An efficient one-pot synthesis of 2,5-disubstituted-1,3,4-thiadiazoles from aldehydes and hydrazides using Lawesson’s reagent

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This article dedicated to Professor George A. Kraus, in honor of his distinguished career in synthetic organic chemistry

Abstract

Five-membered heterocyclic-ring systems, such as thiadiazoles, remain an important and prevalent scaffold in the development of novel leads in medicinal chemistry for a variety of therapeutic targets. A two-step, one-pot synthesis of 2,5-disubstituted-1,3,4-thiadiazole derivatives from aryl hydrazides and aryl aldehydes using Lawesson’s reagent is described, yielding 2,5-disubstituted-1,3,4-thiadiazoles in moderate-to-high yields. Based on preliminary biological experiments, some of the newly synthesized thiadiazoles show antioxidant activity.

Keywords: 1,3,4-Thiadiazole, Lawesson’s reagent, N-acylhydrazone, N-aroylhydrazone, dimethylaminopyridine
Introduction

Heterocyclic compounds are defined, according to IUPAC (International Union of Pure and Applied Chemistry), as cyclic compounds including at least two different atoms such as oxygen, sulfur or nitrogen in the ring. These compounds are important due to their wide range of biological activities. For example, the antiviral Sovaldi (Gilead Sciences), the antipsychotic Abilify (Otsuka), and the anti-inflammatory Nexium are among the most popular and widely used drugs worldwide.1

Among the heterocyclic compounds, 1,3,4-thiadiazole has attracted special interest in recent years in various areas, including pharmaceutical, agricultural, and materials chemistries. 1,3,4-Thiadiazole is a weak base due to the inductive effect of the sulfur in the ring, and possesses a relatively high aromaticity.2,3,4 In addition, the ring is electron deficient due to the electron-withdrawing effects of the nitrogen atoms.2 For these reasons, in the pharmaceutical field, 1,3,4-thiadiazole derivatives are known to exhibit diverse biological activities, such as antimicrobial5, antiviral6, anticonvulsant7, antifungal,8-10 antitubercular,11-13 anticancer,14 and immunomodulatory15 activities. Some examples of commercially-available drugs containing the 1,3,4-thiadiazole ring are Megazol, Acetazolamide (Diamox), Furidiazine, and Desaglybuzole, shown in Figure 1.16,17

![Figure 1. Commercially available 1,3,4-thiadiazole drugs](image)

Synthetic methods to produce 1,3,4-thiadiazoles have been developed and studied over many decades due to the interest following the discovery of their diverse pharmacological and physiological activities. Well-known synthetic methods for 1,3,4-thiadiazoles include starting materials such as N,N’-diacylhydrazines,18,19 thiosemicarbazides20 or thiohydrazides,21,22 as well as the transformation of 1,3,4-oxadiazoles.23 Most existing synthetic methods, however, require harsh conditions, multi-step procedures, and scarce starting materials or experience difficulty in forming non-symmetric 1,3,4-thiadiazoles. Therefore, it is still necessary to develop a more efficient synthetic method to produce 1,3,4-thiadiazoles. We, herein, report a highly efficient, two-step, one-pot synthetic method for 2,5-disubstituted-1,3,4-thiadiazoles from aldehydes and hydrazides in good-to-excellent yields using a sequence of N-aroylhydrazone formation, thionation, cyclization and oxidation.

Results and Discussion

Originally, we thought that the synthesis of 1,3,4-thiadazole (5) could be brought about in a three-step reaction sequence. In Scheme 1, we illustrate the formation of the aroylhydrazone (3) from the corresponding hydrazide (1) and aldehyde (2), followed by thionation of 3 with Lawesson’s reagent (LR)24-26 to give a thiohydrazide intermediate (4). Oxidative cyclization of 4 using an oxidant such as I2, [bis(trifluoroacetoxy)iodobenzene] (PIFA) or FeCl3 yields the disubstituted-1,3,4-thiadiazole (5).
Scheme 1: 1,3,4-thiadiazoles from aryl aldehydes and hydrazides in a three-step sequence

When compound 3 was treated with LR, however, the disubstituted-1,3,4-thiadiazole (5) was formed directly without oxidant, and with separation of the thiohydrazide (4). Therefore, we studied a two-step, one-pot synthesis of 2,5-diphenyl-1,3,4-thiadiazole (5a) from benzyolhydrazide (1a) and benzaldehyde (2a) without isolation of the N-benzyolhydrazone (3a) (Scheme 2). After refluxing for 2 hours, the ethanol was evaporated *in vacuo*. To the reaction mixture of crude 3a (0.1 M) in solvent, LR was added, followed by addition of a base. In other trials, we omitted addition of the base. The resulting mixture was refluxed for 10 hours.

Scheme 2. Two-step, one-pot synthesis of 2,5-diphenyl-1,3,4-thiadiazole (5a) from benzyolhydrazide (1a) and benzaldehyde (2a) without separation of the N-benzyolhydrazone (3a) using LR

To determine the optimal procedure with solvents, thionating agents or additives, this one-pot reaction was investigated under several conditions (Table 1).
Table 1. Optimization of the synthesis of 2,5-diphenyl-1,3,4-thiadiazole (5a) from benzyolhydrazide (1a) and benzaldehyde (2a)\textsuperscript{a}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Thionating reagent [eq]</th>
<th>Solvent</th>
<th>Additive [eq]</th>
<th>Yield (%)\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LR [0.5]</td>
<td>Toluene</td>
<td>-</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>LR [0.8]</td>
<td>Toluene</td>
<td>-</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>LR [1.0]</td>
<td>Toluene</td>
<td>-</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>LR [0.8]</td>
<td>THF</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>LR [0.8]</td>
<td>Ethanol</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
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<td>Toluene</td>
<td>2,6-lutidine [1.2]</td>
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</tr>
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<td>7</td>
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<td>Toluene</td>
<td>DBU [1.2]</td>
<td>79</td>
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<tr>
<td>8</td>
<td>LR [0.8]</td>
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<td>Piperidine [1.2]</td>
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<tr>
<td>9</td>
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<td>Toluene</td>
<td>Pyridine [1.2]</td>
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<tr>
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<td>Toluene</td>
<td>DMAP [1.2]</td>
<td>96</td>
</tr>
<tr>
<td>11</td>
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<td>Toluene</td>
<td>DMAP [1.0]</td>
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<tr>
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<td>Toluene</td>
<td>DMAP [1.6]</td>
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<tr>
<td>13\textsuperscript{c}</td>
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<td>DMAP [1.2]</td>
<td>70</td>
</tr>
<tr>
<td>14</td>
<td>P\textsubscript{4}S\textsubscript{10} [0.8]</td>
<td>Toluene</td>
<td>DMAP [1.2]</td>
<td>13</td>
</tr>
</tbody>
</table>

\textsuperscript{a} The reaction was accomplished with a corresponding aldehyde and hydrazide in ethanol at room temperature. After refluxing for 2 hr, the ethanol was evaporated \textit{in vacuo}. To a remaining crude 3a, LR and solvent were added, followed by addition of a base. The resulting mixture was refluxed for 10 hr.

\textsuperscript{b} Isolated yield.

\textsuperscript{c} Two-pot synthesis including separation of 3a.

Initially, the reaction was started with 0.5 equivalent of LR, since stoichiometrically, one equivalent of LR produces two equivalents of dithiophosphine ylides to thionate a carbonyl group.\textsuperscript{24-26} When 0.5 equivalent of LR was used, 2,5-diphenyl-1,3,4-thiadiazole (5a) was produced in 68% yield (Table 1, entry 1). The amount of LR was gradually increased to 0.8 or 1.0 equivalent (Table 1, entries 2-3). The highest yield (79%) was obtained using 0.8 equivalent of LR (Table 1, entry 2). When tetrahydrofuran (THF), which is more polar than toluene, was used, the yield was only 60%. No reaction occurred when ethanol was used (Table 1, entry 5). Next, the base-additive effect was investigated by adding various bases, while maintaining the amount of LR at 0.8 equivalent in refluxing toluene as described above. When using bases such as 2,6-lutidine, 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), piperidine, pyridine, and dimethylaminopyridine (DMAP), the number of byproducts were lower, and the yields were similar or higher than those in the trials omitting the bases. The highest yield (96%) was obtained when 1.2 equivalents of DMAP were used (Table 1, entry 10), and was superior compared to 1.0 equivalent or 1.6 equivalents of DMAP (Table 1, entries 11-12). On the other hand, the two-step synthesis involving separation of N-arylationdrazone (3) showed a lower overall yield of 70% than the one-pot synthesis (Table 1, entry 13). Using another thionating reagent, P\textsubscript{4}S\textsubscript{10}, yielded only 13% of the desired product (Table 1, entry 14).

Based on the previous experimental results and the literature,\textsuperscript{27} the mechanism of this reaction can be proposed as shown in Scheme 3. Following formation of the N-arylationdrazone intermediate (3), it would react with LR to give the thiohydrazone (4). It is believed that dihydrothiadiazole (4'), which is the preferred
tautomeric form of the thiohydrazone (4), is readily oxidized to produce the disubstituted-1,3,4-thiadiazole (5).

![Scheme 3. Proposed mechanism for formation of the 1,3,4-thiadiazoles.](image)

To clarify the mechanism of this reaction, we needed to prove formation of intermediate 4 and/or 4'. Therefore, we synthesized compounds 4 and 4' by the known literature method.27-29 After the reaction of the phenyl thiohydrazone (9) with benzaldehyde (2a), the ring tautomer dihydrothiadiazole (4') was obtained, rather than the thiohydrazone (4) (Scheme 4). This was confirmed by analyzing $^1$H and $^{13}$C NMR spectra compared with the spectral data from a previous study.29 During our one-pot reaction, a TLC spot of dihydrothiadiazole (4') was also observed below the spot of 2,5-diphenyl-1,3,4-thiadiazole (5a). In addition, a small amount of 4' was isolated and its structure confirmed. As a result, it is suggested that the dihydrothiadiazole intermediate (4') is directly formed from 3, and immediately oxidized under the reaction conditions to produce 2,5-diphenyl-1,3,4-thiadiazole (5a).

![Scheme 4. Results of literature method for synthesis of intermediates 4 and/or 4'.](image)

As mentioned above, the use of a base is, presumably, to inhibit the reverse reaction of N-acylhydrazones (3) to aldehydes (2) and hydrazides (1), and, thereby, improve the overall yield of the reaction. Also, according to the literature, pyridine has been reported to stabilize and activate the phosphine ylide by forming stable complexes with $\text{P}_4\text{S}_{10}$ and Woollins reagents (WR),31 which has a structure similar to LR. LR is known to be in equilibrium with its dithiophosphine ylide in solution (Figure 2). This ylide is said to be the reactive intermediate in the thionation processes with LR.24-26 Therefore, we hypothesized that DMAP would protect the inverse-hydrolysis reaction of N-acylhydrazone (3), stabilize and activate LR by forming a stable DMAP-dithiophosphine complex like pyridine.
To extend the one-pot synthetic method to various 1,3,4-thiadiazoles (5), different combinations of arylhydrazides (1a-n) and benzaldehydes (2a-n) were reacted under the same conditions as 5a. First, the same amounts of aldehyde and hydrazide were reacted in refluxing ethanol for two hours. After the ethanol was evaporated, the remaining crude thiahydrazone (3) in the reaction vessel was reacted in toluene, refluxing with 0.8 equivalent of LR and 1.2 equivalents of DMAP for 12 hours as shown in Scheme 5.

Scheme 5. Synthesis of 2,5-diphenyl-1,3,4-thiadiazole derivatives (5). Note: Benzaldehyde (1.0 mmol) and benzoylhydrazide (1.0 mmol) were refluxed in ethanol for 2 hr, evaporated in vacuo, and then reacted with LR and DMAP in refluxing toluene.

A series of 2,5-disubstituted-1,3,4-thiadiazoles (5a-m) were prepared in moderate-to-high yields (75% to 97%) from hydrazides (1a-n) and aldehydes (2a-n), the results of which are summarized in Table 2.
Table 2: Results of reactions of hydrazides (1) and benzaldehydes (2) to yield 2,5-disubstituted-1,3,4-thiadiazole compounds (5)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Product</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Entry</th>
<th>Product</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
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<td>80</td>
<td>14</td>
<td><img src="image14.png" alt="image" /></td>
<td>85</td>
</tr>
</tbody>
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<sup>a</sup> Isolated yield by flash column chromatography.

In summary, a two-step, one-pot reaction was accomplished in refluxing ethanol using the same amounts of hydrazide 1 and aldehyde 2 without separating the hydrazine intermediate 3, and in the absence of added oxidant.

Conclusions

In conclusion, we have developed a highly efficient, two-step, one-pot synthesis of 2,5-disubstituted-1,3,4-thiadiazoles in moderate-to-high yields from benzaldehydes and hydrazines using LR in the absence of an...
additional oxidant. Based on the confirmation of the formation of thia diazoline intermediate, a reaction mechanism has been proposed and the role of the base additives in this reaction has been suggested. According to preliminary biological experiments, some of the newly synthesized thia diazoles show antioxidant activity. These results will be presented in a future study.

**Experimental Section**

**General.**
Melting points were determined using a Barnstead Electrothermal 9100 melting point apparatus. $^1$H NMR and $^{13}$C NMR spectra were recorded on a JEOL 300 MHz spectrometer and JEOL 75MHZ spectrometer, respectively. Chemical shifts (δ) are reported in parts per million (ppm) and coupling constants (J) in Hertz (Hz). The following abbreviations were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br s = broad singlet. High resolution mass spectrometry (HRMS) was performed using a JEOL JMS-700 M station mass spectrometer and electron impact ionization (EI-magnetic sector) mass spectrometer.

**General procedure for synthesis of compounds 5a-5m**
In a round bottom flask, corresponding aldehyde (2) (1.0 mmol) and hydrazide (1) (1.0 mmol) were added in ethanol (5.0 ml) at room temperature. The reaction mixture was refluxed for 2 hr. The ethanol was evaporated in vacuo. To the resulting crude product (3), Lawesson’s reagent (0.8 mmol, 0.8 eq) and toluene (10 ml) were added, followed by 4-(dimethylamino)pyridine (1.2 mmol, 1.2 eq). The resulting mixture was refluxed for 10 to 15 hr until 2,5-diphenyl-2,3-dihydro-1,3,4-thia diazole was not detected by TLC. After evaporation of toluene, the residue was purified by flash-column chromatography.

2,5-Diphenyl-1,3,4-thia diazole (5a)$^{32,33}$ [CAS No. 1456-21-9]. White solid; Yield: 96%; mp 134-135 ºC (Lit. 140 or 132 ºC); $^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 7.47-7.56 (m, 4H), 7.98-8.07 (m, 4 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 127.98, 129.23, 130.24, 131.15, 168.23 (thia diazole C)

2-(4-Fluorophenyl)-5-phenyl-1,3,4-thia diazole (5b)$^{33}$ [CAS No. 16020385-48-9]. White solid; Yield: 97%; mp 174-175 ºC (Lit. 173 ºC) $^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 7.21 (t, J 8.5 Hz, 2 H), 7.48-7.55 (m, 3 H), 7.98-8.07 (m, 4 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 116.27, 116.56, 127.97, 129.25, 130.01, 131.23, 162.83, 166.17 (F-Phenyl-4-C), 166.99 (thia diazole C), 168.28 (thia diazole C)

2-(4-Chlorophenyl)-5-phenyl-1,3,4-thia diazole (5c)$^{32}$ [CAS No. 17453-22-4]: White solid; Yield: 93%; mp 177-178 ºC (Lit. 180 ºC). $^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 7.41-7.56 (m, 5 H), 7.89-8.06 (m, 4 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 128.01, 128.71, 129.11, 129.28, 129.53, 130.05, 131.32, 137.28, 166.98 (thia diazole C), 168.49 (thia diazole C)

2-(4-Bromophenyl)-5-phenyl-1,3,4-thia diazole (5d)$^{33}$ [CAS No. 17453-23-5]. White solid; Yield: 87%; mp 153-154 ºC (Lit. 152 ºC). $^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 7.51-7.53 (m, 3 H), 7.65 (d, J 8.6 Hz, 2 H), 7.90 (d, J 8.6 Hz, 2 H), 8.02 (dd, J 6.6, 2.9 Hz, 2 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 125.77, 128.18, 129.31, 129.46, 130.20, 131.50, 132.66, 167.24 (thia diazole C), 168.69 (thia diazole C)

2-(4-Methoxyphenyl)-5-phenyl-1,3,4-thia diazole (5e)$^{33}$ [CAS No. 1456-67-3]. White solid; Yield: 93% from phenylhydrazide and 4-methoxybenzaldehyde, 89% from 4-methoxybenzohydrazide and benzaldehyde; mp137-138 ºC (Lit. 136 ºC). $^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 3.85 (s, 3 H), 6.96-7.05 (m, 2 H), 7.43-7.54 (m, 3 H), 7.91-8.05 (m, 4 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 55.60, 114.77, 123.13, 128.08, 129.37, 129.73, 130.58, 131.15, 162.22 (MeO-Phenyl-4-C), 167.62 (thia diazole C), 168.19 (thia diazole C)
2-(3,5-Dimethoxyphenyl)-5-phenyl-1,3,4-thiadiazole (5f). White solid; Yield: 85%; mp 144-145 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.88 (s, 6 H), 6.60 (t, J 2.2 Hz, 1 H), 7.18 (d, J 2.2 Hz, 2 H), 7.47-7.55 (m, 3 H), 8.01 (dd, J 6.6, 2.9 Hz, 2H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.73, 103.56, 106.02, 128.14, 129.39, 130.35, 131.36, 131.97, 161.42, 168.36 (thiadiazole C), 168.48 (thiadiazole C); HRMS (EI+): m/z Calcd. for C₁₆H₁₄N₂O₅S¹⁺: 298.0776; found: 298.0764

2-(4-Ethylphenyl)-5-phenyl-1,3,4-thiadiazole (5g). White solid; Yield: 80%; mp 90-91 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 1.28 (t, J 7.6 Hz, 3 H), 7.22 (q, J 7.7 Hz, 2 H), 7.33 (d, J 8.3 Hz, 2 H), 7.44-7.57 (m, 3 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.52, 114.72, 116.32, 116.62, 122.89, 126.77, 126.81, 129.64, 129.90, 130.02, 162.19, 162.84, 166.17, 166.30 (thiadiazole C), 168.18 (thiadiazole C); HRMS (EI+): m/z Calcd. for C₁₆H₁₄N₂S⁺: 266.0872; found: 266.0872

2-(4-Fluorophenyl)-5-(4-methoxyphenyl)-1,3,4-thiadiazole (5h). White solid; Yield: 80%; mp 160-161 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.89 (s, 3 H) 7.01 (d, J 9.0 Hz, 2 H), 7.19 (t, J 8.6 Hz, 2 H), 7.95 (d, J 8.8 Hz, 2 H), 8.00 (dd, J 8.8, 5.1 Hz, 2 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.59, 114.80, 122.91, 129.04, 129.20, 129.64, 129.75, 137.22, 162.31, 166.33 (thiadiazole C), 168.43 (thiadiazole C)

2-(4-Chlorophenyl)-5-(4-methoxyphenyl)-1,3,4-thiadiazole (5i).³⁴ [CAS No. 17572-63-3]: White solid; Yield: 85%; mp 190-191 °C; Lit. 186-187 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.89 (s, 3 H) 7.01 (d, J 8.8 Hz, 2 H), 7.48 (d, J 8.6 Hz, 2 H), 7.95 (dd, J 8.8, 2.9 Hz, 4 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.59, 114.80, 122.91, 129.04, 130.29, 129.64, 129.75, 137.22, 162.31, 166.33 (thiadiazole C), 168.43 (thiadiazole C)

2-(4-bromophenyl)-5-(4-methoxyphenyl)-1,3,4-thiadiazole (5j). White solid; Yield: 83%; mp 215 °C; Lit. 213 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.89 (s, 3 H) 7.01 (d, J 8.6 Hz, 2 H), 7.63 (d, J 8.4 Hz, 2 H), 7.88 (d, J 8.4 Hz, 2 H), 7.96 (d, J 8.6 Hz, 2 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.59, 114.77, 122.85, 125.52, 129.36, 129.73, 132.59, 162.28, 166.41 (thiadiazole C), 168.45 (thiadiazole C); HRMS (EI+): m/z Calcd. For: C₁₅H₁₁BrN₂O₂⁺: 345.9775; Found: 345.9764

2,5-Bis-(4-methoxyphenyl)-1,3,4-thiadiazole (5k).³⁵ [CAS No. 17453-03-1]. White solid; Yield: 78%; mp 167-169 °C; Lit. 170-172 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.88 (s, 6 H), 7.00 (d, J 8.8 Hz, 4 H), 7.94 (d, J 8.8 Hz, 4 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.58, 114.72, 123.28, 129.61, 162.06, 167.40 (thiadiazole C)

2-(3,5-Dimethoxyphenyl)-5-(4-methoxyphenyl)-1,3,4-thiadiazole (5l). Light beige solid; Yield: 75%; mp 134-135 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 3.88 (s, 6 H), 3.89 (s, 3 H), 6.59 (t, J 2.3 Hz, 1 H), 7.01 (d, J 8.8 Hz, 2 H), 7.16 (d, J 2.3 Hz, 2 H), 7.95 (d, J 8.8 Hz, 2 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 55.57, 55.72, 103.42, 105.94, 114.74, 123.05, 129.69, 132.13, 161.41, 162.22, 167.56 (thiadiazole C), 168.25 (thiadiazole C); HRMS (EI+): m/z Calcd. for C₁₇H₁₆N₂O₃S⁺: 328.0882; Found: 328.0869

2-(4-Ethylphenyl)-5-(4-methoxyphenyl)-1,3,4-thiadiazole (5m). White solid; Yield: 85%; mp 101-102 °C. ¹H NMR (300 MHz, CDCl₃) δ (ppm) 1.28 (t, J 7.6 Hz, 3 H), 7.22 (q, J 7.5 Hz, 2 H), 3.89 (s, 3 H), 7.01 (d, J 9.0 Hz, 2 H), 7.32 (d, J 8.3 Hz, 2 H), 7.96 (d, J 9.0 Hz, 2 H), 7.92 (d, J 8.3 Hz, 2 H); ¹³C NMR (75 MHz, CDCl₃) δ (ppm) 15.35, 28.88, 55.56, 114.68, 123.16, 127.99, 128.07, 128.84, 129.63, 147.85, 162.06, 167.72 (thiadiazole C), 167.76 (thiadiazole C); HRMS (EI+): m/z Calcd. For: C₁₇H₁₆N₂O₂⁺: 296.0983; Found: 296.1002

Procedure for synthesis of compound (8)²⁷,²⁸

In a round-bottom flask, following flame drying, 40 ml of 1M phenylmagnesium bromide (40 mmol) in THF was added. It was then cooled to 0 °C, and 2.42 ml of carbon disulfide (40 mmol) was slowly introduced dropwise. It was stirred at room temperature for 12 hr and then poured into 100 g of ice water and 3.78 g of chloroacetic acid (40 mmol). Anhydrous sodium carbonate 3.36g (20 mmol) was added and stirred for 24 hr at 90 °C. The liquid was adjusted to pH 2 with concentrated hydrochloric acid, and a red solid was obtained by recrystallization in a mixture of ethyl acetate and hexane.
2-(Phenylcarbonothionylthio)acetic acid (8) [CAS No. 942-91-6]. Yield: 72%; mp 125-126 °C [Lit. 123-125 °C].
$^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 4.28 (s, 2 H), 7.41 (t, $J$ 7.7 Hz, 2 H), 7.57 (t, $J$ 7.5 Hz, 1 H), 8.03 (d, $J$ 7.9 Hz, 2 H), 10.52 (br. s, 1 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 38.76, 127.23, 128.69, 133.18, 144.20, 173.86, 225.89.

Procedure for synthesis of compound 9

Compound 8 (2.0 g, 9.4 mmol) was dissolved in 1 M NaOH (10 mL, 1 eq) and H$_2$O (10 ml). Upon addition of hydrazine hydrate (1.7 g, 55%, 18.8 mmol), the orange color disappeared. After consumption of the starting material, the reaction mixture was acidified to pH 5-6 with dilute HCl (aq) and stirred for 1 hr while cooling in an ice bath. A white solid was filtered and recrystallized from water to produce benzothiohydrazide (9) as white crystals.

Benzothiohydrazide (9) [CAS No. 20605-40-7]. White solid; Yield: 60%; mp 80-82 °C [Lit. 78-80 °C].
$^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 6.25 (br. s, 1 H), 7.37-7.46 (m, 3 H), 7.70 (d, $J$ 7.0 Hz, 2 H), 12.13 (br. s, 1 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 127.82, 129.63, 129.69, 131.64, 167.97.

Procedure for synthesis of compound (4')

In a round-bottom flask, benzaldehyde (0.5 mmol) and 9 (0.5 mmol) were added in ethanol (5 ml) for 2 hr at room temperature. After the reaction was complete, the ethanol was evaporated under vacuum, and the product was obtained by recrystallization in a mixture of ethyl acetate and hexane.

2,5-Diphenyl-2,3-dihydro-1,3,4-thiadiazole (4') [CAS No. 82243-06-9]. Yield: 92%; mp 78-79 °C [Lit. 76-78 °C].
$^1$H NMR (300 MHz, CDCl$_3$) δ (ppm) 6.36 (s, 1 H, C-5 H), 7.29-7.42 (m, 6 H), 7.43-7.53 (m, 2 H), 7.61-7.75 (m, 2 H); $^{13}$C NMR (75 MHz, CDCl$_3$) δ (ppm) 74.72 (C-5), 126.65, 127.21, 128.69, 129.69, 129.92, 130.37, 140.93, 146.65.

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