.-H.; Reball, J.; Mottweiler, J.; Bolm, C. Transition metal-free direct C–H bond thiolation of 1,3,4-oxadiazoles and related heteroarenes. *Chem. Commun.* **2012**, *48*, 11307-11309. (c) Huang, D.; Chen, J.; Dan, W.; Ding, J.; Liu, M.; Wu, H. A Metal-Free Sulfenylation and Bromosulfenylation of Indoles: Controllable Synthesis of 3-Arylthioindoles and 2-Bromo-3-arylthioindoles. *Adv. Synth. Catal.* **2012**, *354*, 2123-2128. (d) Prasad, C. D.; Balkrishna, S. J.; Kumar, A.; Bhakuni, B. S.; Shrimali,

K.; Biswas, S.; Kumar, S. Transition-Metal-Free Synthesis of Unsymmetrical Diaryl Chalcogenides from Arenes and Diaryl Dichalcogenides. *J. Org. Chem.* **2013**, *78*, 1434-1443.

(10) For example: Wu, Q.; Zhao, D.; Qin, X.; Lan, J.; You, J. Synthesis of di(hetero)aryl sulfides by directly using arylsulfonyl chlorides as a sulfur source. *Chem. Commun*. **2011**, *47*, 9188-9190.

(11) For examples: (a) Yang, F.-L.; Tian, S.-K. Iodine-Catalyzed Regioselective Sulfenylation of Indoles with Sulfonyl Hydrazides. *Angew. Chem., Int. Ed.* **2013**, *52*, 4929-4932. (b) Kang, X.; Yan, R.; Yu, G.; Pang, X.; Liu, X.; Li, X.; Xiang, L.; Huang, G. Iodine-Mediated Thiolation of Substituted Naphthols/Naphthylamines and Arylsulfonyl Hydrazides via C(sp^2)–H Bond Functionalization. *J. Org. Chem.* **2014**, *79*, 10605-10610.

(12) (a) Hostier, T.; Ferey, V.; Ricci, G.; Pardo D. G.; Cossy, J. TFA-promoted direct C–H sulfenylation at the C2 position of non-protected indoles. *Chem. Commun.* **2015**, *51*, 13898-13901. (b) Tian, H.; Yang, H.; Zhu, C.; Fu, H. Arylthiolation of Arylamine Derivatives with (Arylthio)-pyrrolidine-2,5-diones. *Adv. Synth. Catal.* **2015**, *357*, 481-488. (c) Hostier, T.; Ferey, V.; Ricci, G.; Pardo, D. G.; Cossy, J. Synthesis of Aryl Sulfides: Metal-Free C–H Sulfenylation of Electron-Rich Arenes. *Org. Lett.* **2015**, *17*, 3898-3901. (d) Tudge, M.;Tamiya, M.; Savarin, C.; Humphrey, G. R. Development of a Novel, Highly Efficient Halide-Catalyzed Sulfenylation of Indoles. *Org. Lett*. **2006**, *8*, 565-568.

(13) For examples: (a) Xu, Z,-b; Lu, G,-p; Cai, C. Acid-induced chemoselective arylthiolations of electron-rich arenes in ionic liquids from sodium arylsulfinates: the reducibility of halide anions in [Hmim]Br. *Org. Biomol. Chem.* **2017**, *15*, 2804-2808. (b) Xiao, F.; Chen, S.; Tian, J.; Huang, H.; Liu, Y.; Deng, G.-J. Chemoselective cross-coupling reaction of sodium sulfinates with phenols under aqueous conditions. *Green Chem.* **2016**, *18*, 1538-1546. (c) Xiao, F.; Xie, H.; Liu, S.; Deng, G.-J. Iodine-Catalyzed Regioselective Sulfenylation of Indoles with Sodium Sulfinates. *Adv. Synth.Catal.* **2014**, *356*, 364-368.

(14) For examples: (a) Qi, H.; Zhang, T.; Wan, K.; Luo, M. Catalytic Synthesis of 3-Thioindoles Using Bunte Salts as Sulfur Sources under Metal-Free Conditions. *J. Org. Chem.* **2016**, *81*, 4262-4268. (b) Miao, T.; Li, P.; Zhang, Y.; Wang, L. A Sulfenylation Reaction: Direct Synthesis of 3-Arylsulfinylindoles from Arylsulfinic Acids and Indoles in Water. *Org. Lett.* **2015**, *17*, 832-835.

(15) (a) Lin, Y.-m.; Lu, G.-p.; Wang, G.-x.; Yi, W.-b. Odorless, Regioselective Synthesis of Diaryl Sulfides and α-Thioaryl Carbonyls from Sodium Arylsulfinates via a Metal- Free Radical Strategy in Water. *Advanced Synthesis & Catalysis*. **2016**, *358*, 4100-4105. (b) Lin, Y.-m.; Lu, G.-p.; Cai, C.; Yi, W.-b. Odorless, One-Pot Regio- and Stereoselective Iodothiolation of Alkynes with Sodium Arenesulfinates under Metal-Free Conditions in Water. *Org. Lett.* **2015**, *17*, 3310-3313. (c) Lin, Y.-m.; Lu, G.-p.; Wang, G.-x.; Yi, W.-b. Acid/Phosphide-Induced Radical Route to Alkyl and Alkenyl Sulfides and Phosphonothioates from Sodium Arylsulfinates in Water. *J. Org. Chem.* **2017**, *82*, 382-389. (d) Li, W.; Yin, G.; Huang, L.; Xiao, Y.; Fu, Z.; Xin, X.; Liu, F.; Li, Z.; He, W. Regioselective and stereoselective sulfonylation of alkynylcarbonyl compounds in water. *Green Chem.* **2016**, *18*, 4879-4883. (e) Xie, L.-Y.; Li, Y.-J.; Qu, J.; Duan, Y.; Hu, J.; Liu, K.-J.; Cao, Z.; He, W.-M. A base-free, ultrasound accelerated one-pot synthesis of 2-sulfonylquinolines in water. *Green Chem.* **2017**, *19*, 5642-5646.

(16) Kita, Y.; Egi, M.; Ohtsubo, M.; Saiki, T.; Takada, T.; Tohma, H. Novel and efficient synthesis of sulfur-containing heterocycles using a hypervalent iodine(III) reagent. *Chem. Commun.* **1996**, 2225-2226.

(17) Yoshimura, A.; Zhdankin, V. V. Advances in Synthetic Applications of Hypervalent Iodine Compounds. *Chem. Rev*. **2016**, *116*, 3328-3435, and references cited therein.

(18) (a) Laird, T. Green Chemistry is Good Process Chemistry. *Org. Process Res. Dev*. **2012**, *16*, 1-2. (b) Dunn, P. J. *Pharmaceutical Process Development*; Blacker, J. A., Williams, M. T., Eds.; Royal Society of Chemistry: London, **2011**; Chapter 6. (c) Jimenez-Gonzales, C.; Constable, D. J. *Green Chemistry and Engineering: A Practical Approach*; Wiley: New York, **2011**. (d) Sheldon, R. A.; Arends, I. W. C. E.; Hanefeld, U. *Green*

Chemistry and Catalysis; Wiley-VCH: Weinheim, **2007**. (e) Prat, D.; Wells, A.; Hayler, J.; Sneddon, H.; McElroy, C. R.; Abou-Shehada, S.; Dunn, P. J. CHEM21 selection guide of classical- and less classical-solvents. *Green Chem.* **2016**, *18*, 288-296.

(19) (a) Lipshutz, B. H.; Isley, N. A.; Fennewald, J. C.; Slack, E. D. On the Way Towards Greener Transition-Metal-Catalyzed Processes as Quantified by E Factors. *Angew. Chem., Int. Ed.* **2013**, *52*, 10952-10958, and references cited therein. (b) Roschangar, F.; Sheldon, R. A.; Senanayake, C. H. Overcoming barriers to green chemistry in the pharmaceutical industry – the Green Aspiration Level™ concept. *Green Chem*. **2015**, *17*, 752-768.

(20) Chen, D.; Feng, Q.; Yang, Y.; Cai, X.-M.; Wang, F.; Huang, S. Metal-free O–H/C–H difunctionalization of phenols by o-hydroxyarylsulfonium salts in water. *Chem. Sci*. **2017**, *8,* 1601.

(21) (a) Lipshutz, B. H.; Ghorai, S. Transitioning organic synthesis from organic solvents to water. What's your E Factor? *Green Chem*. **2014**, *16*, 3660-3679, and references cited therein. (b) Lipshutz, B. H. Applying the Hydrophobic Effect to Transition Metal-Catalyzed Couplings in Water at Room Temperature. In *Transition Metal-Catalyzed Couplings in Process Chemistry: Case Studies from the Pharmaceutical Industry*; Magano, J., Dunetz, J. R., Eds.; Wiley-VCH: Weinheim, Germany, **2013**. (c) Myers, D. *Surfactant Science and Technology*, 3rd ed.; Wiley Inter-Science: Hoboken, NJ, **2006**.

(22) Izquierdo, S.; Essafi, S.; Rosal, I.; Vidossich, P.; Pleixats, R.; Vallribera, A.; Ujaque, G.; Lledós, A.; Shafir, A. Acid Activation in Phenyl-iodine Dicarboxylates: Direct Observation, Structures, and Implications. *J. Am. Chem. Soc.* **2016**, *138*, 12747-12750.

(23) (a) Lipshutz, B. H.; Ghorai, S. "Designer"-Surfactant-Enabled Cross-Couplings in Water at Room Temperature. *Aldrichimica Acta*. **2012**, *45*, 3. (b) Lipshutz, B. H.; Ghorai, S. Transition-Metal-Catalyzed Cross-Couplings Going Green: in Water at Room Temperature. *Aldrichimica Acta*. **2008**, *41*, 59. (c) Lipshutz, B. H.; Ghorai, S.; Leong, W. W. Y.; Taft, B. R.; Krogstad, D. V. Manipulating Micellar Environments for Enhancing Transition Metal-Catalyzed Cross-Couplings in Water at Room Temperature. *J. Org. Chem.* **2011**, *76*, 5061-5073 and references therein. (d) Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A.; Gaston, R. D.; Gadwood, R. C. TPGS-750-M: A Second-Generation Amphiphile for Metal-Catalyzed Cross-Couplings in Water at Room Temperature. *J. Org. Chem.* **2011**, *76*, 4379-4391. (e) Lipshutz, B. H.; Gallou, F.; Handa, S. Evolution of Solvents in Organic Chemistry. *ACS Sustainable Chem. Eng.* **2016**, *4*, 5838-5849.

(24) (a) Kita, Y.; Tohma, H.; Hatanaka, K.; Takada, T.; Fujita, S.; Mitoh, S.; Sakurai, H.; Oka, S. Hypervalent Iodine-Induced Nucleophilic Substitution of para-Substituted Phenol Ethers. Generation of Cation Radicals as Reactive Intermediates. *J. Am. Chem. Soc.* **1994**, *116*, 3684-3691. (b) Kita, Y.; Takada, T.; Mihara, S.; Whelan, B. A.; Tohma, H. Novel and Direct Nucleophilic Sulfenylation and Thiocyanation of Phenol Ethers Using a Hypervalent Iodine(III) Reagent. *J. Org. Chem.* **1995**, *60*, 7144-7148.

(25) Ye, X.; Wang, J.; Ding，S.; Hosseyni, S.; Wojtas, L.; Akhmedov, N. G.; Shi, X. Investigations on Gold-Catalyzed Thioalkyne Activation Toward Facile Synthesis of Ketene Dithioacetals. *Chem. Eur. J.* **2017**, *23*, 10506-10510.

(26) Zhang, S.; Qian, P.; Zhang, M.; Hu, M.; Cheng, J. Copper-Catalyzed Thiolation of the Di- or Trimethoxybenzene Arene C−H Bond with Disulfides. *J. Org. Chem.* **2010**, *75*, 6732-6735.

(27) Wang, D.; Guo, S.; Zhang, R.; Lin, S.; Yan, Z. TBAI–HBr system mediated generation of various thioethers with benzenesulfonyl chlorides in PEG_{400}. *RSC Adv.* **2016**, *6*, 54377-54381.

(28) Yasunari, M.; Motonori, K.; Takahiro, N.; Sakae, U. Vanadium-Catalyzed Sulfenylation of Indoles and 2-Naphthols with Thiols under Molecular Oxygen. *J. Org. Chem*. **2004**, *69*, 7688-7693.

(29) Zhang, Y.; Ngeow, K. C.; Ying, J. Y. The First N-Heterocyclic Carbene-Based Nickel Catalyst for C−S Coupling. *Org. Lett*. **2007**, *9*, 3495-3498.