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Rhodium-Catalyzed Synthesis of Unsymmetric Di(heteroaryl) Sulfides Using Heteroaryl Ethers and *S*-Heteroaryl Thioesters via Heteroarylthio Exchange

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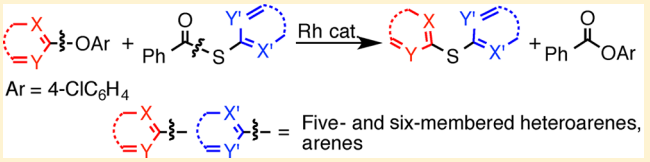
Supporting Information

ABSTRACT: Unsymmetric di(heteroaryl) sulfides were synthesized by a rhodium-catalyzed heteroarylthio exchange reaction of heteroaryl aryl ethers and *S*-(heteroaryl) thioesters. The reaction has broad applicability, giving diverse unsymmetric di(heteroaryl) sulfides containing five- and six-membered heteroarenes. No base is required in this reaction, which has been developed by the judicious design of organic substrates.



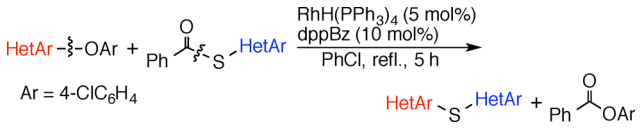
Unsymmetric diaryl sulfides are widely used in the preparation of materials and pharmaceuticals, and their heteroaryl derivatives, unsymmetric di(heteroaryl) sulfides, are an interesting group of multiple heteroatom compounds that exhibit notable chemical and biological functions.[1] They are generally synthesized by the substitution reaction of heteroaryl halides and heteroaryl thiols in the presence of stoichiometric amounts of bases[2] by classical aromatic nucleophilic substitution reactions[1,3] or copper- and palladium-catalyzed substitution reactions.[4] Silver-catalyzed oxidative C−H heteroarylthiolation of benzothiazole with 2-pyridylthiol using a stoichiometric amount of $Cu(OAc)_2$ has recently been reported.[5]

The use of bases is required for kinetic and thermodynamic reasons. In the absence of a base, hydrogen halides are formed from aryl halides and thiols, and the addition of a base neutralizes hydrogen halides to give metal halides and water, which makes the reaction largely exothermic owing to the large neutralization energy.[6] According to the Bell−Evans−Polanyi principle,[7] the exothermic nature of the reaction, when stronger bases are used, can reduce the required activation energy, which largely accelerates the reaction. Thus, the use of a base implies the release of large chemical energy, which can be inferred by considering, for example, that NaOH is regenerated from NaCl using large electrochemical energy. Development of a versatile method for the synthesis of unsymmetric bis(heteroaryl) sulfides without using stoichiometric amounts of bases is desired to conduct the synthesis in an energy-saving manner. It is also worth noting that such a method avoids the use of thiols, which makes manipulation of the reaction more facile.

It was considered interesting to use the less chemical energy derived from neutral organic compounds in place of bases, and the reactions of diphenyl ether with different phenylthiolating reagents were examined by calculations. Thermodynamic analysis by preliminary DFT calculations shows that the reaction of diphenyl ether and *S*-phenyl thiobenzoate to form diphenyl sulfide and phenyl benzoate is exothermic (−39.5 kJ/mol).[8] It is more exothermic than the reaction of diphenyl ether and *S*-phenyl methansulfonic acid giving diphenyl sulfide and methansulfonic acid phenyl ester (−4.8 kJ/mol), the reaction of diphenyl ether and thioanisole to give diphenyl sulfide and anisole (+13.4 kJ/mol), and the reaction of diphenyl ether and *N*-(phenylthio)succinimide to give diphenyl sulfide and *N*-(phenoxy)succinimide (+115.3 kJ/mol).

This analysis suggests that the synthesis of di(heteroaryl) sulfides can be conducted without using bases by the judicious design of organic substrates.[9] Described in this paper is the rhodium-catalyzed synthesis of unsymmetric di(heteroaryl) sulfides by the heteroarylthio exchange reaction of heteroaryl aryl ethers[10] and *S*-(heteroaryl) thioesters (Scheme 1). The C−O bonds of the heteroaryl aryl ethers are converted to the C−S bonds to yield unsymmetric di(heteroaryl) sulfides with concomitant C−O and C−S bond exchange. This method is applicable to the synthesis of various unsymmetric di(heteroary) sulfides containing five- and six-membered heteroarenes. A base, which would provide a large amount of chemical energy, is not employed here to make the reaction exothermic, and the synthesis is conducted using neutral and stable organic substrates, heteroaryl aryl ethers and thioesters, in an energy-saving manner.[6] In the present reaction, esters are formed as the organic coproduct, which can easily be recovered and used for other purposes. It is considered preferable

Scheme 1. Rhodium-Catalyzed Synthesis of Unsymmetric Di(heteroaryl) Sulfides



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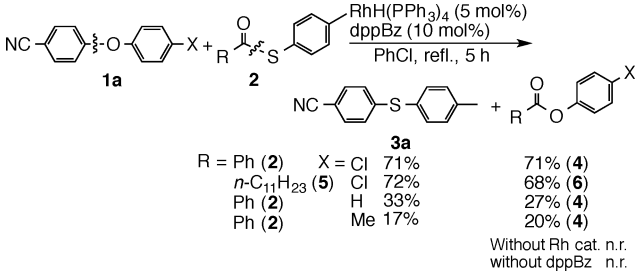
compared with the formation of inorganic metal halides derived from metal bases.

The study began with the examination of rhodium-catalyzed arylthio exchange reactions of diaryl ethers: Diaryl sulfides were formed from diaryl ethers and thioesters. When 4-(4-chlorophenoxy)benzonitrile **1a** was reacted with *S*-(4-tolyl) benzothioate **2** (1 equiv) in the presence of $RhH(PPh_3)_4$ (5 mol %) and dppBz (10 mol %, dppBz = 1,2-bis(diphenylphosphino)benzene) in refluxing chlorobenzene for 5 h, 4-(4-tolylthio)benzonitrile **3a** (71%) and (4-chlorophenyl) benzoate **4** (71%) were obtained with recovery of **1a** (25%) and **2** (28%) (Scheme 2). 4-Chlorophenyl 4-tolyl sulfide was not formed. No

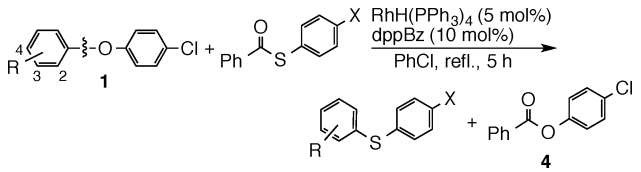
Scheme 2. Rhodium-Catalyzed Arylthio Exchange Reactions of Diaryl Ethers



reaction occurred in the absence of $RhH(PPh_3)_4$ or dppBz. The reaction of **1a** and *S*-(4-tolyl) dodecanethioate **5** also gave **3a** (72%). Neutral and stable thioester **2** can be used as a thiolating reagent of diaryl ethers. The reaction of 4-(phenoxy)benzonitrile (33%) and 4-(4-tolyloxy)benzonitrile (17%) with **2** also proceeded, where yields of the sulfides were reduced, likely because of the stronger C−O bonds.

Several diaryl sulfides were obtained in quantitative yields from diaryl ethers **1** with electron-withdrawing groups and benzothioates **2**, **7**, and **8** with *S*-(4-tolyl), *S*-(4-methoxyphenyl), and *S*-(4-chlorophenyl) groups, respectively (Scheme 3). **1b** reacted with **2** even when using a lower catalyst loading (1 mol %), giving **3b** (89%) and **4** (88%).

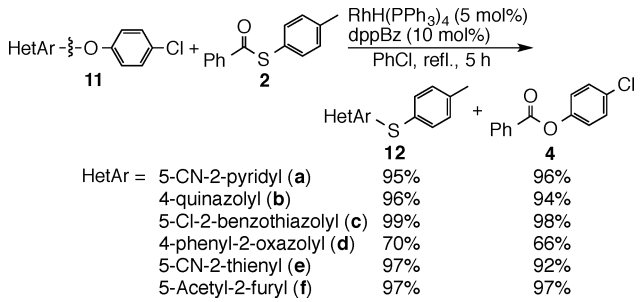
Scheme 3. Rhodium-Catalyzed Synthesis of Unsymmetric Diaryl Sulfides



Using this method, heteroaryl *p*-tolyl sulfides containing five- and six-membered heteroarenes **12a**−**12f** were obtained in quantitative yields by the reaction of heteroaryl 4-chlorophenyl ethers **11a**−**11f** and thioester **2** (Scheme 4). The weak heteroaryl C−O bonds of the heteroaryl aryl ethers **11** were selectively cleaved and converted to the C−S bonds.

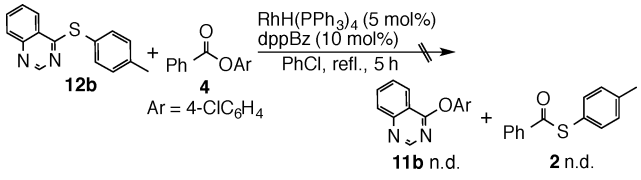
The reverse reaction to form a heteroaryl aryl ether from a heteroaryl aryl sulfide did not proceed. When **12b** was reacted

Scheme 4. Rhodium-Catalyzed Synthesis of Heteroaryl Aryl Sulfides



with an aryl ester **4** using the same rhodium complex, **11b** and **2** were not formed (Scheme 5). The heteroaryl aryl sulfide formation reaction is energetically favorable, perhaps because of the formation of a thermodynamically more stable ester from the thioester.

Scheme 5. Reverse Reaction



The use of *S*-(heteroaryl) benzothioates as thiolating reagents provided unsymmetric bis(heteroaryl) sulfides from heteroaryl (4-chlorophenyl) ethers. The reaction of six-membered heteroaryl aryl ethers and *S*-(heteroaryl) benzothioates (1 equiv) proceeded in high yields (Table 1). The heteroaryl 4-chlorophenyl ethers containing 2-triazyl, 4-quinazolinyl, 2-pyrimidyl, and 2-pyridyl groups reacted with *S*-(2-pyridyl) benzothioate, and the corresponding heteroaryl 2-pyridyl sulfides **15a**−**15e** were obtained in high yields. The reaction of benzooxazolyl, benzothiazolyl, and 2-acetylfulyl 4-chlorophenyl ethers with *S*-(2-pyridyl) benzothioate also gave the corresponding sulfides containing five-membered heteroarenes **15f** and **15g**. The reaction of *S*-(3-pyridyl) and *S*-(4-pyridyl) benzoates gave the 4-pyridyl and 3-pyridyl derivatives **15h**−**15o**. The position of the nitrogen atom in the *S*-pyridyl thioester was not crucial, which indicated a broad scope for this method. *S*-(2-Furyl) and *S*-(2-thienyl) benzothioates reacted with heteroaryl 4-chlorophenyl ethers to give the heteroaryl sulfides **15p**−**15u** in high yields. The sulfide structure was confirmed by X-ray crystal structure analysis of **15m** and **15r** (see Supporting Information).[11] This method is a novel catalytic procedure for the synthesis of diverse unsymmetric di(heteroaryl) sulfides from readily available heteroaryl aryl ethers. The oxidation reaction of unsymmetric di(heteroaryl) sulfide **15e** using *m*-CPBA gave sulfoxide derivative **16** (see Experimental Section).[12] This is a simple and facile synthetic method of unsymmetric diheteroaryl sulfoxide.

Di(heteroaryl) sulfide was not formed by the reaction of heteroaryl thiol and heteroaryl aryl ether under these reaction conditions. The reaction of 2-(4-chlorophenyloxy)-5-cyanopyridine **13e** and 4-pyridylthiol **17** did not provide 5-cyanopyridyl 4-pyridyl sulfide **15m** in the presence of $RhH(PPh_3)_4$ (5 mol %) and dppBz (10 mol %) (Scheme 6). The involvement of a benzoylrhodium intermediate in the

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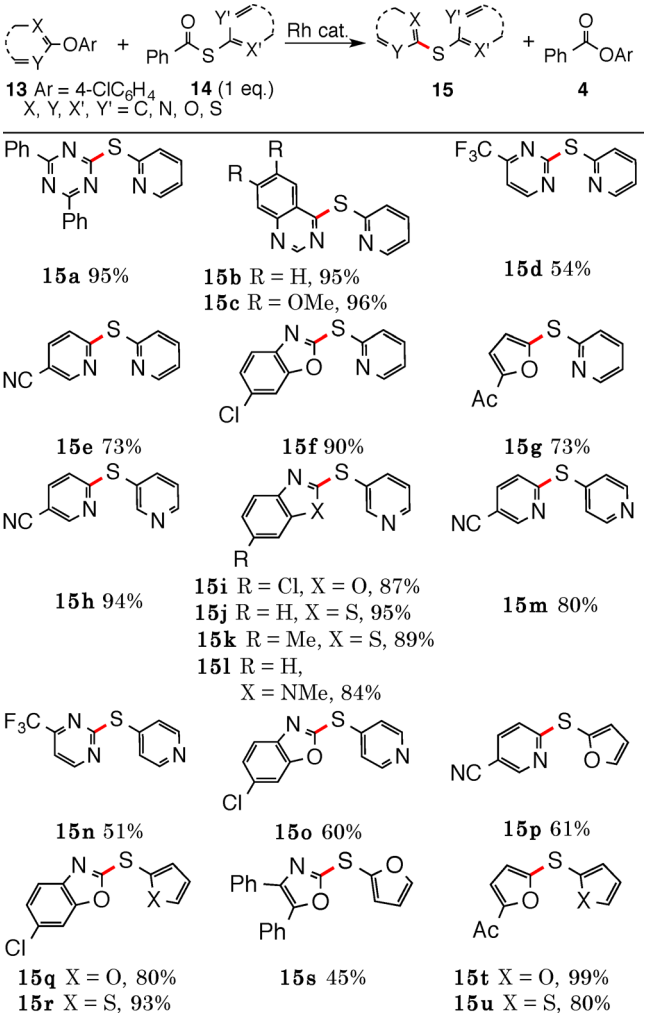
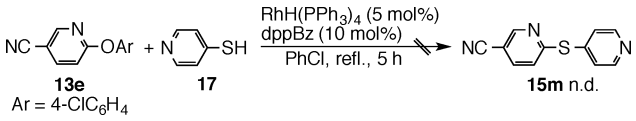
Table 1. Rhodium-Catalyzed Synthesis of Unsymmetric Bis(heteroaryl) Sulfides[a]



[a]The C−S bonds formed by the reaction are shown in red.

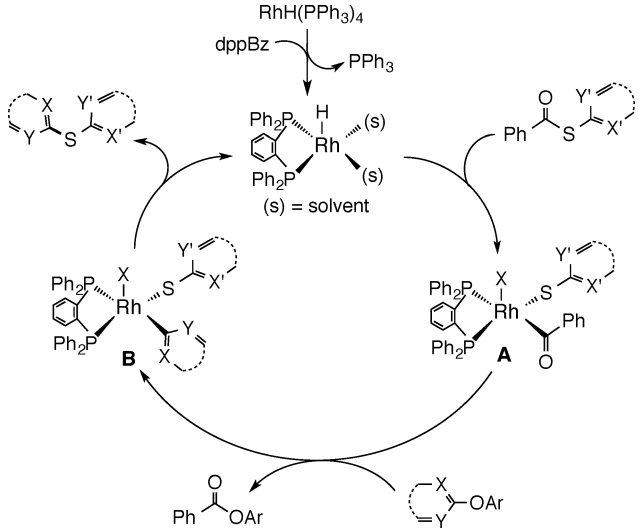
rhodium-catalyzed heteroarylthio exchange reaction is suggested (vide infra).

Scheme 6. Heteroarylthio Exchange Reaction Using 4-Pyridylthiol



A possible mechanism of the reaction is as follows (Scheme 7). The phosphine ligand in $RhH(PPh_3)_4$ is exchanged with dppBz, and the oxidative addition of *S*-(heteroaryl) thioester provides the benzoylrhodium intermediate **A**. The intermediate **A** then undergoes the exchange reaction with heteroaryl aryl ether forming HetAr′-Rh(III)-SHetAr complex **B** and ester, and the unsymmetrical di(heteroaryl) sulfides are liberated by the reductive elimination with the regeneration of the rhodium catalyst. In the present reaction, the heteroaryl C−O bond is regioselectively cleaved, and the other C−O bond does not react. It is considered that the heteroaryl groups and aryl groups with an electron-withdrawing substituent weaken the C−O bond.[13]

Scheme 7. Proposed Reaction Mechanism



In summary, unsymmetric di(heteroaryl) sulfides were synthesized from heteroaryl aryl ethers and *S*-(heteroaryl) thioesters by a rhodium-catalyzed heteroarylthio exchange reaction. Diverse unsymmetric di(heteroaryl) sulfides containing five- and six-membered heteroarenes were obtained in high yield. The reaction, which does not require a stoichiometric amount of a base, does not rely on the neutralization, which releases a large amount of chemical energy. Compared to the method employing metal bases, the less chemical energy is used in the present method employing organic substrates. In addition, the organic substrate method has an advantage of the reaction to be fine-tuned, and then an energy-saving reaction can be developed by the judicious design of organic substrates.

EXPERIMENTAL SECTION

General Information. ^1H and ^{13}C NMR spectra were recorded on 400 MHz instrument, and tetramethylsilane was used as a standard. The following abbreviations (or combinations thereof) were used to explain multiplicities: s = singlet, d = doublet, t = triplet, q = quadruplet, m = multiplet. IR spectra were measured on an FT/IR spectrometer. Melting points were determined with a micromelting point apparatus without correction. High-resolution mass spectra (HRMS) were measured on quadrupole or EI-TOF. *S*-(2-Pyridyl) and *S*-(4-pyridyl) benzothioates,[14] *S*-(3-pyridyl) benzothioate,[15] *S*-(2-furyl) benzothioate,[16] and *S*-(2-thienyl) benzothioate[17] were synthesized by the literature methods.

General Procedure for Synthesis of the 4-(4-Tolylthio)-benzonitrile 3a. In a two-necked flask were placed $RhH(PPh_3)_4$ (14.4 mg, 5 mol %), 1,2-bis(diphenylphosphino)benzene (dppBz, 11.2 mg, 10 mol %), 4-(4-chlorophenoxy)benzonitrile (0.25 mmol, 57.3 mg), and *S*-(*p*-tolyl) benzothioate (0.25 mmol, 57.0 mg) in chlorobenzene (0.5 mL) under an argon atomosphere, and the mixture was heated at reflux for 5 h. The solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel (eluent: hexane/ethyl acetate = 10/1) giving 4-(4-tolylthio)benzonitrile **3a** (40.0 mg, 71%) and 4-chlorophenyl benzoate **4** (41.4 mg, 71%). Other complexs such as $RhCl(PPh_3)_3$, $[RhCl(cod)_2]_2$, $Rh(acac)_3$, and $Pd(OAc)_2$ in the presence of dppBz were ineffective. The use of several bidentate ligands revealed a high efficiency of dppBz for this reaction: 1,2-bis(diphenylphosphino)ethane (60%), *cis*-1,2-bis(diphenylphosphino)ethylene (10%), 1,3-bis(diphenylphosphino)propane (not detected), and 1,4-bis(diphenylphosphino)butane (not detected). Monodentate ligands tris(4-methoxyphenyl)phosphine and tris(4-

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chlorophenyl)phosphine and a tridentate ligand bis(2-diphenylphosphinoethyl)phenylphosphine were ineffective. These results show that the bidentate phosphine ligands with phosphino groups separated by two carbon atoms are essential. The reaction did not proceed in refluxing *o*-dichlorobenzene and THF.

Characterization Data. *4-(4-Tolylthio)benzonitrile (**3a**).* Colorless solid (40.0 mg, 71%). Mp 100.0−101.0 °C (hexane). Lit.[18] 100 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.41 (3H, s), 7.12 (2H, d, J = 8.4 Hz), 7.25 (2H, d, J = 8.8 Hz), 7.42 (2H, d, J = 8.4 Hz), 7.45 (2H, d, J = 8.4 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.3, 108.2, 118.9, 126.7, 126.8, 130.7, 132.3, 134.9, 140.0, 146.6. IR (KBr) ν 3081, 2224, 1591, 1484, 1402, 1081 cm^{-1}. MS (EI) m/z 225.0 (M$^+$, 100%). HRMS Calcd for $C_{14}H_{11}NS$: 225.0612. Found: 225.0600.

*4-Chlorophenyl Benzoate (**4**).*[19] Colorless solid (41.4 mg, 71%). Mp 87.0−87.5 °C (hexane). Lit.[20] 82.0−83.0 °C (hexane/benzene). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (2H, d, J = 8.8 Hz), 7.39 (2H, d, J = 8.8 Hz), 7.51 (2H, t, J = 7.6 Hz), 7.64 (1H, t, J = 7.6 Hz), 8.19 (2H, d, J = 8.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 123.0, 128.6, 129.1, 129.5, 130.1, 130.2, 131.2, 133.7, 149.4, 164.8. IR(KBr) 1732, 1585, 1488, 1402 cm^{-1}. MS (EI) m/z 232 (M$^+$, 10%), 105 (M$^+$ − COC_6H_5, 100%). HRMS Cald for $C_{13}H_9O_2Cl$: 232.0291. Found: 232.0285.

*4-Chlorophenyl Dodecanoate (**6**).* Colorless solid (52.9 mg, 68%). Mp 34.5−35.0 °C (hexane). Lit.[21] 40.0−42.0 °C (acetone). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 7.2 Hz), 1.23−1.43 (16H, m), 1.74 (2H, q, J = 7.6 Hz), 2.54 (2H, t, J = 7.6 Hz), 7.03 (2H, d, J = 8.0 Hz), 7.32 (2H, d, J = 8.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 14.1, 22.7, 24.9, 29.1, 29.2, 29.3, 29.4, 29.6, 31.9, 34.3, 122.9, 129.4, 131.0, 149.2, 172.0. IR (KBr) 2917, 2848, 1749, 1490, 1147 cm^{-1}. MS (EI) m/z 310.0 (M$^+$, 15%), 183 (M$^+$ − 127, 100%). HRMS Cald for $C_{18}H_{27}O_2Cl$: 310.1700. Found: 310.1693. One carbon peak of aliphatic region was overlapped in ^{13}C NMR.

*4-(4-Tolylthio)-2-(trifluoromethyl)benzonitrile (**3b**).*[22] Colorless solid (72.4 mg, 99%). Mp 65.5−66.5 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, s), 7.19 (1H, dd, J = 8.4, 2.0 Hz), 7.29 (2H, d, J = 8.0 Hz), 7.43 (3H, d, J = 8.0 Hz), 7.59 (1H, d, J = 8.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.3, 105.4 (d, J = 2.3 Hz), 115.6, 122.9 (q, J = 272.6 Hz), 123.6 (q, J = 4.4 Hz), 125.2, 128.6, 131.1, 133.0 (q, J = 32.8 Hz), 134.6, 135.2, 140.8, 148.3. ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.3. IR (KBr) ν 3028, 2232, 1310 cm^{-1}. MS (EI) m/z 293 (M$^+$, 100%). HRMS Calcd for $C_{15}H_{10}F_3NS$: 293.0486. Found: 293.0491.

*4-(4-Tolylthio)-3-(trifluoromethyl)benzonitrile (**3c**).* Colorless solid (72.5 mg, 99%). Mp 96.5−97.5 °C (hexane/ethyl acetate = 4:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, s), 6.94 (1H, d, J = 8.4 Hz), 7.29 (2H, d, J = 7.6 Hz), 7.35 (2H, d, J = 8.4 Hz), 7.47 (1H, dd, J = 8.4, 1.6 Hz), 7.87 (1H, d, J = 1.6 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.3, 108.2, 117.6, 122.7 (q, J = 273.3 Hz), 125.3, 127.4 (q, J = 32.1 Hz), 128.6, 130.1 (q, J = 5.9 Hz), 131.1, 134.5, 135.7, 140.9, 146.8. ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.6. IR (KBr) ν 3099, 3067, 2232, 1133 cm^{-1}. MS (EI) m/z 293 (M$^+$, 100%), 91 (M$^+$-202, 26%). HRMS Calcd for $C_{15}H_{10}F_3NS$: 293.0486. Found: 293.0491.

*4-(4-Tolylthio)benzophenone (**3d**).*[23] Colorless solid (74.6 mg, 98%). Mp 74.0−75.0 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.39 (3H, s), 7.18 (2H, d, J = 8.4 Hz), 7.24 (2H, d, J = 7.6 Hz), 7.43 (2H, d, J = 8.0 Hz), 7.46 (2H, d, J = 7.2 Hz), 7.56 (1H, t, J = 7.2 Hz), 7.67 (2H, d, J = 8.4 Hz), 7.75 (2H, d, J = 7.2 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.3, 126.5, 128.0, 128.2, 129.8, 130.5, 130.7, 132.2, 134.4, 134.5, 137.7, 139.3, 145.2, 195.8. IR (KBr) ν 3028, 2232, 1310 cm^{-1}. MS (EI) m/z 304 (M$^+$, 100%), 227 (M$^+$ − 77, 57%). HRMS Calcd for $C_{20}H_{16}OS$: 304.0922. Found: 304.0905.

*4-[(4-Methoxyphenyl)thio]-2-(trifluoromethyl)benzonitrile (**9**).* Colorless oil (70.1 mg, 91%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.87 (3H, s), 7.01 (2H, d, J = 8.8 Hz), 7.16 (1H, dd, J = 8.4, 1.6 Hz), 7.39 (1H, d, J = 1.6 Hz), 7.48 (2H, d, J = 8.8 Hz), 7.59 (1H, d, J = 8.4 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 55.4, 105.1 (d, J = 2.2 Hz), 115.6 (d, J = 6.7 Hz), 115.8, 118.8, 122.1 (q, J = 273.3 Hz), 123.1 (q, J = 4.4 Hz), 128.1, 132.9 (q, J = 32.8 Hz), 134.6, 137.2, 148.9, 161.3 (d, J = 3.0 Hz). ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.3. IR (KBr) ν 2944, 2229, 1253, 1174, 1030 cm^{-1}. MS (EI) m/z 309 (M$^+$, 100%), 294 (M$^+$ − 15, 34%). HRMS Calcd for $C_{15}H_{10}F_3NOS$: 309.0435. Found: 309.0427.

*4-(4-Chlorophenyl)-2-(trifluoromethyl)benzonitrile (**10**).* Colorless solid (77.6 mg, 99%). Mp 75.0−76.0 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25 (1H, ddd, J = 8.4, 2.0, 0.8 Hz), 7.47 (5H, m), 7.64 (1H, d, J = 8.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 106.2 (d, J = 2.2 Hz), 115.4, 122.0 (q, J = 273.3 Hz), 124.2 (q, J = 5.2 Hz), 127.7, 129.2, 130.5, 133.2 (q, J = 32.8 Hz), 134.9, 136.1, 136.7, 146.7. ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.3. IR (KBr) ν 3082, 2225, 1593, 1475, 1308 cm^{-1}. MS (EI) m/z 313 (M$^+$, 100%). HRMS Calcd for $C_{14}H_7ClF_3NS$: 312.9940. Found: 312.9917.

*6-(4-Tolylthio)-3-pyridinecarbonitrile (**12a**).* Colorless solid (53.6 mg, 95%). Mp 75.0−75.5 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, s), 6.87 (1H, d, J = 8.8 Hz), 7.29 (2H, d, J = 8.0 Hz), 7.48 (2H, d, J = 8.0 Hz), 7.61 (1H, dd, J = 8.4, 2.0 Hz), 8.63 (1H, d, J = 1.6 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.4, 104.8, 116.9, 119.9, 124.8, 130.9, 135.6, 138.8, 140.7, 152.1, 168.6. IR (KBr) ν 3053, 2228, 1581, 1449, 826 cm^{-1}. MS (EI) m/z 226 (M$^+$, 47%), 225 (M$^+$ − 1, 100%). HRMS Calcd for $C_{13}H_{10}N_2S$: 226.0565. Found: 226.0546.

*4-(4-Tolylthio)quinazoline (**12b**).* Yellow solid (60.3 mg, 96%). Mp 102.2−102.5 °C (hexane). Lit.[24] 104.0−105.0 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, s), 7.30 (2H, d, J = 8.0 Hz), 7.51 (2H, d, J = 8.0 Hz), 7.62 (1H, t, J = 8.0 Hz), 7.87 (1H, t, J = 8.4 Hz), 7.96 (1H, d, J = 8.4 Hz), 8.21 (1H, d, J = 8.0 Hz), 8.87 (1H, s). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.5, 123.3, 123.4, 123.8, 127.5, 128.8, 130.3, 133.8, 135.7, 140.1, 148.3, 154.0, 171.8. IR (KBr) ν 2915, 1909, 1502, 1540, 1485 cm^{-1}. MS (EI) m/z 252 (M$^+$, 50%), 251 (M$^+$ − 1, 100%). HRMS Calcd for $C_{15}H_{12}N_2S$: 252.0721. Found: 252.0718.

*2-(4-Tolylthio)-5-chlorobenzothiazole (**12c**).* Colorless solid (71.8 mg, 99%). Mp 93.0−94.0 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.44 (3H, s), 7.30 (2H, d, J = 7.6 Hz), 7.35 (1H, dd, J = 8.8, 2.0 Hz), 7.59 (1H, d, J = 2.0 Hz), 7.62 (2H, d, J = 8.0 Hz), 7.75 (1H, d, J = 8.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.4, 120.4, 122.5, 125.8, 126.8, 130.0, 130.8, 135.6, 136.6, 141.4, 152.6, 171.6. IR (KBr) ν 2917, 1430, 1099, 1004, 810 cm^{-1}. MS (EI) m/z 291 (M$^+$, 78%), 290 (M$^+$ − 1, 100%). HRMS Calcd for $C_{14}H_{10}ClNS_2$: 290.9894. Found: 290.9910.

*2-(4-Tolylthio)-4-phenyloxazole (**12d**).* Colorless solid (46.9 mg, 70%). Mp 66.5−67.0 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.37 (3H, s), 7.20 (2H, d, J = 8.0 Hz), 7.29 (1H, t, J = 7.2 Hz), 7.37 (2H, t, J = 7.2 Hz), 7.51 (2H, d, J = 8.0 Hz), 7.69 (2H, d, J = 7.2 Hz), 7.87 (1H, s). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.2, 125.2, 125.5, 128.2, 128.7, 130.2, 130.5, 133.4, 135.5, 139.4, 142.4, 158.9. IR (KBr) ν 3108, 1491, 1445 cm^{-1}. MS (EI) m/z 267 (M$^+$, 100%), 135 (M$^+$ − 132, 39%). HRMS Calcd for $C_{16}H_{13}NOS$: 267.0718. Found: 267.0732.

*5-(4-Tolylthio)-2-thiophenecarbonitrile (**12e**).* Colorless oil (56.1 mg, 97%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.34 (3H, s), 7.00 (1H, d, J = 4.0 Hz), 7.16 (2H, d, J = 8.0 Hz), 7.32 (2H, d, J = 8.0 Hz), 7.44 (1H, d, J = 4.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.1, 110.9, 113.6, 130.1, 130.4, 131.7, 137.7, 139.1, 146.1. IR (KBr) ν 3094, 2920, 2212, 1492, 1415, 807 cm^{-1}. MS (EI) m/z 231 (M$^+$, 100%). HRMS Calcd for $C_{12}H_9NS_2$: 231.0176. Found: 231.0185.

*1-[5-(4-Tolylthio)-2-furanyl]ethanone (**12f**).* Yellow solid (56.4 mg, 97%). Mp 86.0−86.5 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.34 (3H, s), 2.44 (3H, s), 6.52 (1H, d, J = 3.6 Hz), 7.13 (1H, d, J = 3.2 Hz), 7.14 (2H, d, J = 8.0 Hz), 7.29 (2H, d, J = 8.4 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.1, 26.0, 117.2, 118.2, 128.9, 130.2, 131.1, 138.3, 151.7, 154.7, 186.3. IR (KBr) ν 3084, 2920, 1650, 1447, 1306, 1036 cm^{-1}. MS (EI) m/z 232 (M$^+$, 100%), 190 (M$^+$ − 42, 50%). HRMS Calcd for $C_{13}H_{12}O_2S$: 232.0558. Found: 232.0550.

*2,4-Diphenyl-6-(2-pyridinylthio)-1,3,5-triazine (**15a**).* Colorless solid (81.4 mg, 95%). Mp 162.0−163.0 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (1H, ddd, J = 7.6, 5.2, 1.2 Hz), 7.47 (4H, t, J = 7.6 Hz), 7.56 (2H, tt, J = 7.2, 1.2 Hz), 7.84 (1H, dt, J = 7.6, 2.0 Hz), 7.92 (1H, td, J = 6.8, 0.8 Hz), 8.46 (4H, td, J = 8.4, 1.6 Hz), 8.73 (1H, ddd, J = 4.8, 0.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 123.6, 128.6, 129.0, 130.9, 132.7, 135.3, 136.9, 150.4, 152.2, 170.5, 182.1. IR (KBr) ν 3049, 2880, 1505, 1362, 1252 cm^{-1}. MS (EI) m/z 342 (M$^+$, 95%), 136 (M$^+$ − 206, 100%). HRMS Calcd for $C_{20}H_{14}N_4S$: 342.0939. Found: 342.0934.

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*4-(2-Pyridinylthio)quinazoline (**15b**).* Pale orange solid (56.7 mg, 95%). Mp 116.5−117.5 °C (hexane/AcOEt = 3/1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (1H, t, J = 4.8 Hz), 7.65 (1H, t, J = 8.0 Hz), 7.77−7.85 (2H, m), 7.90 (1H, dt, J = 8.0, 0.8 Hz), 7.99 (1H, d, J = 8.8 Hz), 8.22 (1H, dd, J = 8.4 Hz), 8.71 (1H, dd, J = 5.2, 1.2 Hz), 8.91 (1H, s). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 123.6, 124.0, 127.8, 128.9, 131.0, 134.1, 137.2, 148.7, 150.7, 151.6, 153.7, 170.3. IR (KBr) ν 3045, 1559, 1542, 1482, 989 cm^{-1}. MS (EI) m/z 239 (M^+, 79%), 238 (M^+ − 1, 100%). HRMS Calcd for $C_{13}H_9N_3S$: 239.0517. Found: 239.0515. One carbon peak of **15b** of aliphatic region was overlapped in ^{13}C NMR.

*4-(2-Pyridinylthio)-6,7-dimethoxyquinazoline (**15c**).* Colorless solid (72.0 mg, 96%). Mp 134.0−135.0 °C (hexane/AcOEt = 4/1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.05 (3H, s), 4.06 (3H, s), 7.29 (1H, s), 7.33 (1H, ddd, J = 7.2, 4.8, 1.6 Hz), 7.36 (1H, s), 7.77 (1H, dt, J = 7.2, 2.0 Hz), 7.81 (1H, ddd, J = 7.6, 1.2, 0.8 Hz), 8.66 (1H, ddd, J = 5.2, 2.0, 1.2 Hz), 8.81 (1H, s). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 56.3, 56.4, 101.7, 107.1, 119.4, 123.2, 130.0, 137.2, 146.8, 150.3, 150.5, 152.7, 156.0, 165.7. IR (KBr) ν 2925, 2854, 1232, 1017 cm^{-1}. MS (EI) m/z 299 (M^+, 100%), 284 (M^+ − 15, 89%). HRMS Calcd for $C_{15}H_{13}N_3O_2S$: 299.0728. Found: 299.0728. One carbon peak of aliphatic region was overlapped in ^{13}C NMR.

*2-(2-Pyridinylthio)-4-(trifluoromethyl)pyrimidine (**15d**).*[25] Yellow oil (34.8 mg, 54%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (1H, d, J = 4.8 Hz), 7.34 (1H, dd, J = 4.8, 1.6 Hz), 7.77 (1H, dt, J = 8.0, 2.0 Hz), 7.81 (1H, td, J = 8.0, 1.2 Hz), 8.66 (1H, ddd, J = 4.8, 0.8 Hz), 8.74 (1H, d, J = 4.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 112.8 (q, J = 3.0 Hz), 120.0 (q, J = 274.1 Hz), 123.6, 130.0, 137.3, 150.5, 152.2, 156.0 (q, J = 36.5 Hz), 159.8, 173.1. ^{19}F NMR (376 MHz, $CDCl_3$) δ −70.3. IR (neat) ν 3051, 2992, 1572, 1560, 1335, 1224, 1120, 834 cm^{-1}. MS (EI) m/z 257 (M^+, 100%). HRMS Calcd for $C_{10}H_6F_3N_3S$: 257.0235. Found: 257.0234.

*6-(2-Pyridinylthio)-3-pyridinecarbonitrile (**15e**).* Pale yellow solid (38.9 mg, 73%). Mp 95.5−97.0 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (1H, ddd, J = 7.6, 4.8, 0.8 Hz), 7.44 (1H, dd, J = 8.4, 0.8 Hz), 7.63 (1H, dd, J = 8.0, 0.8 Hz), 7.74 (1H, dd, J = 7.2, 2.0 Hz), 7.76 (1H, dd, J = 8.8, 2.4 Hz), 8.64 (1H, dt, J = 4.4, 0.8 Hz), 8.67 (1H, d, J = 2.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 106.3, 116.6, 122.7, 123.4, 128.5, 137.6, 139.0, 150.8, 152.2, 153.1, 164.4. IR (KBr) ν 3045, 2228, 1582, 1572, 1454, 1107, 833 cm^{-1}. MS (EI) m/z 213 (M^+, 45%), 212 (M^+ − 1, 100%). HRMS Calcd for $C_{11}H_7N_3S$: 213.0361. Found: 213.0342.

*6-Chloro-2-(2-pyridinylthio)benzoxazole (**15f**).* Colorless solid (59.1 mg, 90%). Mp 77.0−78.0 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27 (1H, m), 7.30 (1H, dd, J = 8.8, 2.0 Hz), 7.49 (1H, d, J = 2.0 Hz), 7.58 (1H, d, J = 8.4 Hz), 7.73 (2H, m), 8.56 (1H, dt, J = 4.8, 1.2 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 110.9, 119.9, 123.0, 125.2, 126.3, 130.7, 137.6, 140.5, 150.4, 151.9, 152.4, 161.2. IR (KBr) ν 3070, 3045, 1504, 1424, 1210, 1101, 760 cm^{-1}. MS (EI) m/z 262 (M^+, 100%), 227 (M^+ − 35, 15%). HRMS Calcd for $C_{12}H_7ClN_2OS$: 261.9968. Found: 261.9966.

*1-[5-(2-pyridinylthio)-2-furanyl]ethanone (**15g**).* Red solid (40.1 mg, 73%). Mp 103.5−104.5 °C (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.51 (3H, s), 6.91 (1H, d, J = 3.6 Hz), 6.98 (1H, d, J = 8.4 Hz), 7.09 (1H, t, J = 4.8 Hz), 7.26 (1H, d, J = 3.2 Hz), 7.55 (1H, dt, J = 8.0, 0.8 Hz), 8.43 (1H, d, J = 4.0 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 26.1, 118.0, 121.0, 121.6, 121.8, 137.2, 146.5, 149.9, 155.8, 158.0, 186.6. IR (KBr) ν 3128, 3085, 1673, 1453, 1287, 942 cm^{-1}. MS (EI) m/z 219 (M^+, 100%), 176 (M^+-43, 52%). HRMS Calcd for $C_{11}H_9NO_2S$: 219.0354. Found: 219.0374.

*6-(3-Pyridinylthio)-3-pyridinecarbonitrile (**15h**).* Colorless oil (50.1 mg, 94%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09 (1H, dd, J = 8.8, 1.2 Hz), 7.44 (1H, ddd, J = 7.6, 4.8, 0.8 Hz), 7.73 (1H, dd, J = 8.4, 2.0 Hz), 7.93 (1H, dt, J = 8.0, 2.0 Hz), 8.61 (1H, dd, J = 2.0, 0.8 Hz), 8.72 (1H, dd, J = 4.8, 1.6 Hz), 8.78 (1H, dd, J = 2.0, 0.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 105.8, 116.5, 120.5, 124.4, 125.9, 139.0, 143.0, 150.7, 152.2, 155.2, 165.2. IR (neat) ν 3046, 2231, 1582, 1455, 1103 cm^{-1}. MS (EI) m/z 213 (M^+, 28%), 212 (M^+ − 1, 100%). HRMS Calcd for $C_{11}H_6N_3S$ (M^+ − H): 212.0277. Found: 212.0274. The mass spectrometry of the compound **15i** ($C_{11}H_7N_3S$, Calcd: 213.0361) was not analyzed to overlap with the mass peak including a isotope of the carbon ($C_{10}{}^{13}CH_7N_3S$, Calcd: 213.0311). Therefore, the high-resolution mass spectrometry was analyzed in M^+ − H.

*6-Chloro-2-(3-pyridinylthio)benzoxazole (**15i**).* Colorless solid (57.3 mg, 87%). Mp 121.0−122.0 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27 (1H, d, J = 8. 0 Hz), 7.46 (3H, m), 8.06 (1H, d, J = 8.0 Hz), 8.72 (1H, d, J = 4.4 Hz), 8.89 (1H, d, J = 1.2 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 110.7, 119.5, 124.3, 124.4, 125.2, 130.2, 140.4, 142.0, 150.8, 151.9, 154.2, 162.7. IR (KBr) ν 3102, 3048, 3008, 1506, 1017 cm^{-1}. MS (EI) m/z 262 (M^+, 100%), 227 (M^+ − 35, 15%). HRMS Calcd for $C_{12}H_7ClN_2OS$: 261.9968. Found: 261.9966.

*2-(3-Pyridinylthio)benzothiazole (**15j**).* Colorless solid (57.9 mg, 95%). Mp 98.0−99.0 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (1H, m), 7.42 (2H, m), 7.69 (1H, ddd, J = 8.0, 1.2, 0.4 Hz), 7.89 (1H, ddd, J = 7.6, 1.2, 0.4 Hz), 8.05 (1H, ddd, J = 8.0, 2.4, 1.6 Hz), 8.72 (1H, dd, J = 4.8, 2.0 Hz), 8.92 (1H, dd, J = 2.4, 0.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 120.8, 122.1, 124.4, 124.7, 126.3, 127.5, 135.5, 142.3, 150.9, 153.5, 154.6, 166.6. IR (KBr) ν 3033, 1566, 1461, 1426, 1407, 1006 cm^{-1}. MS (EI) m/z 244 (M^+, 66%), 243 (M^+ − 1, 100%). HRMS Calcd for $C_{12}H_7N_2S_2$ (M^+ − H): 243.0045. Found: 243.0050. The mass spectrometry of the compound **15g** ($C_{12}H_8N_2S_2$, Calcd: 244.0129) was not analyzed to overlap with the mass peak including a isotope of the carbon ($C_{11}{}^{13}CH_8N_2S_2$, Calcd: 244.0079). Therefore, the high-resolution mass spectrometry was analyzed in M^+ − H.

*6-Methyl-2-(3-pyridinylthio)benzothiazole (**15k**).* Colorless solid (53.9 mg, 89%). Mp 96.0−97.0 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.44 (3H, s), 7.09 (1H, d, J = 7.6 Hz), 7.22 (1H, s), 7.39 (1H, ddd, J = 8.0, 5.2, 0.8 Hz), 7.46 (1H, d, J = 8.0 Hz), 8.04 (1H, ddd, J = 8.0, 2.4, 2.0 Hz), 8.68 (1H, dd, J = 4.8, 1.6 Hz), 8.88 (1H, dd, J = 2.4, 0.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 21.6, 110.3, 118.5, 124.3, 125.2, 125.7, 135.1, 139.5, 141.7, 150.5, 152.1, 153.9, 160.7. IR (KBr) ν 1510, 1217, 1091 cm^{-1}. MS (EI) m/z 242 (M^+, 100%), 241 (M^+ − 1, 52%). HRMS Calcd for $C_{13}H_{10}N_2OS$: 242.0514. Found: 242.0515.

*N-Methyl-2-(3-pyridinylthio)benzimidazole (**15l**).* Colorless solid (50.5 mg, 84%). Mp 95.5−96.5 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.79 (3H, s), 7.28 (4H, m), 7.77 (1H, ddd, J = 8.0, 2.4, 1.6 Hz), 8.51 (1H, dd, J = 4.4, 1.6 Hz), 8.66 (1H, dd, J = 2.4, 0.4 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 30.7, 109.4, 119.8, 122.6, 123.4, 124.1, 129.3, 136.4, 138.4, 143.1, 146.6, 148.8, 150.9. IR (KBr) ν 3050, 1567, 1327, 1017 cm^{-1}. MS (EI) m/z 241 (M^+, 78%), 240 (M^+-1, 100%). HRMS Calcd for $C_{13}H_{11}N_3S$: 241.0674. Found: 241.0672.

*6-(4-Pyridinylthio)-3-pyridinecarbonitrile (**15m**).* Orange solid (42.8 mg, 80%). Mp 114.5−115.5 °C (ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26 (1H, dd, J = 8.4, 1.2 Hz), 7.48 (2H, dd, J = 4.4, 1.2 Hz), 7.79 (1H, dd, J = 8.4, 2.4 Hz), 8.67 (2H, dd, J = 4.4, 1.6 Hz), 8.69 (1H, dd, J = 2.0, 0.8 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 106.7, 116.4, 122.0, 127.6, 139.3, 140.3, 150.6, 152.5, 163.3. IR (KBr) ν 3077, 2228, 1099, 806 cm^{-1}. MS (EI) m/z 213 (M^+, 44%), 212 (M^+ − 1, 100%). HRMS Calcd for $C_{14}H_7ClF_3NS$: 312.9940. Found: 312.9917. The structure of **15m** was also determined by X-ray analysis. X-ray Crystallography: CCDC-1484411 contains the supplementary crystallographic data for this paper. The data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

*2-(4-Pyridinylthio)-4-(trifluoromethyl)pyrimidine (**15n**).* Brown solid (33.0 mg, 51%). Mp 149.0−150.0 °C (ethyl acetate/hexane = 4:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 (2H, d, J = 6.0 Hz), 7.64 (1H, d, J = 5.2 Hz), 8.64 (2H, d, J = 6.0 Hz), 9.06 (1H, dd, J = 4.8, 0.4 Hz). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 114.7, 119.7 (q, J = 274.0 Hz), 127.4, 130.8, 155.7, 157.6 (q, J = 37.3 Hz), 161.9, 199.9. ^{19}F NMR (376 MHz, $CDCl_3$) δ −70.0. IR (KBr) ν 3049, 2880, 1505, 1362, 1252 cm^{-1}. MS (EI) m/z 257 (M^+, 100%). HRMS Calcd for $C_{10}H_6F_3N_3S$: 257.0235. Found: 257.0225.

*6-Chloro-2-(4-pyridinylthio)benzoxazole (**15o**).* Colorless solid (39.3 mg, 60%). Mp 145.0−146.0 °C (hexane/ethyl acetate = 4:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (1H, dd, J = 8.4, 2.0 Hz), 7.50 (1H, d, J = 2.0 Hz), 7.57 (2H, dd, J = 4.8, 1.6 Hz), 7.58 (1H, d, J = 8.4

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Hz), 8.64 (2H, dd, J = 4.8, 1.6 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 111.0, 119.9, 125.47, 125.52, 131.0, 139.2, 140.2, 150.4, 151.8, 160.3. IR (KBr) ν 3028, 2980, 1508, 1209, 809 cm^{-1}. MS (EI) m/z 262 (M^+, 100%), 227 (M^+ − 35, 21%). HRMS Calcd for $C_{12}H_7ClN_2OS$: 261.9968. Found: 261.9945.

*6-(2-Furylthio)-3-pyridinecarbonitrile (**15p**).* Brown solid (30.8 mg, 61%). Mp 73.0−74.0 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 6.54 (1H, dd, J = 2.0, 0.8 Hz), 7.07 (1H, dd, J = 8.4, 0.8 Hz), 7.62 (1H, t, J = 2.0 Hz), 7.70 (1H, dd, J = 8.4, 2.0 Hz), 7.73 (1H, dd, J = 1.6, 0.8 Hz), 8.65 (1H, dd, J = 2.0, 0.8 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 105.3, 109.9, 114.6, 116.7, 119.6, 139.0, 145.0, 147.7, 152.1, 167.1. IR (KBr) ν 3033, 2225, 1584, 1435 cm^{-1}. MS (EI) m/z 202 (M^+, 100%). HRMS Calcd for $C_{10}H_6N_2OS$: 202.0201. Found: 202.0191.

*6-Chloro-2-(furylthio)benzoxazole (**15q**).* Colorless solid (50.3 mg, 80%). Mp 87.0−87.5 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 6.67 (1H, dd, J = 1.6, 0.8 Hz), 7.26 (1H, dd, J = 8.4, 2.0 Hz), 7.45 (1H, d, J = 2.0 Hz), 7.50 (1H, d, J = 8.4 Hz), 7.59 (1H, t, J = 1.6 Hz), 7.79 (1H, dd, J = 1.6, 0.8 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 107.6, 110.7, 114.6, 119.4, 125.1, 129.9, 140.7, 144.5, 147.1, 152.0, 163.7. IR (KBr) ν 3130, 1508, 1461, 1257 cm^{-1}. MS (EI) m/z 251 (M^+, 100%). HRMS Calcd for $C_{11}H_6ClNO_2S$: 250.9808. Found: 250.9789.

*6-Chloro-2-(2-thienylthio)benzoxazole (**15r**).* Yellow solid (62.3 mg, 93%). Mp 75.0−76.0 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 7.15 (1H, dd, J = 5.6, 4.0 Hz), 7.25 (1H, dd, J = 8.4, 1.6 Hz), 7.42 (1H, d, J = 2.0 Hz), 7.48 (1H, dd, J = 3.6, 1.2 Hz), 7.50 (1H, d, J = 8.8 Hz), 7.63 (1H, dd, J = 5.6, 1.6 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 110.8, 119.6, 122.4, 125.1, 128.1, 130.0, 133.3, 138.0, 140.6, 151.9, 163.7. IR (KBr) ν 3065, 1493, 1458, 1216, 911 cm^{-1}. MS (EI) m/z 267 (M^+, 100%), 115 (M^+ − 152, 37%). HRMS Calcd for $C_{11}H_6ClNOS_2$: 266.9579. Found: 266.9610. The structure of **15r** was also determined by X-ray analysis. X-ray Crystallography: CCDC-1506251 contains the supplementary crystallographic data for this paper. The data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

*4,5-Diphenyl-2-(2-furylthio)oxazole (**15s**).* Colorless solid (36.0 mg, 45%). Mp 93.0−94.0 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 6.68 (1H, dd, J = 1.6, 0.8 Hz), 7.34 (6H, m), 7.51 (3H, m), 7.62 (2H, dd, J = 8.4, 4.0 Hz), 7.76 (1H, m). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 109.3, 114.6, 126.3, 127.9, 128.3, 128.4, 128.5, 128.6, 131.8, 136.8, 144.0, 146.2, 147.7, 156.6. IR (KBr) ν 3128, 1505, 1206, 1014 cm^{-1}. MS (EI) m/z 319 (M^+, 100%). HRMS Calcd for $C_{19}H_{13}NO_2S$: 319.0667. Found: 319.0666. One carbon peak of aromatic region was overlapped in ^{13}CNMR.

*1-[5-(2-Furylthio)-2-furanyl]ethanone (**15t**).* Brown oil (51.6 mg, 99%). ^1H NMR (400 MHz, $CDCl_3$) δ 2.44 (3H, s), 6.41 (1H, d, J = 3.6 Hz), 6.50 (1H, dd, J = 1.6, 0.8 Hz), 7.12 (1H, d, J = 3.6 Hz), 7.47 (1H, t, J = 1.6 Hz), 7.64 (1H, dd, J = 1.6, 1.2 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 25.8, 111.9, 113.8, 114.5, 118.5, 144.1, 145.4, 151.9, 154.1, 185.9. IR (neat) ν 3139, 1677, 1456, 1012 cm^{-1}. MS (EI) m/z 208 (M^+, 100%), 166 (M^+ − 42, 29%). HRMS Calcd for $C_{10}H_8O_3S$: 208.0194. Found: 208.0202.

*1-[5-(2-Thienylthio)-2-furyl]ethanone (**15u**).* Yellow solid (44.9 mg, 80%). Mp 73.5−74.5 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 2.44 (3H, s), 6.46 (1H, d, J = 3.6 Hz), 7.03 (1H, dd, J = 5.2, 3.6 Hz), 7.11 (1H, d, J = 4.0 Hz), 7.33 (1H, dd, J = 3.2, 1.2 Hz), 7.45 (1H, dd, J = 5.6, 1.6 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 25.9, 115.3, 118.2, 127.8, 128.3, 131.3, 135.3, 152.0, 154.3, 186.2. IR (KBr) ν 3079, 1651, 1448, 1027 cm^{-1}. MS (EI) m/z 224 (M^+, 100%), 182 (M^+ − 42, 34%). HRMS Calcd for $C_{10}H_8O_2S_2$: 223.9966. Found: 223.9968.

Procedure for Oxidation Reaction of 6-(2-Pyridinylthio)-3-pyridinecarbonitrile 15e. (2-Pyridinylthio)-3-pyridinecarbonitrile **15e** (0.25 mmol, 53.3 mg) dissolved in CH_2Cl_2 (1.25 mL) at 0 °C under an argon atomosphere. A solution of *m*-CPBA (0.25 mmol, 43.4 mg) in CH_2Cl_2 (1.0 mL) was added dropwise to the cooled solution. The mixture was stirred at 0 °C for 6 h and then extracted sequentially with 2 M NaOH, 1 M HCl, and 10% $NaHCO_3$. The organic layer was dried over $MgSO_4$ and filtered. Solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel (eluent: ethyl acetate) giving 6-(2-pyridinylsulfinyl)-3-pyridinecarbonitrile **16** (25.8 mg, 45%). Mp 140.0−141.0 °C (ethyl acetate). ^1H NMR (400 MHz, $CDCl_3$) δ 7.39 (1H, ddd, J = 8.0, 4.8, 1.2 Hz), 7.90 (1H, dt, J = 7.6, 1.6 Hz), 8.01 (1H, d, J = 8.0 Hz), 8.14 (1H, dd, J = 8.0, 1.6 Hz), 8.23 (1H, dd, J = 8.0, 0.8 Hz), 8.65 (1H, m), 8.87 (1H, dd, J = 2.0, 0.8 Hz). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 111.2, 115.6, 119.5, 119.9, 125.6, 138.3, 141.2, 150.5, 152.3, 162.8, 168.7. IR (KBr) ν 3434, 2233, 1576, 1450, 1054 cm^{-1}. MS (EI) m/z 229 (M^+, 100%). HRMS Calcd for $C_{11}H_7N_3OS$: 229.0310. Found: 229.0309.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02585.

^1H, ^{13}C, and ^{19}F spectra of compounds **3a−3d**, **4**, **6**, **9**, **10**, **12a−12f**, **15a−15u**, and **16**; computational studies including Cartesian coordinates (PDF)

X-ray crystallographic data for **15m** (CIF)

X-ray crystallographic data for **15r** (CIF)

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Notes

The authors declare no competing financial interest.

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