



Cite this: *RSC Adv.*, 2020, 10, 41041

Received 3rd October 2020  
 Accepted 31st October 2020

DOI: 10.1039/d0ra08441g

[rsc.li/rsc-advances](http://rsc.li/rsc-advances)

# The synthesis of *N,N'*-disulfanediy-bis(*N'*-((*E*)-benzylidene)acetohydrazide) from (*E*)-*N'*-benzylideneacetohydrazide and $S_8$ †

Hong-Yan Liu,<sup>a</sup> Yu Chen,<sup>b</sup> Li-Qiang Hao,<sup>a</sup> Guo-Dong Wang,<sup>a</sup> Hong-Shuang Li<sup>ID</sup><sup>a</sup> and Cheng-Cai Xia<sup>ID</sup><sup>\*a</sup>

Herein we report an oxidative coupling reaction for N–S–S bond formation from (*E*)-*N'*-benzylideneacetohydrazide and  $S_8$  to furnish substituted *N,N'*-disulfanediy-bis(*N'*-((*E*)-benzylidene)acetohydrazide). It provides a direct approach for the synthesis of disulfides with good yields.

## Introduction

Disulfide bonds are important structural units which were found prevalently in natural or endogenous peptides.<sup>1</sup> They have been applied in digital light processing 3D printing,<sup>2</sup> and as bioactive agrochemicals,<sup>3</sup> antimicrobials,<sup>4</sup> and synthetic intermediates.<sup>5</sup> In addition, it is well-established that the disulfide linkage can be cleaved with the tripeptide glutathione (GSH),<sup>6</sup> which is over-expressed in cancer cells associated with strong biomedical activities.<sup>7</sup> Especially, a number of *S,S'*-bis(heterosubstituted) disulfides with N–S–S–N units exhibit a wide spectrum of biological activity (Fig. 1).<sup>8</sup> Thus, developing an efficient and practical procedure for the synthesis of disulfides is highly desirable. Numerous strategies have been

developed for the formation of disulfide bonds.<sup>9</sup> Among these pathways, the most common approach involves the substitution of a sulfenyl derivative with a thiol or thiol derivative and these

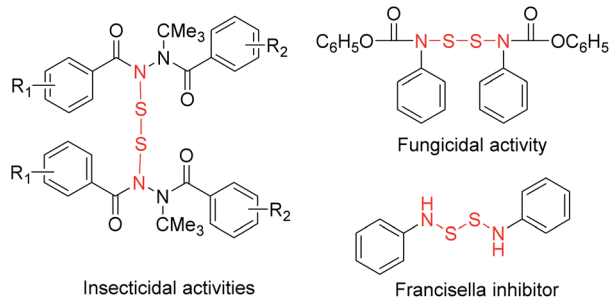


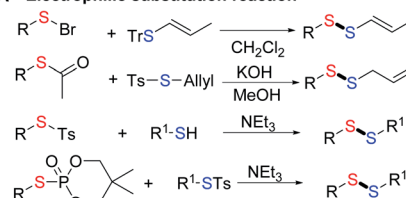
Fig. 1 Selected biologically active pharmaceuticals derived from *S,S'*-bis(heterosubstituted) disulfides.

<sup>a</sup>School of Pharmacy College, Institute of Pharmacology, Shandong First Medical University, Shandong Academy of Medical Sciences, Tai'an, 271016, China. E-mail: [xiachc@163.com](mailto:xiachc@163.com)

<sup>b</sup>School of Shandong Polytechnic College, Jining, 272067, China

† Electronic supplementary information (ESI) available. CCDC 2008330. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0ra08441g

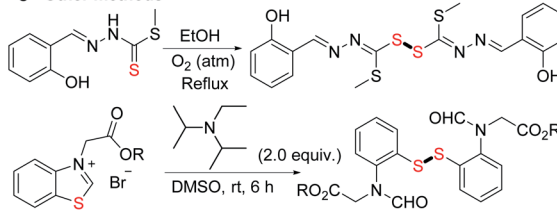
### A Electrophilic substitution reaction



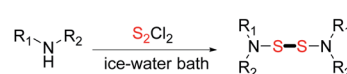
### B Oxidative coupling of thiols



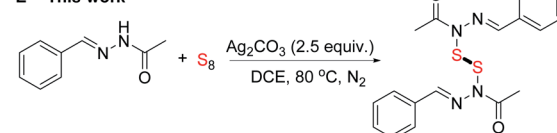
### C Other methods



### D React with disulfur dichloride



### E This work



Scheme 1 Strategies for the preparation of disulfides.

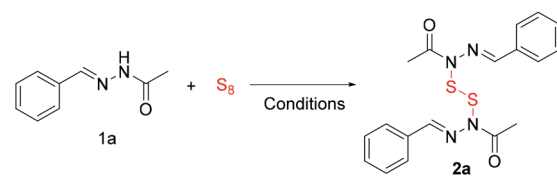


predecessor's work have been summarized by Witt (Scheme 1A).<sup>10</sup> In recent decades, oxidative coupling of thiols has developed into an efficient approach for producing disulfides. Many oxidants such as oxygen or air,<sup>11,12</sup> hydrogen peroxide,<sup>13</sup> halogens,<sup>14</sup> high-valent sulfur compounds<sup>15</sup> and other agents<sup>16</sup> were applied (Scheme 1B). In addition, methyl (*E*)-2-(2-hydroxybenzylidene)hydrazine-1-carbodithioate<sup>17</sup> and *N*-phenacylbenzothiazolium bromides<sup>18</sup> have also been used as starting materials to produce disulfides (Scheme 1C). Different from these C–S–S–C bonds, there are only a few reports in the literatures that describe N–S–S–N bond formation. In these cases, secondary amines reacted with disulfur dichloride to afford *S,S'*-bis(heterosubstituted) disulfides (Scheme 1D).<sup>8,19</sup> As part of our continuing efforts into the development of the C–S bonds formation,<sup>20</sup> herein we report an efficient method for generating *N,N'*-disulfanediyil bis(*N'*-(*E*)-benzylidene) acetohydrazide from (*E*)-*N'*-benzylideneacetohydrazide and S<sub>8</sub>. To the best of our knowledge, it is the first example of the formation of N–S–S–N bonds from S<sub>8</sub> in moderate yields, and the reaction conditions are simple and mild (Scheme 1E).

## Results and discussion

As an initial experiment, we treated the model substrate (*E*)-*N'*-benzylideneacetohydrazide **1a** and S<sub>8</sub> using Ag<sub>2</sub>CO<sub>3</sub> as the

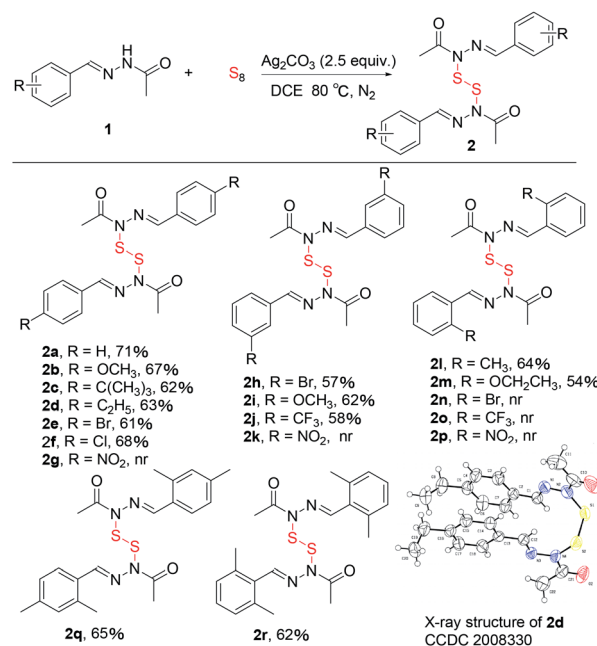
Table 1 Optimization of reaction conditions<sup>a,b</sup>



Entry	Additive (equiv.)	S <sub>8</sub> (equiv.)	Temp (°C)	Time (h)	Yield <sup>b</sup> (%)
1	Ag <sub>2</sub> CO <sub>3</sub> (1.0)	S <sub>8</sub> (0.3)	80	3	46
2	Ag <sub>2</sub> CO <sub>3</sub> (2.0)	S <sub>8</sub> (0.3)	80	3	61
3	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	3	71
4	Ag <sub>2</sub> CO <sub>3</sub> (3.0)	S <sub>8</sub> (0.3)	80	3	66
5	Ag <sub>2</sub> CO <sub>3</sub> (4.0)	S <sub>8</sub> (0.3)	80	3	64
6	Ag <sub>2</sub> CO <sub>3</sub> (0.5)	S <sub>8</sub> (0.3)	80	3	32 <sup>c</sup>
7	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.2)	80	3	42
8	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.4)	80	3	63
9	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.6)	80	3	60
10	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	60	3	40
11	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	90	3	49
12	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	100	3	52
13	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	110	3	53
14	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	120	3	50
15	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	2	41
16	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	4	68
17	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	6	61
18	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	12	59
19	Ag <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	3	46 <sup>d</sup> , 48 <sup>e</sup>
20	K <sub>2</sub> CO <sub>3</sub> (2.5)	S <sub>8</sub> (0.3)	80	3	0

<sup>a</sup> Reaction conditions: **1a** (0.2 mmol), S<sub>8</sub> (0.3 mmol), Ag<sub>2</sub>CO<sub>3</sub> (2.5 equiv.) in CH<sub>2</sub>ClCH<sub>2</sub>Cl (2.0 mL) was stirred at sealed tube, N<sub>2</sub>, 80 °C for 3 h. <sup>b</sup> Isolated yields. <sup>c</sup> Added K<sub>2</sub>S<sub>2</sub>O<sub>8</sub> (2.5 equiv.). <sup>d</sup> Air. <sup>e</sup> O<sub>2</sub>.

Table 2 Scope of various substituents on the benzene ring of the aromatic aldehyde **1**<sup>a,b</sup>

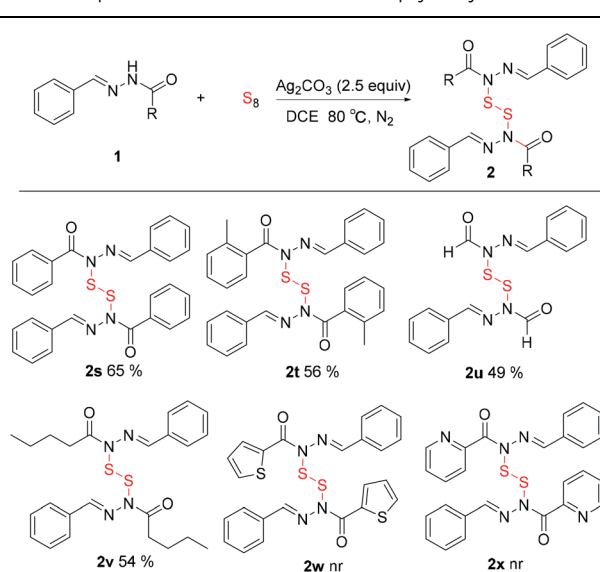


<sup>a</sup> Reaction conditions: **1a** (0.2 mmol), S<sub>8</sub> (0.3 mmol), Ag<sub>2</sub>CO<sub>3</sub> (2.5 equiv.) in CH<sub>2</sub>ClCH<sub>2</sub>Cl (2.0 mL) was stirred at sealed tube, N<sub>2</sub>, 80 °C for 3 h. <sup>b</sup> Isolated yields.

oxidant in 1,2-dichloroethane at 80 °C (Table 1). First, the screening of the loading of Ag<sub>2</sub>CO<sub>3</sub> was carried out, and it was found that 2.5 equiv. of Ag<sub>2</sub>CO<sub>3</sub> provided the best result (Table 1, entries 1–5). After this, we only obtained 32% yield when it added 2.5 equiv. of K<sub>2</sub>S<sub>2</sub>O<sub>8</sub> and reduced the loading of Ag<sub>2</sub>CO<sub>3</sub> to 0.5 equiv. (Table 1, entry 6). Meanwhile, we also evaluated the amount of S<sub>8</sub>, and the use of 0.3 equiv. of the material gave the highest yield (Table 1, entries 3, 7–9). The temperature also played an important role in the reaction. Various temperatures, such as 60, 90, 100, 110 and 120 °C were also screened, but the yields are poor (Table 1, entries 10–14). Finally, there was no obvious improvement on shortening the reaction time to 2 h or prolonging the reaction time to 4, 6, or 12 h (Table 1, entries 15–18). Impressively, control experiments revealed that the reactions performed under O<sub>2</sub> and air atmosphere provided slightly decreased yields (Table 1, entry 19). And it has been shown that K<sub>2</sub>CO<sub>3</sub> replaced Ag<sub>2</sub>CO<sub>3</sub> has no reaction (Table 1, entry 20).

With the standard reaction conditions in hand (Table 1, entry 3), we subsequently investigated the scope of the benzoylquinones (Table 2). Substrates derived from aromatic aldehydes with the *para*-substituted groups, such as 4-OMe (**2b**), 4-C(CH<sub>3</sub>)<sub>3</sub> (**2c**), 4-C<sub>2</sub>H<sub>5</sub> (**2d**), 4-Br (**2e**), 4-Cl (**2f**), afforded the corresponding products in good yields. Unfortunately, the product with an electron-withdrawing group such as 4-NO<sub>2</sub> (**2g**) could not be detected. Gratifyingly, the substrates with *meta*-substituted groups such as electron-withdrawing 3-Br (**2h**) and 3-CF<sub>3</sub> (**2j**) and electron-donating 3-OMe (**2i**) also give good yields. But, the product with a 3-NO<sub>2</sub> group (**2k**) could not be observed.

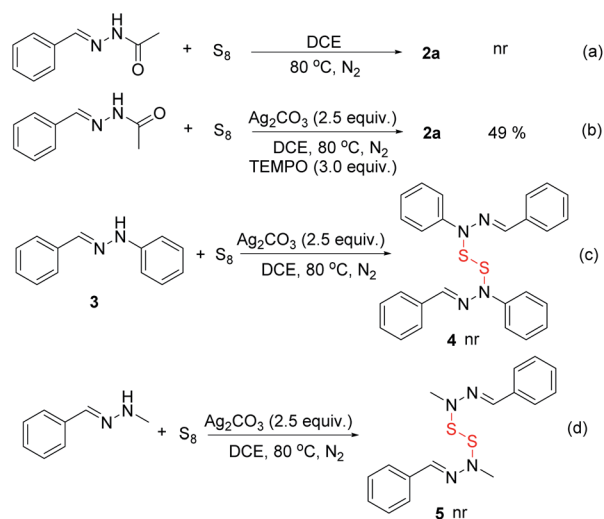


Table 3 Scope of various substituents of caprylic hydrazide **1**<sup>a,b</sup>

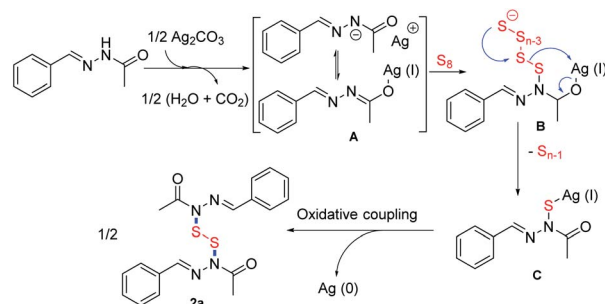
<sup>a</sup> Reaction conditions: **1a** (0.2 mmol),  $S_8$  (0.3 mmol),  $Ag_2CO_3$  (2.5 equiv.) in  $CH_2ClCH_2Cl$  (2.0 mL) was stirred at sealed tube,  $N_2$ , 80 °C for 3 h.  
<sup>b</sup> Isolated yields.

Subsequently, many components with the electron-donating groups such as 2- $CH_3$  (**2l**) and 2- $OC_2H_5$  (**2m**) at the *ortho* position on the benzene ring gave good yields. However, the substrates with a halogen group such as 2-Br (**2n**) and electron-withdrawing groups such as 2- $CF_3$  (**2o**), 2- $NO_2$  (**2p**) at the *ortho*-position did not provide the corresponding products. To our delight, many disubstituted substrates such as **2q** and **2r** also gave the related products in 62–65% yields. In addition, the structure of the product (**2d**) was confirmed by X-ray crystallography. Notably, the gram-scale synthesis was achieved under the standard conditions, giving the product **2a** in 46% yield.

Various acyl hydrazides were also examined to explore the limits of the reaction. As shown in Table 3, benzohydrazide (**2s**),



Scheme 2 Mechanistic studies.



Scheme 3 Postulated reaction mechanism.

2-methylbenzohydrazide (**2t**) all afforded good yields. Furthermore, the alkyl hydrazide such as formyl hydrazide (**2u**), valeryl hydrazide (**2v**) also afforded the corresponding products in 49–54% yields. Surprisingly, thiophene-2-carbohydrazide (**2w**) picolinohydrazide (**2x**) failed to produce the requisite disulfides.

To understand the mechanism of the reaction, several control experiments were carried out (Scheme 2). First, product **2a** was not obtained without  $Ag_2CO_3$  (Scheme 2a), which indicated that  $Ag_2CO_3$  was crucial to facilitate this reaction. Second, we found that the desired product **2a** was only slightly decreased when the radical scavenger such as TEMPO was added to the reaction mixture (Scheme 2b). The result indicates that a free radical pathway might be ruled out in this transformation. Third, replacing (*E*)-*N'*-benzylideneacetohydrazide with (*E*)-*N'*-benzylidenebenzohydrazide produced the desired compound **2s** in 65% yield under the standard conditions. Additionally, the product **4** was not observed when (*E*)-1-benzylidene-2-phenylhydrazine **3** was used as the substrate under the standard reaction conditions (Scheme 2c). Furthermore, when (*E*)-1-benzylidene-2-methylhydrazine was used in the reaction, the target product **5** was not detected (Scheme 2d). Based on these results, we knew that the acetyl group was essential for the reaction and an oxygen atom of acetyl group was also necessary. Additionally, the reactions carried out under  $O_2$  and air atmosphere have slightly decreased the yields of the product and the by-products increased (Table 1, entries 18 and 19).

On basis of these preliminary studies and previous reports,<sup>21–28</sup> a plausible pathway for the preparation of **2a** from (*E*)-*N'*-benzylideneacetohydrazide is proposed in (Scheme 3). Initially,  $Ag_2CO_3$  react with **1** to produce the intermediate (**A**). Next, **A** reacts with  $S_8$  to provide the intermediate **B**. The intermediate **C** is then produced through an electrophilic attack of elemental sulfur.<sup>21,22</sup> Finally, **2a** was obtained *via* facile oxidative coupling of the intermediate **C**.

## Conclusions

In summary, we have developed a silver-mediated oxidative coupling reaction for N-S/S-S bond formation using (*E*)-*N'*-benzylideneacetohydrazide and  $S_8$  as the starting materials under neutral conditions. In these processes, *N,N'*-disulfanediy bis(*N'*-(*E*-benzylidene) acetohydrazides) have been successfully synthesized. Moreover, this method provides a direct way to form the disulfides in moderate yields.



## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We gratefully thank the Shandong Provincial Natural Science Foundation (ZR2017LB006) and Academic promotion program of Shandong First Medical University (no. 2019LJ003) for financial support.

## Notes and references

- 1 A. Taguchi, K. Kobayashi, Y. Cui, K. Takayama, A. Taniguchi and Y. Hayashi, Disulfide-driven cyclic peptide synthesis of human endothelin-2 with a solid-supported Npys-Cl, *J. Org. Chem.*, 2020, **85**, 1495.
- 2 X. P. Li, R. Yu, Y. Y. He, Y. Zhang, X. Yang, X. J. Zhao and W. Huang, Self-healing polyurethane elastomers based on a disulfide bond by digital light processing 3D printing, *ACS Macro Lett.*, 2019, **8**, 1511.
- 3 F. J. R. Mejías, S. M. Lopez-Haro, R. M. Varela, J. M. G. Molinillo, J. J. Calvino and F. A. Macías, *In situ* eco encapsulation of bioactive agrochemicals within fully organic nanotubes, *ACS Appl. Mater. Interfaces*, 2019, **11**, 41925.
- 4 Ş. D. Doğan, S. Buran, M. G. Gündüz, C. Özkul, V. S. Krishna and D. Sriram, Synthesis of disulfide-bridged *N*-phenyl-*N'*-(alkyl/aryl/heteroaryl) urea derivatives and evaluation of their antimicrobial activities, *Chem. Biodiversity*, 2019, **16**, e190046.
- 5 (a) J. N. Zhao, F. Yang, Z. Y. Yu, X. F. Tang, Y. F. Wu, C. F. Ma and Q. W. Meng, Copper(i)-catalyzed sulfenylation of 1,3-dicarbonyl substrates with disulfides under mild conditions, *Synlett*, 2019, **30**, 2295; (b) J. N. Zhao, F. Yang, Z. Y. Yu, X. F. Tang, Y. F. Wu, C. F. Ma and Q. W. Meng, Visible light-mediated selective  $\alpha$ -functionalization of 1,3-dicarbonyl compounds *via* disulfide induced aerobic oxidation, *Chem. Commun.*, 2019, **55**, 13008; (c) Z. H. Shang, Q. Y. Chen, L. L. Xing, Y. L. Zhang, L. Wait and Y. F. Du, *In situ* formation of RSCl/ArSeCl and their oxidative coupling with enamionone derivatives under transition-metal free conditions, *Adv. Synth. Catal.*, 2019, **361**, 4926; (d) M. Mesgar, J. Nguyen-Le and O. Daugulis, 1,2-Bis(arylthio)arene synthesis *via* aryne intermediates, *Chem. Commun.*, 2019, **55**, 9467; (e) C. C. Xia, Z. J. Wei, Y. Yang, W. B. Yu, H. X. Liao, C. Shen and P. F. Zhang, Palladium-catalyzed thioetherification of quinolone derivatives *via* decarboxylative C–S cross-couplings, *Chem.-Asian J.*, 2016, **11**, 360.
- 6 (a) P. Kumar, B. Liu and G. A. Behl, A comprehensive outlook of synthetic strategies and applications of redox-responsive nanogels in drug delivery, *Macromol. Biosci.*, 2019, **19**, 1900071; (b) B. Sui, C. Cheng and P. Xu, Pyridyl disulfide functionalized polymers as nanotherapeutic platforms, *Adv. Ther.*, 2019, **2**, 1900062; (c) J. F. Quinn, M. R. Whittaker and T. P. Davis, Glutathione responsive polymers and their application in drug delivery systems, *Polym. Chem.*, 2017, **8**, 97; (d) M. H. Lee, Z. Yang, C. W. Lim, Y. H. Lee, S. Dongbang, C. Kang and J. S. Kim, Disulfide-cleavage-triggered chemosensors and their biological applications, *Chem. Rev.*, 2013, **113**, 5071; (e) J. K. Oh, Disassembly and tumor-targeting drug delivery of reduction-responsive degradable block copolymer nanoassemblies, *Polym. Chem.*, 2019, **10**, 1554; (f) H. Mutlu, E. B. Ceper, X. Li, J. Yang, W. Dong, M. M. Ozmen and P. Theato, Sulfur chemistry in polymer and materials Science, *Macromol. Rapid Commun.*, 2019, **40**, 1800650; (g) S. Pottanam-Chali and B. J. Ravoo, Polymer Nanocontainers for intracellular delivery, *Angew. Chem., Int. Ed.*, 2020, **59**, 2962.
- 7 R. Bej, P. Rajdev, R. Barmana and S. Ghosh, Hyperbranched polydisulfide, *Polym. Chem.*, 2020, **11**, 990.
- 8 (a) F. E. Adelowo, I. A. O. Ojo and O. S. Amuda, Synthesis and fungicidal activity of some sulphide derivatives of *O*-phenyl-*N*-substituted phenylcarbamates, *Adv. Biol. Chem.*, 2011, **1**, 122; (b) R. F. Sun, Y. L. Zhang, L. Chen, Y. Q. Li, Q. S. Li, H. B. Song, R. Q. Huang, F. C. Bi and Q. M. Wang, Design, synthesis and insecticidal activities of new *N*-benzoyl-*N'*-phenyl-*N'*-sulfenylureas, *J. Agric. Food Chem.*, 2009, **57**, 3661; (c) P. Ramaraju, D. Gergeres, E. Turos, S. Dickey, D. V. Lim, J. Thomas and B. Anderson, Synthesis and antimicrobial activities of structurally novel *S,S'*-bis(heterosubstituted) disulfides, *Bioorg. Med. Chem. Lett.*, 2012, **22**, 3623.
- 9 (a) A. I. Uraev, S. E. Nefedov, K. A. Lyssenko, V. G. Vlasenko, V. N. Ikorskii, D. A. Garnovskii, N. I. Makarova, S. I. Levchenkov, I. N. Shcherbakov, M. R. Milenković and G. S. Borodkina, Synthesis, structure, spectroscopic studies and magnetic properties of  $\text{Cu}_2\text{N}_2\text{O}_4$ -,  $\text{Cu}_2\text{N}_2\text{O}_2(\text{S}_2)$ -,  $\text{Cu}_2\text{N}_2\text{S}_4$ -chromophores based on aminomethylene derivatives of pyrazole-5-one(thione), *Polyhedron*, 2020, **188**, 114623; (b) L. Li, Q. Chen, H. H. Xu, X. H. Zhang and X. G. Zhang, DBU-promoted demethoxylation thioannulation of alkynyl oxime ethers with sulfur for the synthesis of bisisothiazole-4-yl disulfides, *J. Org. Chem.*, 2020, **85**(15), 10083; (c) H. X. Yue, J. H. Wang, Z. H. Xie, J. Tian, D. Y. Sang and S. P. Liu, 1,3-Diisopropylcarbodiimide-mediated synthesis of disulfides from thiols, *ChemistrySelect*, 2020, **5**(14), 4273; (d) A. Parida, K. Choudhuri and P. Mal, Unsymmetrical disulfides synthesis *via* sulfenium ion, *Chem.-Asian J.*, 2019, **14**(15), 2579.
- 10 M. Musiejuk, J. Doroszuk, B. Jędrzejewski, G. O. Nieto, M. M. Navarro and D. Witt, Diastereoselective synthesis of *Z*-alkenyl disulfides from thiophosphorylated ketones and thiosulfonates, *Adv. Synth. Catal.*, 2020, **362**, 533.
- 11 (a) S. M. S. Chauhan, A. Kumar and K. A. Srinivas, Oxidation of thiols with molecular oxygen catalyzed by cobalt(II) phthalocyanines in ionic liquid, *Chem. Commun.*, 2003, **18**, 2348; (b) J. A. Fernández-Salas, S. Manzini and S. P. Nolan, Efficient ruthenium-catalysed S–S, S–Si and S–B bond forming reactions, *Chem. Commun.*, 2013, **49**, 5829; (c) M. Li and J. M. Hoover, Aerobic copper-catalyzed



- decarboxylative thiolation, *Chem. Commun.*, 2016, **52**, 8733; (d) Y. Dou, X. Huang, H. Wang, L. Yang, H. Li, B. Yuan and G. Yang, Reusable cobalt-phthalocyanine in water: efficient catalytic aerobic oxidative coupling of thiols to construct S–N/S–S bonds, *Green Chem.*, 2017, **19**, 2491; (e) W. P. Sohtun, A. Kannan, K. H. Krishna, D. Saravanan, M. S. Kumar and M. Velusamy, Synthesis, characterization, crystal structure and molecular docking studies of a S-methyldithiocarbamate derivative: bis[2-hydroxy-benzylidenehydrazono] (methylthio) methyl]disulfide, *Acta Chim. Slov.*, 2018, **65**, 621; (f) Y. H. Zhang, D. W. Yang, Y. Li, X. Y. Zhao, B. M. Wang and J. P. Qu, Biomimetic catalytic oxidative coupling of thiols using thiolate-bridged dinuclear metal complexes containing iron in water under mild conditions, *Catal. Sci. Technol.*, 2019, **9**, 6492.
- 12 (a) A. Dhakshinamoorthy, M. Alvaro and H. Garcia, Aerobic oxidation of thiols to disulfides using iron metal–organic frameworks as solid redox catalysts, *Chem. Commun.*, 2010, **46**, 6476; (b) M. Oba, K. Tanaka, K. Nishiyama and W. Ando, Aerobic oxidation of thiols to disulfides catalyzed by diaryl tellurides under photosensitized conditions, *J. Org. Chem.*, 2011, **76**, 4173; (c) A. Corma, T. Ródenas and M. J. Sabater, Aerobic oxidation of thiols to disulfides by heterogeneous goldcatalysts, *Chem. Sci.*, 2012, **3**, 398; (d) P. Das, S. Ray, A. Bhaumik, B. Banerjee and C. Mukhopadhyay, Cubic Ag<sub>2</sub>O nanoparticle incorporated mesoporous silica with large bottle-neck like mesopores for the aerobic oxidative synthesis of disulfide, *RSC Adv.*, 2015, **5**, 6323.
- 13 (a) A. Hatano, S. Makita and M. Kirihara, Synthesis and characterization of a DNA analogue stabilized by mercapto C-nucleoside induced disulfide bonding, *Bioorg. Med. Chem. Lett.*, 2004, **14**, 2459; (b) R. Dong, M. Pfeffermann, D. Skidin, F. Wang, Y. Fu, A. Narita, M. Tommasini, F. Moresco, G. Cuniberti, R. Berger, K. Müllen and X. Feng, Persulfurated coronene: a new generation of “Sulflower”, *J. Am. Chem. Soc.*, 2017, **139**, 2168.
- 14 (a) R. Priefer, Y. J. Lee, F. Barrios, J. H. Wosnick, A. M. Lebuis, P. G. Farrell and D. N. Harpp, Dicubyl Disulfide, *J. Am. Chem. Soc.*, 2002, **124**, 5626; (b) M. H. Ali and M. McDermott, Oxidation of thiols to disulfides with molecular bromine on hydrated silica gel support, *Tetrahedron Lett.*, 2002, **43**, 6271; (c) E. Bourlès, R. A. Sousa, E. Galardon, M. Selkti, A. Tomas and I. Artaud, Synthesis of cyclic mono- and bis-disulfides and their selective conversion to mono- and bis-thiosulfates, *Tetrahedron*, 2007, **63**, 2466; (d) Y. S. Izmet'ev, S. V. Pestova, O. M. Lezina, S. A. Rubtsova and A. V. Kutchin, Synthesis of novel chiral 18-sulfanyl and sulfonyl dehydroabietane derivatives, *ChemistrySelect*, 2019, **4**, 11034.
- 15 (a) A. R. Hajipour, S. E. Mallakpour and H. Adibi, Selective and efficient oxidation of sulfides and thiols with benzyltriphenylphosphonium peroxymonosulfate in aprotic solvent, *J. Org. Chem.*, 2002, **67**, 8666; (b) R. Leino and J. E. Lönnqvist, A very simple method for the preparation of symmetrical disulfides, *Tetrahedron Lett.*, 2004, **45**, 8489; (c) A. D. Hudwekar, P. K. Verma, J. Kour, S. Balgotra and S. D. Sawant, Effect of sodium and fluorine Co-doping on the properties of fluorite-like rare-earth molybdates of Nd<sub>5</sub>Mo<sub>3</sub>O<sub>16</sub> type, *Eur. J. Org. Chem.*, 2019, **6**, 1242.
- 16 (a) H. Firouzabadi, N. Iranpoor, H. Parham, A. Sardarian and J. Toofan, Oxidation of thiols to their disulfides with bis trinitratoceric(IV)<sup>1</sup> chromate [Ce(NO<sub>3</sub>)<sub>3</sub>]<sub>2</sub>CrO<sub>4</sub> and pyridinium chlorochromate, *Synth. Commun.*, 1984, **14**, 717; (b) L. Delaude and P. Laszlo, A novel oxidizing reagent based on potassium ferrate(VI)<sup>1</sup>, *J. Org. Chem.*, 1996, **61**, 6360; (c) S. Patel and B. K. Mishra, Cetyltrimethylammonium dichromate: a mild oxidant for coupling amines and thiols, *Tetrahedron Lett.*, 2004, **45**, 1371.
- 17 W. P. Sohtun, A. Kannan, K. Hari Krishna, D. Saravanan, M. Suresh Kumar and M. Velusamy, Synthesis, characterization, crystal structure and molecular docking studies of a S-methyldithiocarbamate derivative: bis[2-hydroxy-benzylidenehydrazono] (methylthio) methyl] disulfide, *Acta Chim. Slov.*, 2018, **65**, 621.
- 18 S. C. Sahoo and S. C. Pan, Synthesis of N-formyl-2-benzoyl benzothiazolines, 2-substituted benzothiazoles, and symmetrical disulfides from N-phenacylbenzothiazolium bromides, *Org. Lett.*, 2019, **21**, 6208.
- 19 (a) K. T. Koshy, M. D. Burdick and D. W. Knuth, Multiphase photodegradation of methyl N-[[[(1,1-dimethylethyl)(5,5-dimethyl-2-thioxo-1,3,2-dioxaphosphorinan-2-yl)-am-no]thio]methylamino]carbonyl]oxy]ethanimidothioate, *J. Agric. Food Chem.*, 1983, **31**, 625; (b) D. Raban, D. Noyd and L. Bermann, Mass spectral fragmentation of disulfenamides, *Phosphorus Sulfur Relat. Elem.*, 1976, **1**, 153.
- 20 (a) C. C. Xia, Z. J. Wei, Y. Yang, W. B. Yu, H. X. Liao, C. Shen and P. F. Zhang, Palladium-catalyzed thioetherification of quinolone derivatives via decarboxylative C–S cross-couplings, *Chem.–Asian J.*, 2016, **11**, 360; (b) C. C. Xia, Z. J. Wei, C. Shen, J. Xu, Y. Yang, W. K. Su and P. F. Zhang, Palladium-catalyzed direct ortho-sulfonylation of azobenzenes with arylsulfonyl chlorides via C–H activation, *RSC Adv.*, 2015, **5**, 52588; (c) C. C. Xia, K. Wang, J. Xu, Z. J. Wei, C. Shen, G. Y. Duan, Q. Zhu and P. F. Zhang, Copper(II)-catalyzed remote sulfonylation of aminoquinolines with sodium sulfonates via radical coupling, *RSC Adv.*, 2016, **6**, 37173; (d) K. Wang, G. D. Wang, G. Y. Duan and C. C. Xia, Cobalt(II)-catalyzed remote C5-selective C–H sulfonylation of quinolines via insertion of sulfur dioxide, *RSC Adv.*, 2017, **7**, 51313.
- 21 J. M. Liu, Y. Y. Zhang, Y. Y. Yue, Z. X. Wang, H. B. Shao, K. L. Zhuo, Q. Z. Lv and Z. G. Zhang, Metal-free dehydrogenative double C–H sulfuration to access thieno [2,3-*b*] indoles using elemental sulfur, *J. Org. Chem.*, 2019, **84**, 12946.
- 22 Z. W. Chen, P. Liang, F. Xu, R. L. Qiu, Q. Tan, L. P. Long and M. Ye, Lewis acid-catalyzed intermolecular annulation: three-component reaction toward imidazo [1,2-*a*] pyridine thiones, *J. Org. Chem.*, 2019, **84**, 9369.



- 23 V. Khakyzadeh, A. Rostami, H. Veisi, B. S. Shaghasemi, E. Reimhult, R. Luque, Y. Z. Xia and S. Darvishi, Direct C–S bond formation *via* C–O bond activation of phenols in a crossover Pd/Cu dual-metal catalysis system, *Org. Biomol. Chem.*, 2019, **17**, 4491.
- 24 P. Q. Zhou, Y. B. Huang, W. Q. Wu, W. T. Yu, J. X. Li, Z. Z. Zhu and H. F. Jiang, Direct access to bis-S-heterocycles *via* copper-catalyzed three component tandem cyclization using S<sub>8</sub> as a sulfur source, *Org. Biomol. Chem.*, 2019, **17**, 3424.
- 25 T. B. Nguyen and P. Retailleau, DIPEA-promoted reaction of 2-nitrochalcones with elemental sulfur: an unusual approach to 2-benzoylbenzothiophenes, *Org. Lett.*, 2017, **19**, 4858.
- 26 T. B. Nguyen, Elemental sulfur and molecular iodine as efficient tools for carbon–nitrogen bond formation *via* redox reactions, *Asian J. Org. Chem.*, 2017, **6**, 477.
- 27 T. B. Nguyen, Recent Advances in the synthesis of heterocycles *via* reactions involving elemental sulfur, *Adv. Synth. Catal.*, 2017, **359**, 1106.
- 28 T. B. Nguyen, Recent Advances in the synthesis of heterocycles *via* reactions involving elemental sulfur, *Adv. Synth. Catal.*, 2020, **362**(17), 3448.

