Novel Synthetic Method of Thiols using Heterogeneous Cobalt Catalysts from Hydrogen, Elemental Sulfur and Alkenes and Other Substrates

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2024

Contents

Chapter 1: General Introduction

Chapter 1 General Introduction

1.1 General application of thiols

Thiols are important organosulfur compounds widely used in pharmaceuticals and materials science.[1-5] For example, thiols with different structures were used as food additives, gas odorants, and perfumes in relation to the special smell (Figure 1.1). 4-Methyl-4-sulfanylpentan-2-one (4MSP) and 3-sulfanylpentan-1-ol (3SH) were detected in the wine flavor.[6] 3-Methyl-3-sulfanilbutan-1-ol (3MSB) used as a pheromone in cat urine was also detected.[7] Prop-2-ene-1-thiol and cyclopentanthiol are found in allium and garlic and are often added to health foods as additives.[8,9] Ethanethiol and 2-methylpropane-2-thiol are added to natural gas as the odorant to prevent gas leaks.[10] Cyclohexanethiol as the catalyst was applied to the synthesis of arylethylamine compounds in good yields (30 examples, 43–88%).[11] 2-Methylpropane-2-thiol as the ligand can synthesize various metal clusters such as $Ag_{62}S_{12}(S^tBu)_{32}^{2+}$,[12] $Ti(S^tBu)_4$,[13] $Au_{30}(S^tBu)_{18}$, and $Au_{30}S(S^tBu)_{18}$.[14]

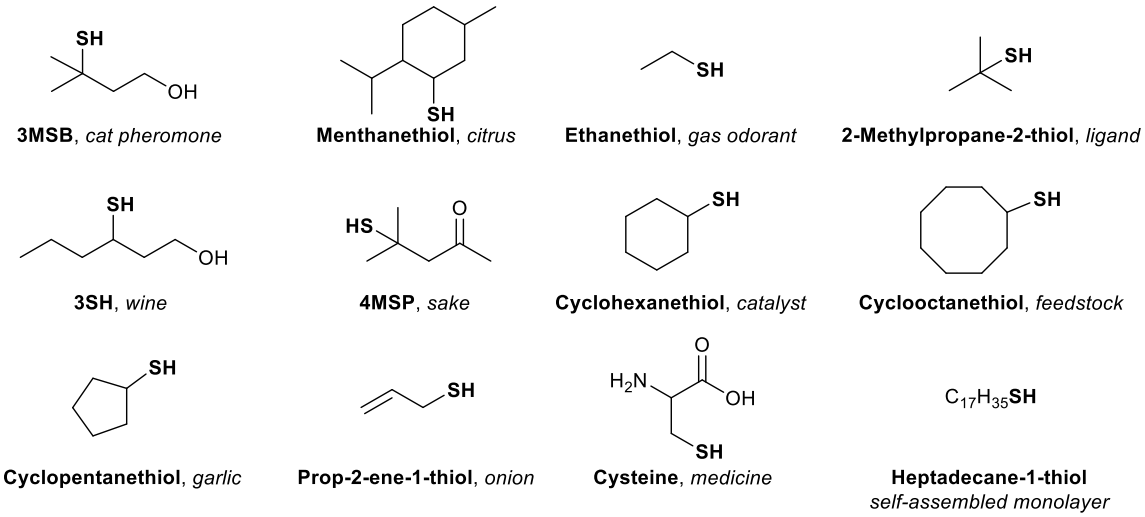
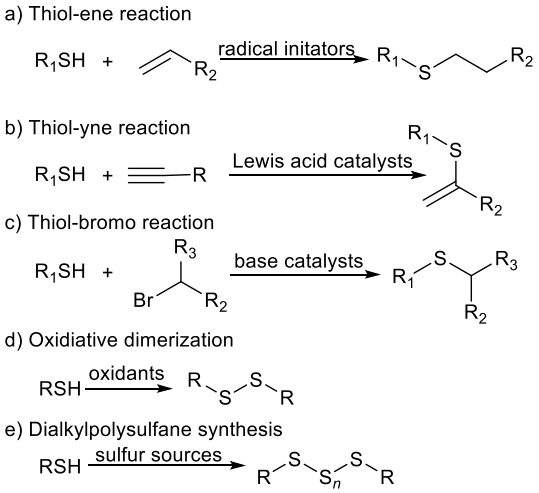


Figure 1.1 Thiols with different smells and applications.

1.2 Thiols used in organic synthesis

Thiols are also important as intermediates in organic synthesis.[15] For example, a thiol can react with alkenes, alkynes, alkyl halides and thiols to synthesize dialkylmonosulfanes, dialkyldisulfanes, dialkylpolysulfanes, thioesters, and other sulfur-based polymers.[16-19] The dehydrogenative S–S bond oxidation,[18,19] thiol-ene reaction,[20] thiol-yne reactions[21] and thiol-bromo reactions[22] are often used in the synthesis of organosulfur compounds from thiols (Scheme 1.1).



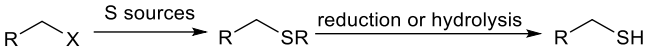
Scheme 1.1 Synthesis of organosulfur compounds using thiols.

Thiol-ene and thiol-yne reactions are powerful methods in the synthesis of sulfur-based materials (Scheme 1.1a and 1.1b).[23-31] For example, many sulfur-base polymers and biomaterials were synthesized using the thiol-ene reaction such as cysteine-base biocompatible molecules,[25] biofunctional silicon nanoparticles,[26] glycoconjugates,[27] polyacetals,[28] polyurethane,[29] polydimethylsiloxane[30] and macrolactone polymers.[31] The thiol-bromo reaction (Scheme 1.1c) also plays a significant role in polymer chemistry and material science.[32-37] This method is used in the synthesis of the star-shaped polymer[38] and the supramolecular polymer.[39]

Thiols also react with other unsaturated hydrocarbon compounds. For example, the addition of thiol to graphene showed high adsorption capacity for heavy metal ions (Cd^{2+}, Pb^{2+}).[40] Thiols can also undergo hydrothiolation with diene using a boron catalyst and showed high regioselective (regioselectivity > 20:1).[41] Furthermore, thiols can be treated with oxidants and other sulfur sources to synthesize disulflanes[42] (Scheme 1.1d) and polysulfanes[43] (Scheme 1.1e). Disulfanes and polysulfanes are commonly used in pharmaceutical[44] and antioxidants.[45]

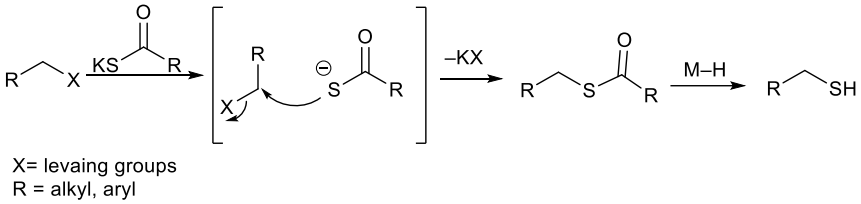
1.3 Thiol synthesis in previous work

In the past 90 years, many thiol synthesis methods have been reported; however, the catalytic thiol synthesis process from sulfur, hydrogen, and alkenes has not yet been researched.[46-48] In fine chemical synthesis, thiol synthesis usually employs thiourea, thiocarboxylic acids and the other thiocarbonyl compounds as sulfur nucleophiles and requires two steps: (A) S_N2-type C–S bond formation. (B) Hydride reduction or hydrolysis (Scheme 1.2).



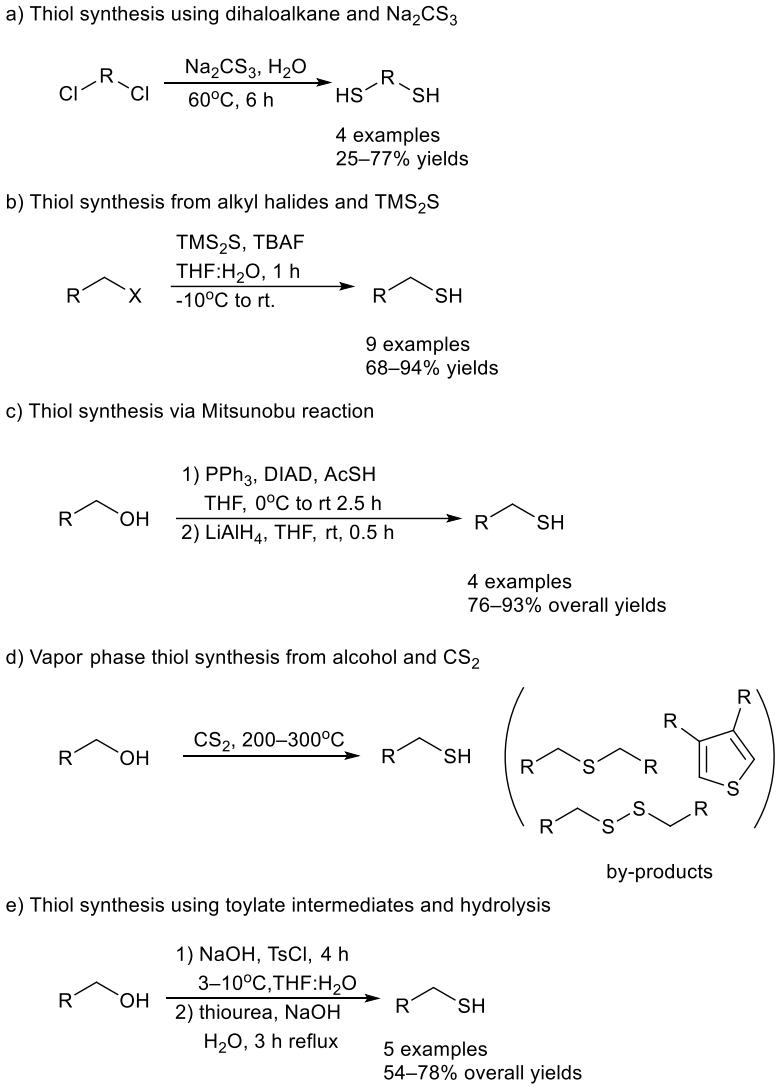
Scheme 1.2 Thiol synthesis through S_N2 type C–S bond formation.

As shown in Scheme 1.3,[48] the sulfur sources such as *S*-potassium thioacetate (KSAc) as the nucleophile attacked the carbon with a leaving group and then the reaction gave the thioester as the reaction intermediates, which were reduced by metal hydride to afford the thiols as the main product. However, this two-step method showed a low atomic economy.



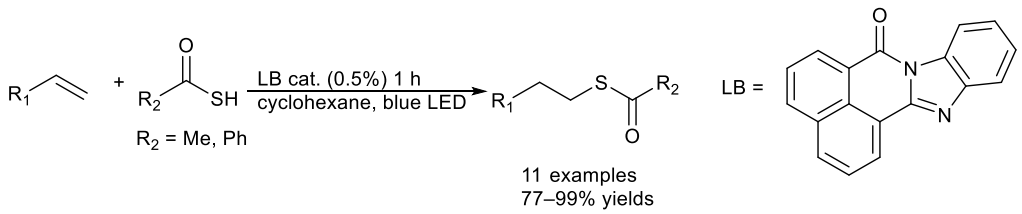
Scheme 1.3 General reaction mechanism for thiol synthesis via S_N2 route.

Martin *et al.* reported dihaloalkanes treated with sodium trithiocarbonate[49] (Scheme 1.4a) to produce thiols in 25–77% yields. However, only chloroethoxy shows an acceptable yield and benzyl chloride gives a low yield at 25% in this reaction. Next, Volante synthesized the thiols via the Mitsunobu reaction from alcohols, which use thioacetic acids as the sulfur source and lithium aluminum hydride as the reductant to give the thiols in 76–93% overall yields (Scheme 1.4c).[50] Hu *et al.* developed a thiol synthesis using 1,1,1,3,3,3-hexamethyldisilathiane ($(TMS)_2S$) and tetrabutylammonium fluoride (TBAF)[51] (Scheme 1.4b) and the reaction gives thiol in high yields of 68–94%. However, these methods use expensive reagents such $(TMS)_2S$, tetrahydrofuran (THF), triphenylphosphine and TBAF. The vapor-phase thiol synthesis from alcohol is also reported by Tomov *et al*.[52] Butanol reacted with carbon disulfide (CS_2) can produce butanethiol as the main product; however, this method requires high reaction temperature over 200–300°C and gives dialkylmonosulfanes, dialkyldisulfanes, alkenes, and thiophenes as the by-products. The thiol synthesis via hydrolysis using thiourea as the sulfur source was also reported in 54–78% yields (Scheme 1.4e).[53]



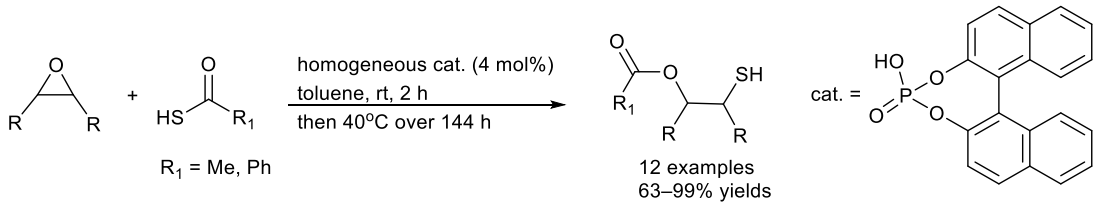
Scheme 1.4 Conventional synthetic methods for thiols

Levin *et al.* reported a thioester synthesis using the proton-coupled electron transfer (PCET) process.[54] Alkenes react with thioacetic acid or thiobenzoic acid and irradiated under blue LED condition to produce the thioesters in 77–99% yields. However, this process uses a photocatalyst and proceeds by a radical mechanism, yielding only terminal thioesters.



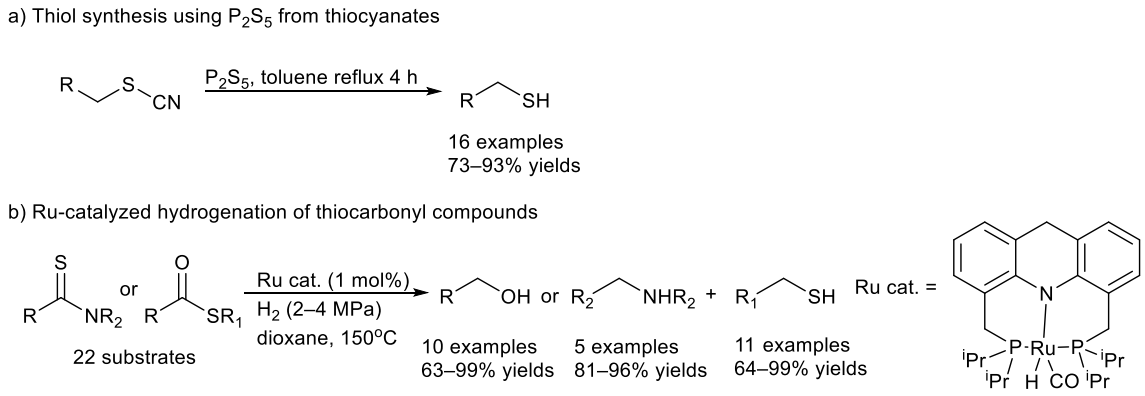
Scheme 1.5 Synthesis of thioester by PCET process.

The thiol synthesis from epoxy compounds also has been studied.[55,56] This reaction uses acid such as acetic acid or phosphoric acid as the catalyst. However, this reaction only gives *β*-hydroxythiol derivatives as the product (Scheme 1.6).



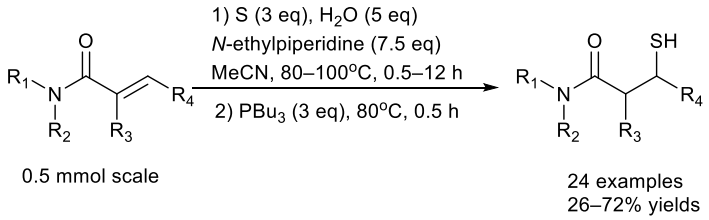
Scheme 1.6 Synthesis of *β*-hydroxythiols from epoxy compound.

The synthesis of thiols from thiocarbonyl compounds or thiocyanides was also investigated. Maurya *et al.* reported the thiol synthesis using thiocyanates and phosphorus pentasulfide (P_2S_5) to afford thiols in yields of 73–93% (Scheme 1.7a).[57] Recently, Luo *et al.* reported ruthenium-catalyzed hydrogenation of thioesters, thiocarbamates, and thioamides (Scheme 1.7b)[58] and the reaction gives the corresponding alcohols, amines, amides, and thiols in high yields. However, these reactions use an expensive Ru catalyst or highly toxic P_2S_5.



Scheme 1.7 Recently synthetic methods for thiols.

Very recently, Németh and co-workers reported a thiol synthesis from elemental sulfur and acrylamides.[59] Although this reaction allows the hydrolysis of polysulfanes to be suppressed in one pot, this method still uses a large excess of organic bases and has low atomic efficiency (Scheme 1.8).



Scheme 1.8 Thiol synthesis using elemental sulfur and acrylamides.

As discussed in the above review, significant problems remained with these methods, including the generation of large amounts of by-products, the use of environmentally unfriendly reagents, and the increased cost of the thiol synthesis process. Thus, developing a novel synthetic method with high atom efficiency is important for industrial-scale thiol synthesis. In the course of the polysulfane synthesis research,[60] thiol as a by-product was observed. This experimental observation suggested a clue for achieving the hydrogen sulfide (H_2S)-reagent-free catalytic thiol synthesis. Herein, the author develops a novel synthetic method of thiols from alkenes, elemental sulfur, and hydrogen with heterogeneous cobalt catalysts. The heterogeneous cobalt-catalyzed thiol synthesis from alkenes using sulfur and hydrogen gas was presented in Chapter 2 and optimization of the catalytic synthesis of thiols using carbonyl compounds, elemental sulfur and hydrogen gas will be shown in Chapter 3.

1.4 Reference

[1] M. van Dijk, D. T. S. Rijkers, R. M. j. Liskamp, C. F. van Nostrum and W. E. Hennink, *Bioconjugate Chem.*, 20, **2009**, 2001–2015.

[2] P. Sang, Q. Chen, D. Y. Wang, W. Guo and Y. Fu, *Chem. Rev.*, **2023**, 123, 1262–1326.

[3] D. Mandler and I. Turyan, *Electroanalysis*, **1996**, 8, 207–213.

[4] Bayer Cropscience AG, Y. Kitagawa, H. Sawada, T. Shigyo and L. Assmann, WO03031420A1. **2003–4–17**.

[5] S. Schoenauer and P. Schieberle, *J. Agric. Food Chem*., **2016**, 64, 3849–3861.

[6] A. Roland, R. Schneider, A. Razungles and F. Cavelier, *Chem. Rev.*, **2011**, 111, 7355–7376.

[7] C. Starkenmann, Y. Niclass, I. Cayeux, R. Brauchi and A. C. Gagnon, *Flavour Fragr. J.*, **2015**, 30, 91–100.

[8] International Flavors & fragrances inc., M. Cynthia, G. Christopher, K. Ira, US3677772A. **1972–6–18.**

[9] F. Challenger and D. Greenwood, *Biochem J.*, **1949**, 44, 87–91.

[10] D. Tenkrat, T. Hlincik and O. Prokes, Natural Gas Odorization, edited by P. Potocnik, IntechOpen Limited, London, **2010**.

[11] A. J. Boyington, C. P. Seath, A. M. Zearfoss, Z. Xu and N. T. Jui, *J. Am. Chem. Soc.*, **2019**, 141, 4147–4153.

[12] S. Jin, S. Wang, Y. Song, M. Zhou, J. Zhang, J. Zhang, Z. Xia, Y. Pei, M. Chen, P. Li and M. Zhu, *J. Am. Chem. Soc.*, **2014**, 136, 15559–15565.

[13] C. J. Carmalt, C. W. Dinnage, I. P. Parkin, A. J. P. White and D. J. Williams, *J. Chem. Soc., Dalton Trans.*, **2001**, 2554–2558.

[14] A. Dass, T. Jones, M. Rambukwella, D. Crasto, K. J. Gagnon, L. Sementa, M. D. Vetta, O. Baseggio, E. Apra, M. Stener and A. Fortunelli, *J. Phys. Chem.*, C **2016**, 120, 6256–6261.

[15] S. Oae, *J. Synth.*, **1986**, 26, 327–341.

[16] F. Goethals, D. Frank and F. D. Prez, *Prog. Polym. Sci*, **2017**, 64, 76–113.

[17] T. Kondo and T. Nitsudo, *Chem. Rev.*, **2000**, 100, 3205–3220.

[18] R. Strudel, *Chem. Rev.*, **2002**, 102, 3905–3945.

[19] D. Witt, *synthesis*, **2008**, 16, 2491–2509.

[20] C. E. Hoyle and C. N. Bowman, *Angew. Chem. Int. Ed.*, **2010**, 49, 1540–1573.

[21] A. Dondoni and A. Marra, *Eur. J. Org. Chem.*, **2014**, 3955–3969.

[22] J. Xu, L. Tao, C. Boyer, A. B. Lowe and T. P. Davis, *Macromolecules*, **2010**, 43, 20–24.

[23] X. Fu, A. Qin and B. Z. Tang, *Aggregate*, **2023**, e350.

[24] O. Daglar, S. Luleburgaz, E. Baysak, U. S. Gunay, G. Hizal, U. Tunca and H. Durmaz, *Eur. Polym. J.*, **2020**, 137, 109926.

[25] A. B. Lowe, *Polym. Chem.*, **2010**, 1, 17–36.

[26] L. Ruizendaal, S. P. Pujari, V. Gevaerts, J. M. J. Paulusse and H. Zuilhof, *Chem. Asian J.*, **2011**, 6, 2776–2786.

[27] A. Dondoni and A. Marra, *Chem. Soc. Rev.*, **2012**, 41, 573–586.

[28] G. Herwig and A. P. Dove, *ACS Macro Lett.*, **2019**, 8, 1268–1274.

[29] K. Jin, E. K. Leitsch, X. Chen, W. H. Heath and J. M. Torkelson, *Macromolecules*, **2018**, 51, 3620–3631.

[30] J. Zhang, Y. Chen and M. A. Brook, *Langmuir*, **2013**, 29, 12432–12442.

[31] Z. Ates, P. D. Thornton and A. Heise, *Polym. Chem.*, **2011**, 2, 309–312.

[32] N. D. Luong, L. H. Sinh, L. Johansson, J. Campell and J. Seppälä, *Chem. Eur. J.*, **2015**, 21, 3183–3186.

[33] R. Castarlenas, A. D. Giuseppe, J. J. Pérez-Torrente and L. A. Oro, *Angew. Chem. Int. Ed.*, **2013**, 52, 211–222.

[34] A. Dondoni and A. Marra, *Eur. J. Org. Chem.*, **2014**, 3955–3969.

[35] H. Du, G. Zha, L. Gao, H. Wang, X. Li, Z. Shen and W. Zhu, *Polym. Chem.*, **2014**, 5, 4002–4008.

[36] J. Xu, L. Tao, C. Boyer, A. B. Lowe and T. P. Davis, *Macromolecules*, **2010**, 43, 20–24.

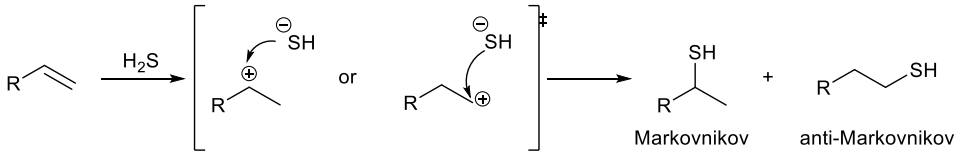
[37] Y. Zhang, G. Chen, Y. Lin, L. Zhao, W. Z. Yuan, P. Lu, C. K. W. Jim, Y. Zhang and B. Z. Tang, *Polym. Chem.*, **2015**, 6, 97–105.
[38] P. L. Yap, Y. L. Auyoong, K. Hanssan, F. Farivar, D. N. H. Tran, J. Ma and D. Losic, *Chem. Eng. J.*, **2020**, 395, 124965.
[39] S. Chen, D. Ströhl and W. H. Binger, *ACS Macro Lett.*, **2015**, 4, 48–52.
[40] V. P. Beyer, B. Cattoz and C. R. Becer, *Macromol. Rapid Commun.*, **2021**, 42, 2000519.
[41] G. Kumar, Z. Qu, S. Ghosh, S. Grimme and I. Chatterjee, *ACS Catal.*, **2019**, 9, 11627–11633.
[42] J. K. Vandavasi, W. Hu, C. Chen and J. Wang, *Tetrahedron*, **2011**, 67, 8895–8901.
[43] B. D. Vineyard, *J. Org. Chem.*, **1967**, 32, 3833–3836.
[44] H. Shinkai, K. Maeda, T. Yamasaki, H. Okamoto and I. Uchida, *J. Med. Chem.*, **2000**, 43, 3566–3572.
[45] J. R. Chauvin, M. Griesser and D. A. Pratt, *Chem. Sci.*, **2019**, 10, 4999–5010.
[46] C. M. Rayner, *Contemp. Org. Synth.*, **1995**, 2, 409–440.
[47] D. J. Procter, *J. Chem. Soc., Perkin Trans. 1*, **2001**, 335–354.
[48] J. Clayden and P. MacLellan, *Beilstein J. Org. Chem.*, **2011**, 7, 582–595.
[49] D. J. Martin and C. C. Greco, *J. Org. Chem.*, **1968**, 33, 1275–1276.
[50] R. P. Volante, *Tetrahedron Lett.*, **1981**, 22, 3119–3122.
[51] J. Hu and M. A. Fox, *J. Org. Chem.*, **1999**, 64, 4959–4961.
[52] A. Tomov and C. Moreau, *Catal. Lett.*, **2000**, 64, 197–200.
[53] A. W. Snow and E. E. Foos, *Synthesis*, **2003**, 4, 509–512.
[54] V. V. Levin and A. D. Dilman, *J. Org. Chem.*, **2019**, 84, 8337–8343.
[55] M. R. Monaco, M. S. Prévost and B. List, *J. Am. Chem. Soc.*, **2014**, 136, 16982–16985.
[56] H. Seliger and H. Görtz, *Synth. Commun.*, **1980**, 175–182.
[57] C. K. Maurya, A. Mazumder and P. K. Gupta, *Beilstein J. Org. Chem.*, **2017**, 13, 1184–1188.
[58] J. Luo, M. Rauch, L. Avram, Y. Ben-David and D. Milstein, *J. Am. Chem. Soc.*, **2020**, 143, 21628–21633.
[59] A. G. Németh, R. Szabó, K. Németh, G. M. Keserű and P. A. Balogh, *Org. Biomol. Chem.*, **2022**, 20, 4361–4368.
[60] DIC Corporation, T. Iba, H. Sakata, WO2014188948A1. **2014–11–27**.

Chapter 2: Thiol Synthesis from Alkenes Using Elemental Sulfur and Hydrogen with Heterogeneous Cobalt Catalysts

Chapter 2 Thiol Synthesis from Alkenes Using Elemental Sulfur and Hydrogen with Heterogeneous Cobalt Catalysts

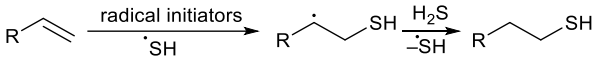
2.1 Introduction

Catalytic synthesis of thiols from alkenes using H_2S as the sulfur source is a well-known synthetic method[1-4] that plays an important role in most industrial thiol synthesis processes.[4] This reaction is an electrophilic addition reaction, which would follow Markovnikov's rule, producing internal thiols and dialkylmonosulfanes as the products (Scheme 2.1).



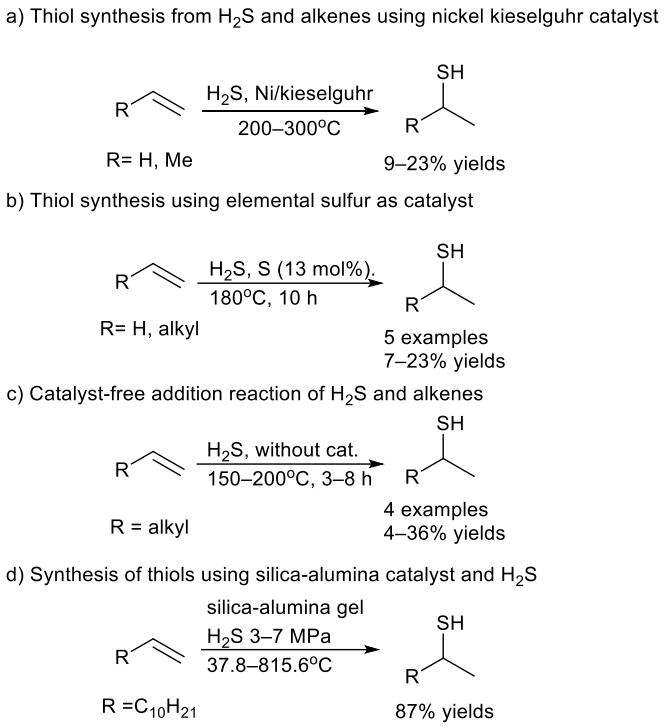
Scheme 2.1 Thiol synthesis via electrophilic addition.

On the other hand, radical addition of H_2S and alkenes was also reported. The SH radical reacted with alkenes to generate the anti-Markovnikov type terminal thiols, dialkyldisulfane and dialkylmonosulfane as the products (Scheme 2.2).[5-7]



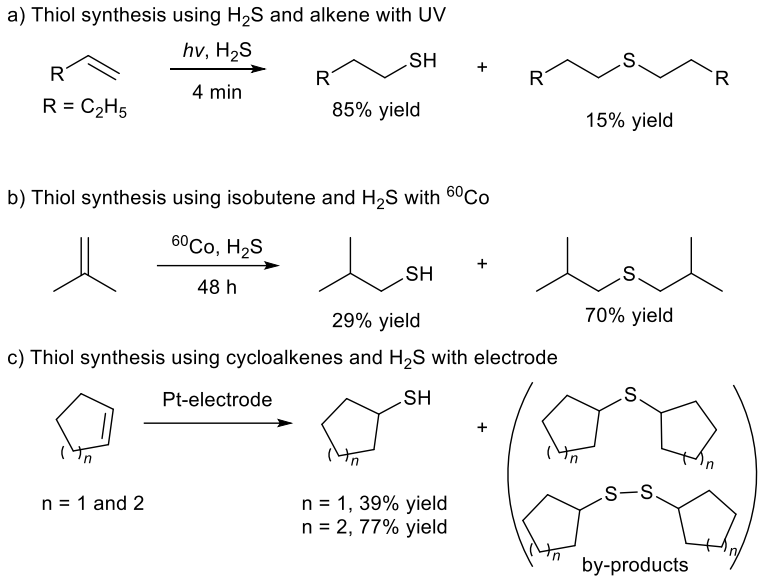
Scheme 2.2 Thiol synthesis via a radical mechanism.

The electrophilic addition of H_2S to alkenes was exhibited in several reports (Scheme 2.3). Duffey *et al.* reported an H_2S addition to olefins using nickel kieselguhr as the catalyst to obtain the corresponding thiols at 9% and 23% yields (Scheme 2.3a).[1] Jones *et al.* reported that elemental sulfur or diethyltetrasulfane-catalyzed the electrophilic addition between H_2S and alkenes. However, the reaction showed low yields of thiol, resulting in 7–23% (Scheme 2.3b).[2] Ipatieff and co-workers reported addition reactions of H_2S to propene, isobutene, and trimethylethylene; however, the reaction still afforded the corresponding thiols in low yields of 4–36% (Scheme 2.3c).[3] In the 1940s, Schulze *et al.* reported an electrophilic addition of H_2S to olefin using a silica-alumina catalyst to produce dodecane-2-thiol in a high yield of 87% and it was applied to an industrial process (Scheme 2.3d).[4]



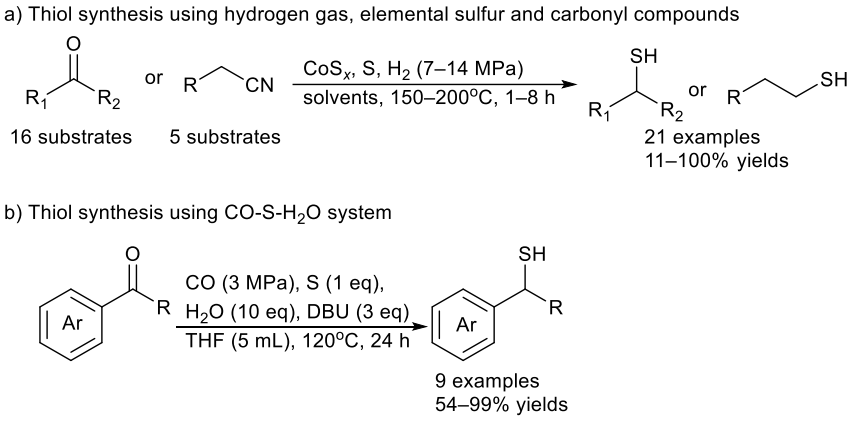
Scheme 2.3 Thiol synthesis from alkenes and H_2S.

In addition, Vaughan *et al.* reported the radical addition of H_2S to alkenes.[5] Ultraviolet (UV) ray was used to decompose the H_2S, and then the SH radical was added to butene to give the thiol in the yield of 85% and only give 15% of dibutylmonosulfane as the by-product (Scheme 2.4a). Sugimoto *et al.* generated the SH radical by irradiation of H_2S and alkenes with the ^{60}Co to synthesize 2-methylpropylthiol.[6] However, this reaction gives dialkylmonosulfanes as the main product and the thiol as the by-product was observed in a low yield of 29% (Scheme 2.4b). The electrolysis of H_2S was also reported.[7] Using a platinum electrode can also generate SH radicals from H_2S and treated with cyclopentene or cyclohexene to afford cycloalkylthiols in 39% and 77% yields (Scheme 2.4c). However, H_2S is a toxic gas, which is facing an ongoing challenge in the safety of the thiol synthesis process. Thus, the development of a safer and low-cost sulfur source instead of H_2S is highly desired.



Scheme 2.4 Thiol synthesis by radical addition.

Among the various sulfur sources, elemental sulfur is one of the most important raw materials that has been used as a sulfurizing agent.[8] Considering the various reductants and sulfur sources, the use of hydrogen gas and elemental sulfur is a promising choice because of their easy handling and cost competitiveness for industrial-scale synthesis. However, in the field of organic synthesis, the use of hydrogen gas as a reductant for the reactions with elemental sulfur has been hardly explored. In the past, several groups have developed synthetic methods for thiols from carbonyl compounds and nitriles with elemental sulfur and hydrogen gas (Scheme 2.5 a, b).[9,10]



Scheme 2.5 Thiol synthesis using elemental sulfur and carbonyl compounds.

However, thiol synthesis from alkenes, elemental sulfur, and hydrogen gas has remained unachieved. Recently, Yamamoto *et al.* reported that dialkylpolysulfanes can be synthesized from

alkenes, elemental sulfur, and hydrogen gas using a heterogeneous Co_3O_4 catalyst. In this reaction, dialkylpolysulfanes were observed as the main product and 2,4,4-trimethylpentane-2-thiol as the by-product was observed in the yield of 3%.[11] This provides a possible idea that heterogeneous transition metal-catalyzed thiol synthesis using alkenes, elemental sulfur and hydrogen gas can be achieved. Cobalt and nickel-based nanomaterials have extensive applications in various fields, including hydrodesulfurization,[12] electrochemical materials[13-18] and catalysts.[19] In particular, cobalt silicate-based materials have garnered significant interest since their thermal stability and abundant availability on Earth.[20] For example, Co_2SiO_4 in the form of an olivine structure is a heterogeneous catalyst used in the photo-degradation of azo dyes,[21] Fischer-Tropsch synthesis,[22] and oxygen evolution reaction.[23] Nickel phyllosilicate catalysts also showed high activity in the hydrogenolysis of 5-hydroxymethylfurfural.[24] To build upon this background, a series of cobalt and nickel oxides were prepared and used in studies on heterogeneous transition metal-catalyzed thiol synthesis from alkenes, elemental sulfur and hydrogen gas.

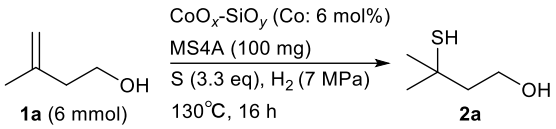
2.2 Results and discussion

2.2.1 Catalysts screening for *α*,*α*-disubstituted alkene **1a**

Compared to common thiols, thiols bearing hydroxy groups are raw materials for the synthesis of various biomolecules.[25] However, since unsaturated alcohols are more reactive than common alkenes, Synthesizing thiols with hydroxy groups from unsaturated alcohols was a difficult challenge.[26] Thus, 3-methyl-3-buten-1-ol **1a**, which is an important industrial feedstock, as the model alkene for this reaction was investigated. Alkene **1a** (6 mmol) along with metal catalysts (metal: 6 mol%), molecular sieve 4A (MS4A, 100 mg) as the co-catalyst and elemental sulfur (3.3 eq) were added, and then a high-pressure hydrogen gas (7 MPa) was introduced and the reaction under 130℃ and solvent-free conditions was performed. After 16 hours of reaction with the cobalt oxide (Co_3O_4), the result showed that 3-methyl-3-sulfanylbutanol **2a** was given a low yield of 11% (Table 2.1, entry 1). Considering the previous report,[11] the difference between the thiol yield and conversion of **1a** can be attributed to the reduction of dialkylpolysulfanes did not proceed. Next, CoS and CoS_2 as catalysts for this reaction were investigated; however, cobalt sulfides used in this reaction decreased the yields of thiol **2a** (Table 2.1, entries 2 and 3, 0.2–8%). Considering that the specific surface area of these cobalt sulfides was lower than the Co_3O_4, the decrease in thiol yield could be attributed to the loss of the specific surface area. Furthermore, the effect of cobalt salt catalysts on the reaction of alkene **1a** was investigated (Table 2.1, entries 4–8). The reaction of **1a** using Lewis acid catalysts gave thiol **2a** in low yield (Table 2.1, entries 4–7, 0.2–43%) and the use of basic cobalt carbonate ($CoCO_3$) increased the yield of thiol **2a** to 83% (Table 2.1, entry 8). The highest thiol yield of 94% was given in the reaction with a cobalt silicate

(CoO_x-SiO_y) as the catalyst. The calcined cobalt silicate (CoO_x-SiO_y-1000) was also used as the catalyst in this reaction; however, the reaction resulted in a low yield of 2% (Table 2.1, entry 10) due to the loss of specific surface area (less than 0.01 m^2/g). The nickel-based catalysts in the reaction were also investigated (Table 2.1, entries 11–13). The reaction of **1a** using NiO as the catalyst also gave thiol **2a** a good yield of 70% (Table 2.1, entry 11); however, NiO_x-CoO_y and NiO_x-SiO_y showed low catalytic activity, resulting in low thiol yields of 45–59% (Table 2.1, entries 12 and 13).

Table 2.1 Catalysts screening for **1a**.



entry[a]	cobalt or nickel cat.	conv. (%)[b]	**2a** (%)[b]
1	Co_3O_4	100	11
2	CoS	100	8
3	CoS_2	100	trace
4	$Co(ClO_4)_2$	100	trace
5	$CoCl_2$	100	5
6	$Co(OAc)_2$	100	8
7	$Co(NO_3)_2$	96	43
8	$CoCO_3$	100	83
9	CoO_x-SiO_y	100	94
10	CoO_x-SiO_y-1000	87	2
11	NiO	97	70
12	NiO_x-CoO_y	95	59
13	NiO_x-SiO_y	97	45

[a]Reaction carried out in H_2 (7 MPa), 3-methyl-3-buten-1-ol **1a** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), cobalt or nickel cat. (Co or Ni: 6 mol%), MS4A (100 mg), 130°C. [b]Conv. and yield of alkene **1a** and thiol **2a** analyzed by GC using tridecane as internal standard. [c]Cobalt 6 mol% and Nickel 1.7 mol% was loaded.

2.2.2 Catalyst characterizations

Several methods have been reported for preparing cobalt silicates; however, many of the methods involve high reaction temperatures (500–1500°C),[27] mechanochemical steps,[28] and require expensive $Co(acac)_3$ as the starting material.[29] In this case, the preparation of CoO_x-SiO_y used in the reaction by a hydrothermal reaction of $Co(NO_3)_2$ with Na_2SiO_3 and CoO_x-SiO_y-1000 was prepared from CoO_x-SiO_y by calcination.[30,31] The resulting cobalt silicate catalysts were analyzed by X-ray diffraction (XRD), scanning transmission electron microscope-energy dispersive X-ray spectroscopy (STEM-EDS), microwave plasma atomic emission spectrometer (MP-AES), and X-ray photoelectron spectroscopy (XPS).

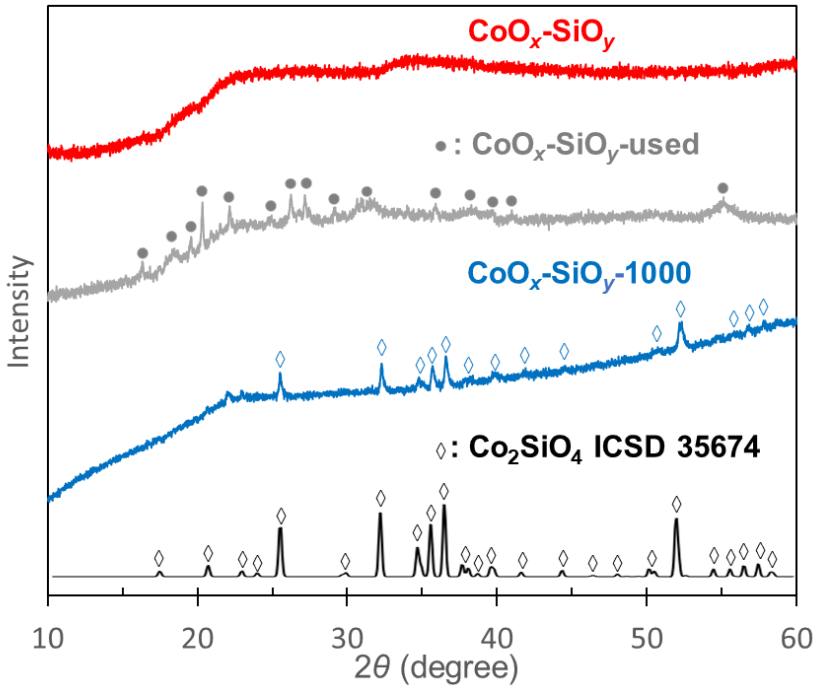


Figure 2.1 XRD patterns of cobalt silicate catalysts and α-Co_2SiO_4.

As shown in Figure 2.1, the XRD pattern of CoO_x-SiO_y showed no peaks, suggesting that the CoO_x-SiO_y has an amorphous structure. The XRD pattern of CoO_x-SiO_y after heating at 1000°C for 3 hours under a hydrogen atmosphere (CoO_x-SiO_y-1000) showed prominent peaks that can be attributed to α-Co_2SiO_4 (ICSD 35674).[21] The recovered catalyst sample (CoO_x-SiO_y-used) after the thiol synthesis also showed clear diffraction peaks; however, the peaks of these crystalline phases did not match the reported peaks of cobalt sulfides and cobalt silicates.

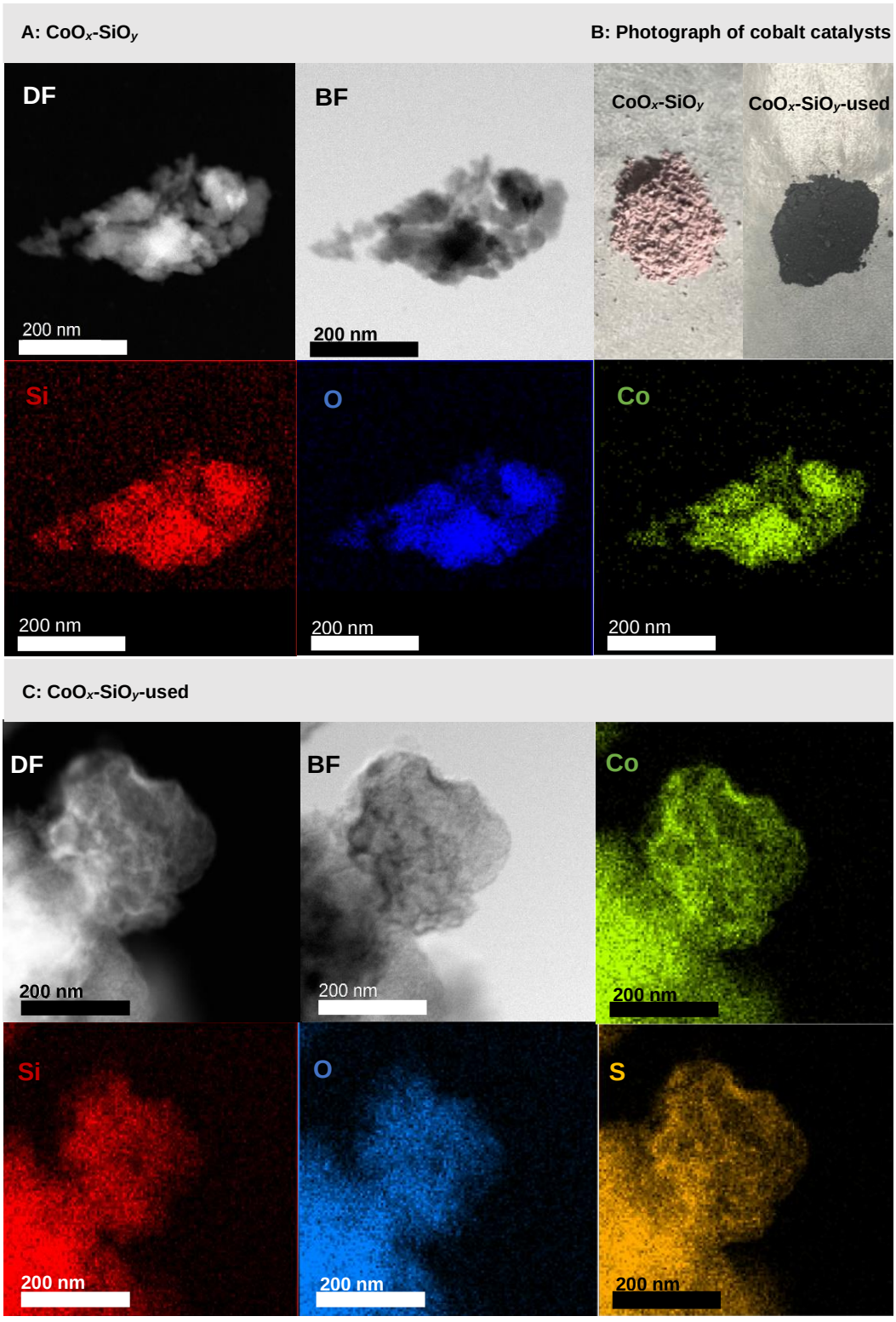


Figure 2.2 STEM-EDS images and photographs of the cobalt silicate catalysts: (A) Amorphous cobalt silicate catalyst. (B) Photographs of catalysts. (C) Cobalt silicate catalyst after the catalytic synthesis of thiol.

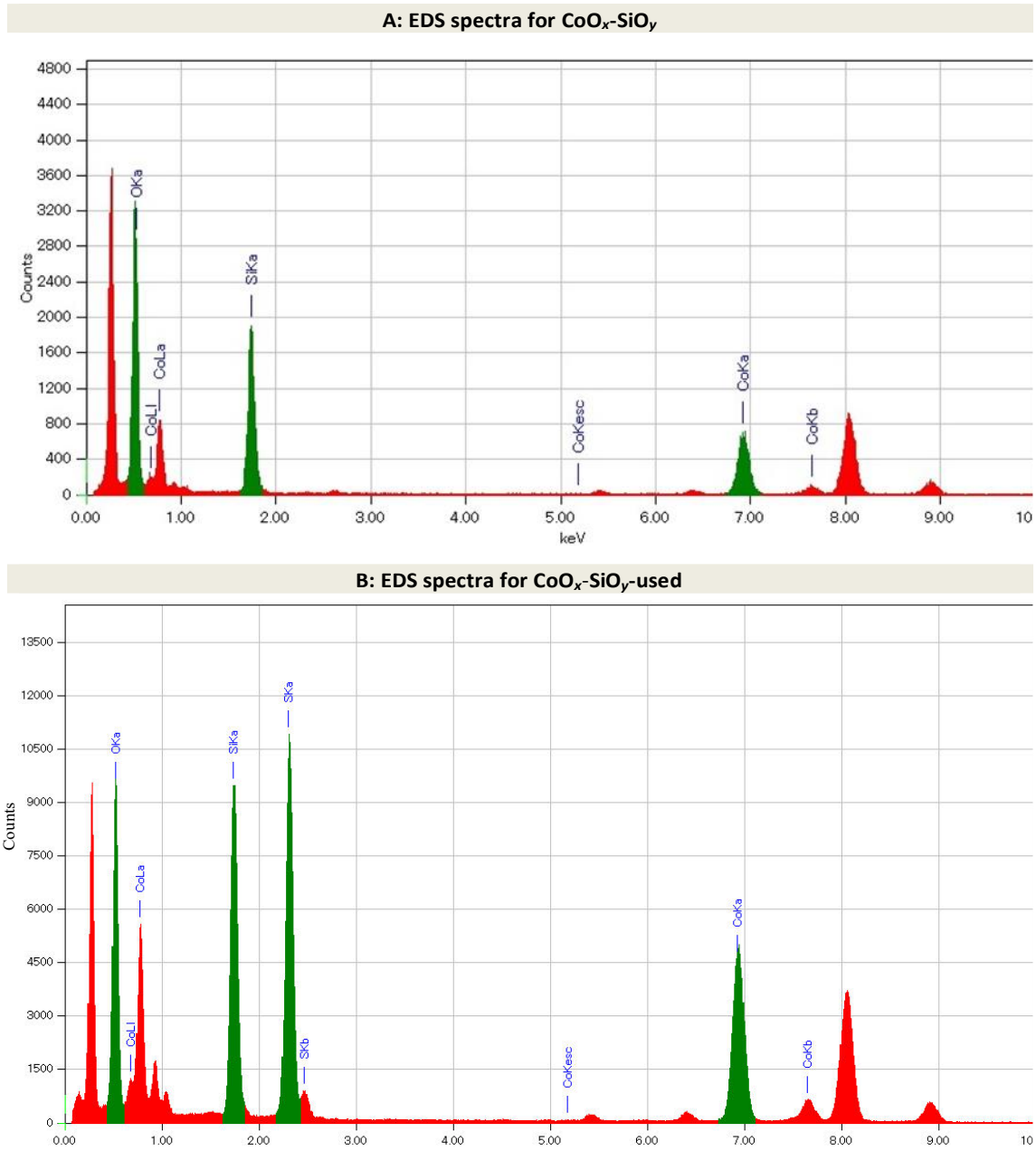


Figure 2.3 EDS measurement for the cobalt silicate catalysts: (A) CoO_x-SiO_y. (B) CoO_x-SiO_y-used.

To determine the elemental composition of the cobalt silicate catalysts before and after the reaction, STEM-EDS analysis was performed as shown in Figure 2.2 and Figure 2.3. The EDS measurement of CoO_x-SiO_y showed a uniform distribution of cobalt, silicon, and oxygen throughout the catalyst (Figure 2.2A and 2.3A). The EDS measurement was also conducted on the CoO_x-SiO_y-used sample as shown in Figure 2.2B and Figure 2.3B, revealing the presence of

cobalt, silicon, and oxygen. Furthermore, sulfur was also detected in the CoO_x-SiO_y-used sample, in addition to the aforementioned elements. Based on these analyses, the author proposed that the sulfurization of the CoO_x-SiO_y catalyst occurs after the reaction.

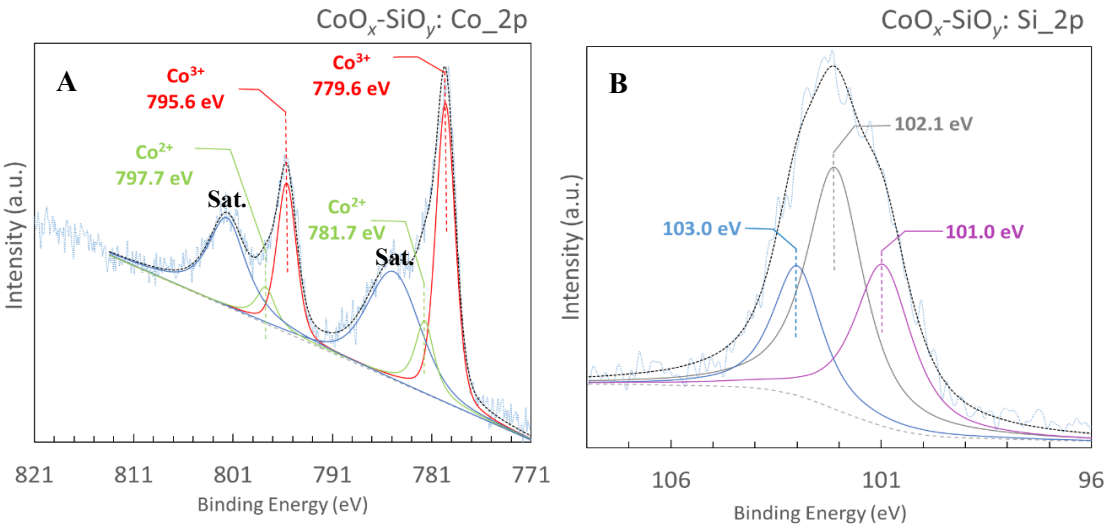


Figure 2.4 XPS spectra of CoO_x-SiO_y: (A) Co 2p. (B) Si 2p.

As shown in Figure 2.4 (A), (B) and Figure 2.5 (A)–(E), the XPS analysis of cobalt silicates was investigated. In the Co 2p region of CoO_x-SiO_y (Figure 2.4A), two distinct cobalt species were observed. The main cobalt species exhibited two peaks at 779.6 eV and 795.6 eV while the minor cobalt species showed peaks at 781.7 eV and 797.7 eV. Two distinct peaks of the cobalt species were separated by a distance of 16.0 eV. The main peak of CoO_x-SiO_y was represented to the Co^{3+} species[22] and the secondary peak of CoO_x-SiO_y was assigned to the Co^{2+} species[29] and the peaks at 784.8 eV and 801.6 eV were the satellite peaks of Co $2p_{3/2}$ and $2p_{1/2}$. The Co 2p for the recovered catalyst was also deconvoluted into two spin-orbit doublets (Figure 2.5A). The first doublet at 779.7 eV and 795.2 eV and the second at 781.7 eV and 797.2 eV were assigned to Co^{3+} species[22] and Co^{2+} species,[29] respectively and the satellite peaks were also observed at 803.7 eV and 784.9 eV. Compared to CoO_x-SiO_y, the Co $2p_{3/2}$ and $2p_{1/2}$ peaks were shifted slightly positively by 0.5 eV. This result may be attributed to the formation of mixed cobalt sulfides, increasing the electron density of the Co center.[32] The peak position of silicon species is known to be susceptible to several causes such as countercations,[33-35] different structures[36-38] and the basicity of CoO_x.[39] Three typical Si 2p peaks were observed as shown in Figure 2.4B. The main peak of Si 2p showed in 102.1 eV, corresponding to the tetravalent state of Si–O–Si.[34] The secondary peak at 103.0 eV was confirmed as Si–O–Co,[29] while the last peak at 101.0 eV indicated the tetravalent state of Si–O–Na.[35]

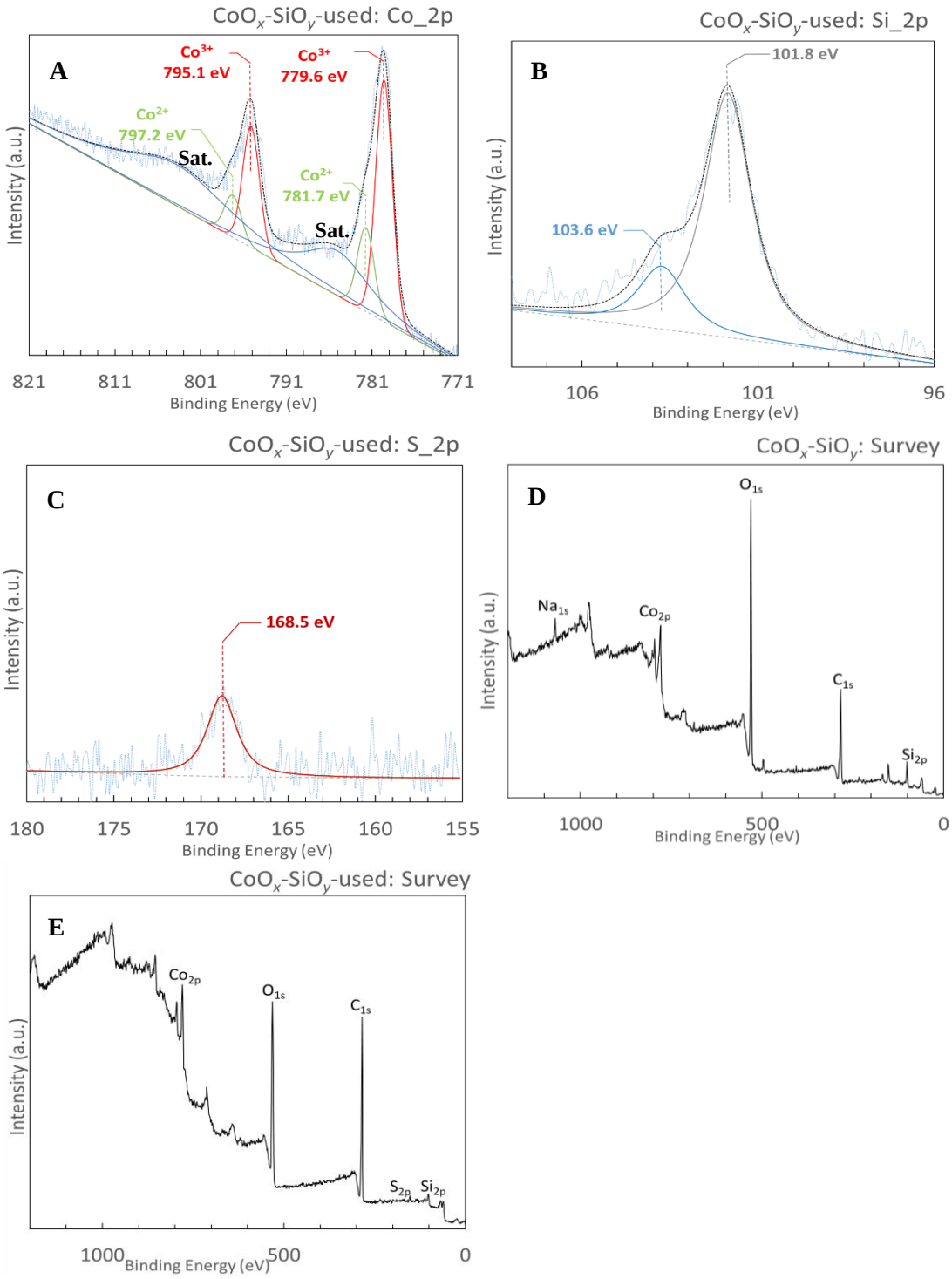


Figure 2.5 XPS spectra for CoO_x-SiO_y-used (B-E): (A) CoO_x-SiO_y-used Co 2p. (B) CoO_x-SiO_y-used Si 2p. (C) CoO_x-SiO_y-used S 2p. (D) CoO_x-SiO_y survey. (E) CoO_x-SiO_y-used survey.

The Si 2p region (Figure 2.5B) for CoO_x-SiO_y-used showed two silicon species have been observed at 103.6 eV and 101.8 eV, suggesting that the two silicon species were assigned to Si–

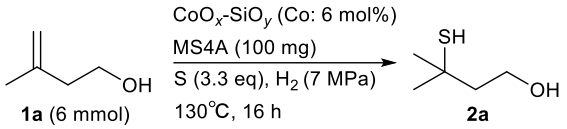
O–Si[34] and Si–O–Co.[23] Furthermore, one sulfur species was observed at 168.5 eV in the S 2p region of CoO_x-SiO_y-used, suggesting the presence of oxidized sulfur species on the surface of the sample (Figure 2.5C).[40] This observation also supports that the CoO_x-SiO_y was sulfurized after the reaction.

To evaluate the specific surface area of the cobalt silicate catalyst, the author examined the N_2 adsorption-desorption isotherms. Both isotherms were analyzed using the Brunauer-Emmett-Teller (BET) method to determine the specific surface area. The CoO_x-SiO_y catalyst exhibited a BET specific surface area of 55.9 m^2/g, which was larger than the value observed for CoO_x-SiO_y-used (30.0 m^2/g). The sulfurization of cobalt species and increased crystallinity would be attributed to the change in the specific surface areas.

2.2.3 Optimization of reaction conditions for *α*,*α*-disubstituted alkene **1a** and terminal alkene **1b**

With the cobalt catalyst study completed, the optimization of the reaction conditions was investigated. Firstly, the equivalent of sulfur was examined; however, when the sulfur equivalent was lowered to 1.7 eq, the alkene conversion and thiol yield decreased to 70% and 56%, respectively (Table 2.2, entry 2). When the reaction without the cobalt catalyst was performed, the author observed a high alkene conversion of 94%; however, the yield of thiol **2a** was lowered to 2% (Table 2.2, entry 3). Considering that MS4A can facilitate the nucleophilic S–S bond exchange with RS_nH,[11] the use of MS4A should promote an increase in the yield of thiol **2a**; however, the reaction without MS4A showed the highest yield of thiol **2a** in 99% (Table 2.2, entry 4). Thus, MS4A was not necessary in this reaction system. When the reaction under MS4A and cobalt catalyst-free conditions was performed, alkene **1a** also showed high conversion (99%) to form the polysulfanes; however, no thiol **2a** was observed in the reaction. (Table 2.2, entry 5). Next, the effect of hydrogen pressure was investigated. Lowering the hydrogen pressure to 5 MPa also gives the thiol a high yield of 86% (Table 2.2, entry 6). However, when the hydrogen pressure was decreased to 3 MPa, the yield of thiol **2a** was decreased to 5%. (Table 2.2, entry 7). Finally, the influence of reaction temperature was also investigated. Thiol **2a** was observed in a high yield of 96% even when the reaction temperature was decreased to 120°C (Table 2.2, entry 8). However, when the reaction temperature was increased to 140°C, the yield of thiol **2a** was decreased to 79% (Table 2.2, entry 9).

Table 2.2 Optimization of reaction conditions for 3-methyl-3-buten-1-ol **1a**.



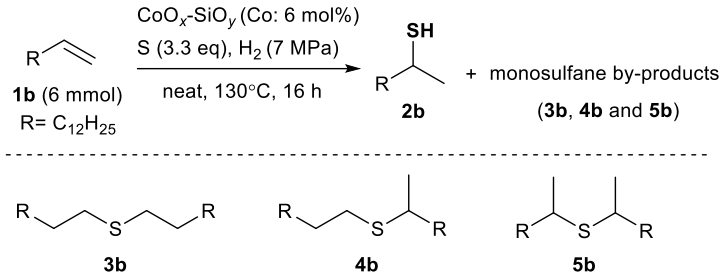
entry[a]	modifications	conv. (%)[b]	**2a** (%)[b]
1	none	100	94
2	sulfur 1.7 eq	70	56
3	without CoO_x-SiO_y	94	2
4	without MS4A	100	99
5[c]	without CoO_x-SiO_y	99	trace
6[c]	H_2 5 MPa	99	86
7[c]	H_2 3 MPa	94	5
8[c]	120°C	99	96
9[c]	140°C	99	79

[a]Standard reaction conditions: H_2 (7 MPa), 3-methyl-3-buten-1-ol **1a** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), CoO_x-SiO_y (Co: 6 mol%), MS4A (100 mg), 130°C, 16 h. [b]Conv. and yield of alkene **1a** and thiol **2a** analyzed by GC using tridecane as internal standard. [c]Under MS4A free condition.

Moreover, the author further investigated the optimization of reaction conditions using tetradecene **1b** as the model alkene. Tetradecene **1b** (6 mmol), sulfur (3.3 eq) and CoO_x-SiO_y (Co: 6 mol%) were added to the reaction. After 16 hours of reaction under 130°C, hydrogen 7 MPa and solvent-free conditions, thiol **2b** was observed in an acceptable yield of 64% (Table 2.3, entry 1). Dialkylmonosulfanes **3b**, **4b**, **5b** and anti-Markovnikov thiol **2b'** as the by-products were observed in the yields of 3%, 10%, 11% and 2% whereas these by-products were not observed in the reaction of α,α-disubstituted alkenes. When the equivalent of sulfur was decreased to 1.7 eq, the yield of **2b** was decreased to 27% and the conversion of **1b** was decreased to 84% (Table 2.3, entry 2). When MS4A as the catalyst was used, alkene **1b** gave in a high conversion of 92%; however, thiol **2b** showed a low yield (Table 2.3, entry 3). Considering the hard and soft acids and bases (HSAB) rule, Al in aluminosilicate is difficult to form Al–H in the catalyst surface; however, hydrogenation of alkenes with basic metal oxide has also been reported.[41-43] Furthermore, heterolytic H_2 activation can also occur using a γ-Al_2O_3 catalyst. Since MS4A has defective sites, Al in MS4A also works as a Lewis acid catalyst and undergoes heterolytic

dissociation of H_2[44,45] thus polysulfanes can be formed under the MS4A-catalyzed reaction conditions. The charge of hydrogen pressure in 3 or 5 MPa was investigated. However, the reactions showed similar low yields, which gave **2b** in yields of 54% and 18% (Table 2.3, entries 4 and 5). The effect of reaction temperature was also investigated. When the reaction temperature was decreased to 120°C, the yield of **2b** was decreased to 55% and when the reaction temperature was increased to 140°C, the yield was increased to 62% (Table 2.3, entries 5 and 6).

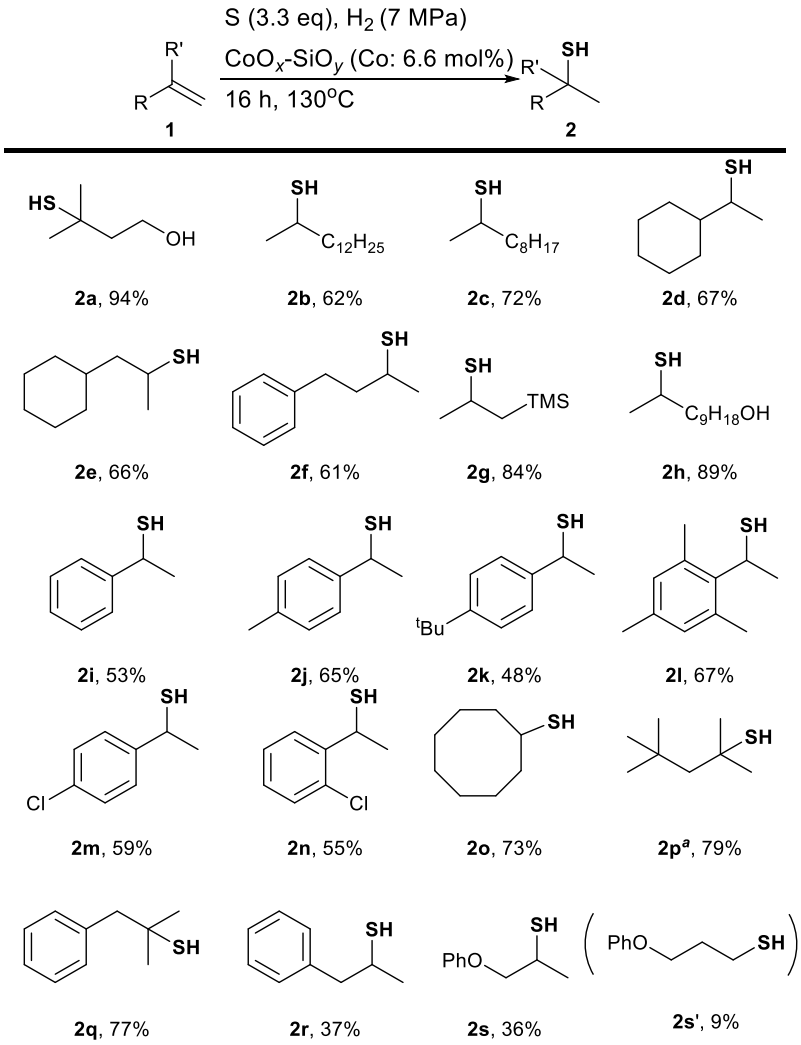
Table 2.3 Optimization of reaction conditions for tetradecene **1b**.



entry[a]	modifications	conv. (%)[b]	**2b** (%)[b]	**3b** (%)[b]	**4b** (%)[b]	**5b** (%)[b]
1	none	99	64	3	10	11
2	sulfur 1.7 eq	84	27	5	14	15
3[c]	MS4A as catalyst	92	2	1	4	4
4	H_2 5 MPa	99	54	3	8	9
5	H_2 3 MPa	99	18	2	6	7
6	120°C	99	55	3	10	11
7	140°C	99	62	3	8	9

[a]Standard reaction conditions: H_2 7 MPa, tetradecene **1b** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), CoO_x-SiO_y (Co: 6 mol%), 130°C, 16 h. [b]Conv. and yield of alkene **1b** and thiol **2b**, dialkylmonosulfane **3b**, **4b** and **5b** analyzed by GC using tridecane as internal standard. [c]MS4A 100 mg was added.

2.2.4 Alkene substrates analysis



Scheme 2.6 Alkene substrates are screening for this reaction.

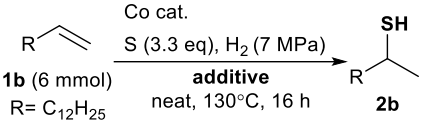
Reaction conditions: alkenes (6 mmol), H_2 (7 MPa), sulfur (3.3 eq), and CoO_x-SiO_y (Co: 6.6 mol%), reacted at 16 h in 130°C. the conv. and yield was determined by GC using decane, tridecane, or tetradecane as internal standards. Alkenes conv. > 99%. [a]Conv. = 83%.

With the optimized conditions having been achieved, the author next scrutinized the possibility of substrates in the reaction conditions. Nineteen of thiols were successfully synthesized using this reaction system (Scheme 2.6). The terminal alkenes, such as alkenes **1b-h** also produced the corresponding thiols **2b-g** in similar yields (**2b**: 62%, **2c**: 72%, **2d**: 67%, **2e**: 66%, **2f**: 61%, **2g**: 84%). Interestingly, alkene **1h** exhibited the highest thiol **2h** in the yield of 89% among the other alkenes. Styrene derivatives **1i-n** in this reaction were also performed and

gave thiol **2i-n** in the middle yields (**2i**: 53%, **2j**: 65%, **2k**: 48%, **2l**: 67%, **2m**: 59%, **2n**: 55%). Cyclooctene **1o** was then used in the reaction, which showed a high yield of 73%. The other α,α-disubstituted alkenes such as diisobutene **1p** and 2-methylallylbenzene **1q** as substrates were also investigated. The reaction provided the corresponding tertiary thiols **2p** and **2q** in high yields of 79% and 77%. The author also investigated the reaction with more reactive allylbenzene **1r** and allylphenyl ether **1s** as the substrates. However, thiol **2i** and **2s** resulted in low yields (37% and 36%) and alkene **1s** gave the highest anti-Markovnikov thiol **2s'** in the yield of 9%.

2.2.5 Recycling analysis of the CoO_x-SiO_y and CoO_x-SiO_y/MS4A

Table 2.4 Recycling experiments of the CoO_x-SiO_y and CoO_x-SiO_y-used.



entry	recycle (run)	Co cat.	conv. (%)[f]	**2b** (%)[f]
1[a]	0	CoO_x-SiO_y	99	64
2[b]	1	CoO_x-SiO_y-used	99	45
3[c]	1	CoO_x-SiO_y-used and fresh MS4A	99	63
4[d]	2	recovered Co/MS4A cat. from entry 3	99	58
5[d]	3	recovered Co/MS4A cat. from entry 4	99	38
6[e]	1	CoO_x-SiO_y-used and Na_2CO_3	99	53
7[e]	1	CoO_x-SiO_y-used and Na_2SiO_3	99	61

[a]CoO_x-SiO_y 86 mg as the catalyst was used. [b]CoO_x-SiO_y-used 86.0 mg as the catalyst was used. [c]MS4A (100 mg) and CoO_x-SiO_y-used 77 mg as the catalyst was used. [d]Recovered CoO_x-SiO_y-used/MS4A-used (177 mg) was used. [e]Na_2SiO_3 and Na_2CO_3 (6 mol%) were used. [f]Conv. of alkene **1b** and yield of thiol **2b** were analyzed by GC using tridecane as an internal standard.

The author also investigated the recyclability of the CoO_x-SiO_y catalyst in this reaction system (Table 2.4). The catalyst was recovered by centrifugation and washed with CS_2 and ethyl acetate three times and dried overnight under a vacuum at room temperature. In the first recycle experiment, the yield of **2b** with the recovered CoO_x-SiO_y dropped from 64% (Table 2.4, entry 1) with the fresh catalyst to 45% (Table 2.4, entry 2). The addition of MS4A as a weak base successfully suppressed the loss of the yield in the first and second recycle experiments with the recovered CoO_x-SiO_y (Table 2.4, entries 3 and 4) whereas the yield of **2b** in the third recycle experiment decreased to 38% (Table 2.4, entry 5). In addition, the recycle experiments with Na_2CO_3 or Na_2SiO_3 as weak bases also showed higher yields than those without base additives.

To investigate the effect of the metal leaching on the loss of the catalytic activity in the recycle experiments, a hot filtration experiment for the reaction of alkene **1b** was performed. The results revealed that the leaching of the cobalt metal was negligibly small. However, the XPS spectra of cobalt silicates showed that Na species disappeared after the reaction (Figure 2.5 D and E), suggesting that the deactivation of the catalyst occurred during the reaction.

2.2.6 Reaction mechanism analysis

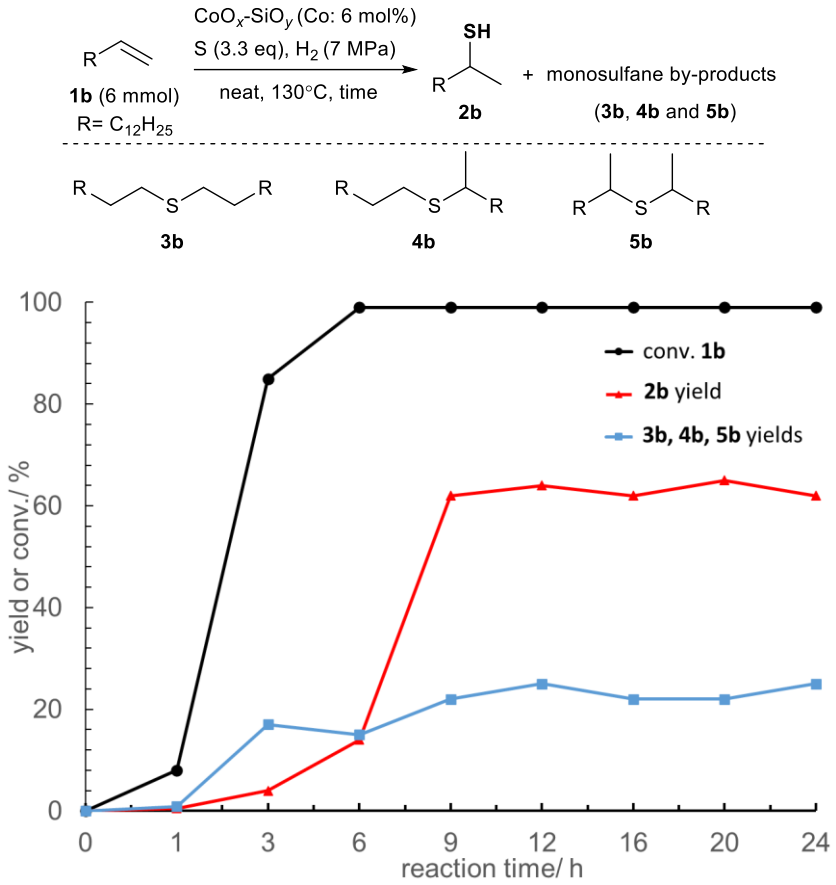
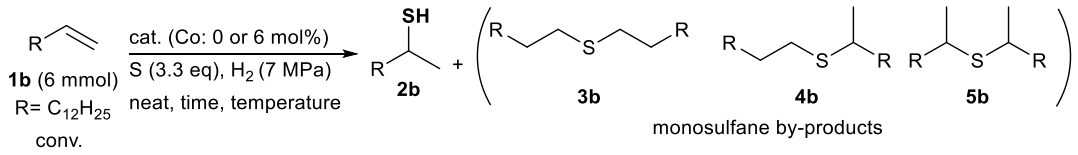


Figure 2.6 Time course of the Co-catalyzed thiol synthesis.

Since the majority of the substrates have been effectively applied in this reaction system, the author will now focus on investigating the reaction mechanism. Consequently, a series of control experiments have been conducted for the cobalt-catalyzed thiol synthesis (Figure 2.6). The time course in this reaction was investigated as shown in Figure 2.6. After 3 hours of reaction, the conversion of alkene **1b** was increased to 85% whereas the thiol showed a low yield of 4%. This result showed that the formation of dialkylpolysulfanes proceeded. The yield of thiol **2b** showed a significant increase between 6–12 hours. After 20 hours, the highest yield of **2b** was observed

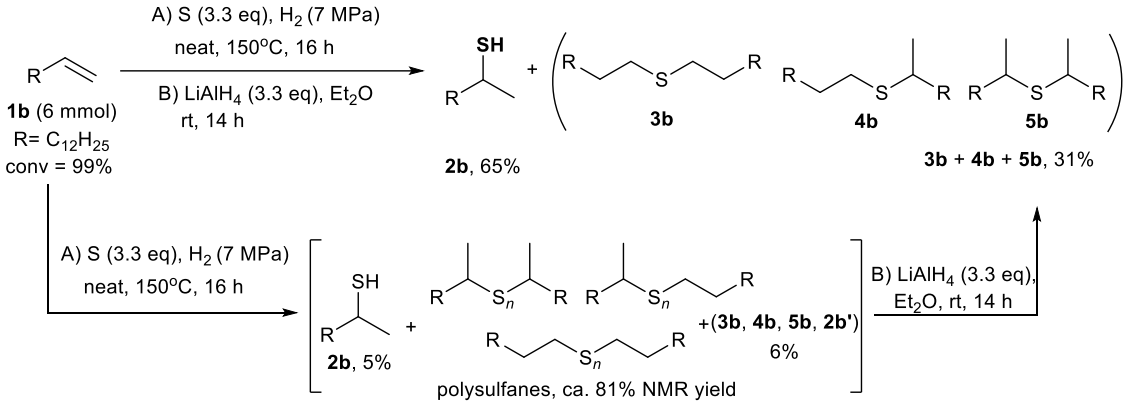
in 65% whereas the by-products **3b**, **4b**, and **5b** were still given in the yield of 25%. The mechanism for the formation of dialkylmonosulfanes **3b**, **4b** and **5b** was not clear. The author supposed a possible route may be attributed to thiol **2b** reacting with alkene and/or the unstable alkylhydropolysulfanes (RS_nH).

Table 2.5 Control experiments in the effect of cobalt catalyst, reaction time and temperature.



entry[a]	cat.	time/h	temperature/ °C	conv.[b]/%	**2b**[b]/%	**3b**+**4b**+**5b**[b]/%
1	none	16	130	32	trace	2
2	none	16	150	99	5	5
3	none	120	150	99	5	trace
4[c]	Co_3O_4	16	150	94	46	10

[a]Standard reaction conditions: H_2 7 MPa, tetradecene **1b** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), 150°C, 16 h. [b]Conv. and yield of alkene **1b** and thiol **2b**, dialkylmonosulfane **3b**, **4b**, **5b** analyzed by GC using tridecane as an internal standard. [c]Co_3O_4 (Co: 6 mol%) was added.



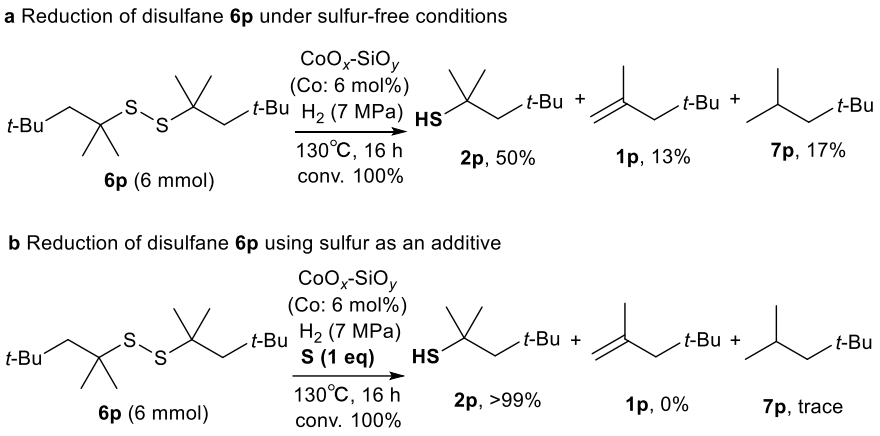
Scheme 2.7 Control experiments in investigation of the reaction intermediate.

To investigate the role of the cobalt catalyst, the reaction of tetradecene **1b** with elemental sulfur (3.3 eq) under cobalt-free conditions was investigated (Table 2.5). After 16 hours of reaction at 130°C, the alkene **1b**, thiol **2b** and monosulfanes showed low conversion (entry 1, 32%) and low yield. Increasing the reaction temperature to 150°C increases the conversion of alkene **1b** to 99%; however, thiol **2b** also resulted in low yield (entries 2 and 3). These results suggested that the reaction gives other organosulfur compounds as reaction intermediates. Taking

the relevant study[11] into consideration, polysulfanes could have been formed as reaction intermediates. To assess this hypothesis, the author performed a hydride reduction to probe the reaction intermediate (Scheme 2.7). After 16 hours of reaction at 150°C without cobalt catalysts, the reaction mixture was analyzed by nuclear magnetic resonance (NMR). The NMR yield of organosulfur compounds, which appear to be polysulfanes was ca. 81% and hydride reduction of the resulting reaction mixture gave thiol **2b** and dialkylmonosulfanes in 65% and 31% NMR yields, respectively, supporting the hypothesis. When Co_3O_4 was used as the catalyst, the yield of thiol **2b** increased to 46% (Table 2.5, entry 4). This result suggested that the homolytic S–S bond cleavage of elemental sulfur proceed under H_2 atmosphere (7 MPa) at 150°C to afford dihydropolysulfanes (HS_nH), following an electrophilic addition of alkenes to give Markovnikov-type polysulfanes, while the reduction of polysulfanes leading to the thiol product did not proceed without cobalt catalysts. Considering that the S–S bond cleavage of polysulfanes depends on its position in the sulfur chain, the central S–S bond of polysulfanes ($RS_nS–SS_nR$, 33.6 ± 2 kcal/mol) and terminal S–S bond of polysulfanes ($RS–S_nR$, 52.0–76.0 kcal/mol) have different bond dissociation energy (BDE). The S–S bond of elemental sulfur has low BDE (S_8: 35.0 kcal/mol) and initiates the homolytic ring-opening reaction at 116°C. Since the BDE of $RS_nS–SS_nR$ is similar to that of elemental sulfur, the cleavage of $RS_nS–SS_nR$ occurs homolytically. However, the terminal S–S bonds have high BDE thus the reaction did not proceed without the cobalt catalyst.[46-48] The use of the cobalt catalyst leads to the heterolytic dissociation of H_2, which promotes the cleavage of terminal S–S bonds to afford thiols.

The author further performed control experiments to investigate the reaction intermediate (Scheme 2.7). The reaction intermediates, which were obtained from tetradecene **1b**, hydrogen gas and sulfur, was reduced by $LiAlH_4$. The NMR analysis of the reaction before and after the hydride reduction showed a significant chemical shift change, suggesting the intermediate was transformed to thiol **2b** (65% NMR yield) and dialkylmonosulfanes (31% NMR yield). Based on these results and the relevant previous report,[11] the reaction gave polysulfanes as the intermediate in ca. 81% NMR yield (Scheme 2.7 and Figure 2.10A).

To elucidate the reduction of polysulfanes, the author subsequently conducted the hydrodesulfurization of diisobutyldislufane **6p**. Firstly, the author performed the reaction under sulfur-free conditions (Scheme 2.8a). Indeed, disulfane **6p** was reduced to thiol **2p** in the yield of 50%. However, the reaction showed a C–S bond disconnection to obtain alkene **1p** and alkane **7p** in 13% and 17% yield. When sulfur (1 eq) was added to the reaction, the yield of thiol **2p** was up to 99% and no alkene **1p** and alkane **7p** were observed (Scheme 2.8b). These results showed that the use of elemental sulfur inhibits thiols adsorption and suppresses the undesired reduction of alkenes and C–S bonds during the reaction.



Scheme 2.8 The hydrodesulfurization of diisobutyldisulfane **6p** using CoO_x-SiO_y.

To confirm the generation of H_2S during the reaction, the gas analysis from the thiol synthesis using tetradecene **1b** and CoO_x-SiO_y was measured using the mass spectrometer (Figure 2.7 A and B). The *m/z* values at 33 and 34 were detected, indicating the presence of H_2S.[49] The gas analysis from the reaction of sulfur and hydrogen with CoO_x-SiO_y under alkene **1b** free conditions as the control experiment also suggested with the generation of H_2S (Figure 2.7B). These results indicated that the hydrogenolysis of sulfur by CoO_x-SiO_y proceeded irrelevant to the presence of alkene substrates. The addition reaction of H_2S and alkenes to form thiol requires high pressure of H_2S gas;[4] however, in this case, the pressure of H_2S was observed at ca. 1–3 atm. Thus, the reaction rules out the electrophilic addition between H_2S and alkenes.

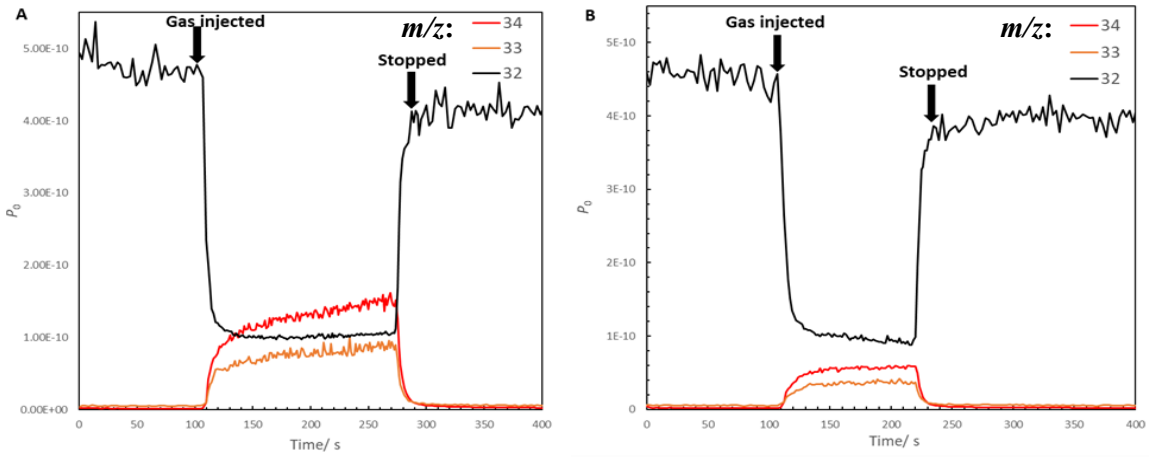
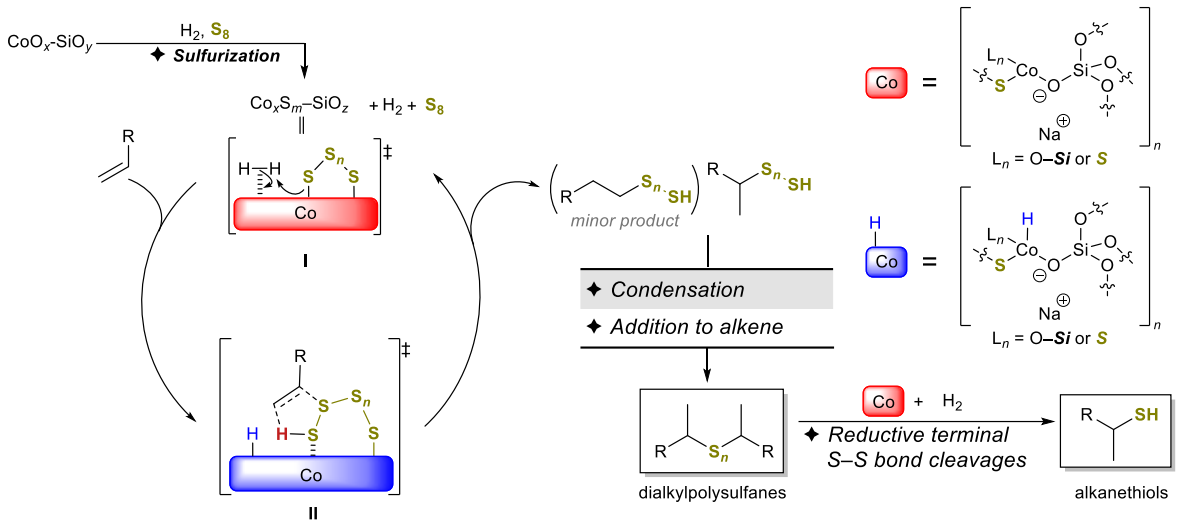


Figure 2.7 Gas analysis for hydrogen reacted with sulfur using mass spectrometer: (A) After **1b** thiol synthesis. (B) After sulfur reacted with hydrogen.

According to the above experiments and the previous study,[11] the author proposed a possible reaction mechanism in Scheme 2.9. Firstly, CoO_x-SiO_y was subjected to sulfurization to form the

Co_xS_m-SiO_z in the initial step. Then, the cleavage of the S–S bond in S_8 occurs followed by heterolytic H_2 activation with the Co_xS_m-SiO_z catalyst to generate the terminal SSH group. In addition, the SSH group in the Co_xS_m-SiO_z surface takes place in an asynchronous concerted step with alkenes to form the five-member ring transition state and gives the Markovnikov-type polysulfanes. Further, the reductive S–S bond cleavage was promoted on the catalyst surface to generate the thiol as the main product.[50,51] Finally, thiols underwent *S*-alkylation to afford dialkylmonosulfanes. As for the role of silicate, the author supposed that the oligomerization of silicon species occurs to form bulky silicate oligomers,[52] which serve as a strong basic ligand adjacent to the cobalt center. The bulky silicate ligands may provide the appropriate steric hindrance and/or suitable distance, promoting the hydrogenolysis of the terminal S–S bonds of polysulfanes.[53] The use of weak bases such as Na_2SiO_3 or Na_2CO_3 would lead to the hydrogenolysis of polysulfanes to provide thiol without significant loss yield in recycling experiments.



Scheme 2.9 Proposed reaction mechanism.

2.3 Conclusion

In summary, the author has developed a novel H_2S-reagent-free method for thiol synthesis using elemental sulfur, hydrogen gas and alkenes. This method is a good example of catalytic synthesis of organosulfur compounds using elemental sulfur and molecular hydrogen and will lead to safer and more efficient industrial processes in the future. The cobalt silicate catalyst (CoO_x-SiO_y) promoted the reaction of α,α-disubstituted alkene **1a** to give thiol **2a** up to 99% yield. In addition, the other substrates have been successfully applied to this reaction system resulting in 36–89% yields. The addition of MS4A to the recovered catalyst (CoO_x-SiO_y-used) showed

acceptable durability and could be reused at least 2 times without significant loss of yield. Moreover, the characterization of cobalt silicates with XRD, XPS, and STEM-EDS indicated the sulfurization of CoO_x-SiO_y under the reaction conditions. Furthermore, the author proposed the possible reaction mechanism involving heterolytic hydrogen activation and the reductive S–S bond cleavage of the poylsulfanes by hydrogen on the catalyst surface. Further investigations to explore the thiol synthesis under low hydrogen pressure conditions are now underway.

2.4 Experimental

2.4.1 General information for chemical materials and instruments

All alkene substrates and reagents were available and without purification. 3-methyl-3-buten-1-ol **1a** was purchased from TCI or Kuraray. Tetradecene **1b**, vinyl cyclohexane **1d**, allyl cyclohexane **1e**, undec-10-en-1-ol **1h**, styrene **1i**, 4-methyl or 4-tert-butyl styrene **1j** and **1k**, cyclooctene **1o**, allyl benzene **1r**, diisobutene **1p**, allyl phenyl ether **1s** were purchased from TCI. Decene **1c**, but-3-en-ylbenzene **1f**, 4-chlorostyrene **1m** were purchased from FUJIFILM Wako Pure Chemical Corporation (Wako). Allyl trimethyl silane **1g** was purchased from ACROS ORGANICS and 2-chlorostryene **1g**, 2,4,6-trimethylstyrene **1l** were purchased from Sigma-Aldrich and the use of 2-methyl-3-phenyl-1-propene **1q** was purchased from Alfa Aesar. The use of available cobalt catalysts was obtained from Alfa Aesar, Sigma-Aldrich, Wako and STREM CHEMICALS, INC. All cobalt or nickel precursors and Na_2SiO_3 were available from Sigma-Aldrich, Wako and KISHIDA Chemical. The deionized water was purchased from FUJIMORI KOGYO CO., LTD. ^{1}H and ^{13}C NMR and HMQC were measured with JEOL JNM-ECS-400 MHz or JNS-ECA-600 MHz at 20°C and the chemical shift of chloroform-d was reported and referenced in ^{1}H 7.26 ppm, ^{13}C 77.16 ppm and the internal standard of tetramethyl silane was referenced to 0.00 ppm. The use of organic solvents for the synthesis such as AcOEt, $CHCl_3$, and THF were purchased from Wako without dehydration. The purification of thiols was carried out with a glass tube oven GTO-2000. Conversion of alkenes and yield of thiols were measured with an Agilent Technologies gas chromatography 6850 GC system equipped with an HP-1 column (0.25 μm film, 0.32 mm diam., 30 m length). The heating program was maintained at 40°C for 5 minutes and then raised to 200°C for 20 minutes at 10 °C/min. It was, then held for 15 min (total run time 40 min, average time 3 min) and the use of internal standards such as tridecane, decane and tetradecane was purchased from TCI or Wako. The Catalysts characterization was investigated by microwave plasma atomic emission spectrometer (Agilent 4100 system), Scanning transmission electron microscopy (STEM, JEOL JEM-ARM200F), X-ray powder diffraction (XRD, Rigaku MiniFlex600 with a Cu$K\alpha$), and X-ray photoelectron spectroscopy (XPS, Shimazu-AXIS-165 $K\alpha$). The use of copper grid was purchased from stem crop. (TMG2-1001.

NU-C10-25, Cu100P). The specific surface area was investigated by BELSORP-mini II-SP. The NMR data and XPS data were analyzed by Delta 6.1.0 and XPSPEAK software. The use of a 40 mL autoclave was purchased from Toyo Kouatsu and the use of personal organic synthesizer PPV-5460 was purchased from EYELA.

2.4.2 Preparation of amorphous cobalt silicate catalyst (CoO_x-SiO_y)

$Co(NO_3)_2 \cdot 6H_2O$ (2.91 g, 10 mmol) was dissolved in 90 mL of deionized water in a 300 mL flask and a Na_2SiO_3 solution (1.22 g, 10 mmol in 10 mL deionized water) was added dropwise to the flask over 3 min. Then, the combined solution was stirred over 3 h under air at room temperature conditions. After completion of the reaction, the resulting precipitate was filtered. The residue was washed three times with 50 mL of deionized water and dried in the air at 70°C for 14 h. The corresponding solid was pulverized and passed through a 125 μm sieve to afford CoO_x-SiO_y as a pink powder (1.6 g, S_{BET} = 55.9 m^2/g). The cobalt content was 25 wt% determined by MP-AES.

2.4.3 Preparation of CoO_x-SiO_y-1000

CoO_x-SiO_y (1.1 g, Co: 25 wt%) was placed on an alumina boat. The sample was then calcined at 1000°C for 3.3 h (5 °C/min) in an H_2 flow (20 mL/min) to give CoO_x-SiO_y-1000 as a purple powder (1.0 g, S_{BET} < 0.01 m^2/g).

2.4.4 Preparation of amorphous nickel silicate catalyst (NiO_x-SiO_y)

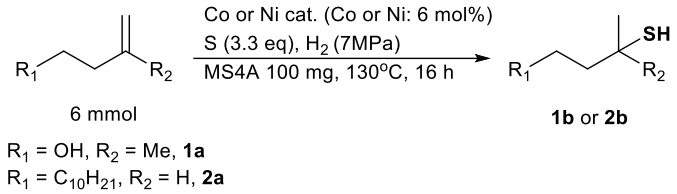
$Ni(OAc)_2 \cdot 4H_2O$ (4.98 g, 20 mmol) was dissolved in 90 mL of deionized water in a 300 mL flask and a Na_2SiO_3 solution (2.44 g, 20 mmol in 10 mL deionized water) was added dropwise to the flask over 3 min. The combined solution was stirred over 3 h under air at room temperature. After completion of the reaction, the resulting precipitate was filtered. The residue was washed three times with 50 mL of deionized water and dried at 70°C under air for 14 h to afford NiO_x-SiO_y as a green solid, which was then pulverized and passed through a 125 μm sieve to give a green powder (4.0 g, S_{BET} = 169.1 m^2/g). The nickel content was 29 wt% determined by MP-AES.

2.4.5 Preparation of nickel cobalt complex oxide catalyst (NiO_x-CoO_y)

$Co(NO_3)_2 \cdot 6H_2O$ (5.82 g, 20 mmol) and $Ni(OAc)_2 \cdot 4H_2O$ (2.48 g, 10 mmol) were dissolved in 150 mL of deionized water in a 300 mL flask and an $(NH_4)_2CO_3$ solution (2.88 g, 30 mmol in

50 mL deionized water) was added dropwise to the flask over 5 min. The combined solution was stirred over 3 h under air at room temperature. After completion of the reaction, the residue was filtered and washed several times with 50 mL of deionized water. The obtained residue was dried at 70°C under air for 15 h. The resulting solid was then pulverized and passed through a 125 μm sieve to give NiO_x-CoO_y as a black powder. The obtained black powder was calcined at 300°C for 6 h to give NiO_x-CoO_y as a black powder (2.16 g, S_{BET} = 53.5 m^2/g). The cobalt and nickel content of NiO_x-CoO_y was 38 wt% and 11 wt%, respectively, determined by MP-AES.

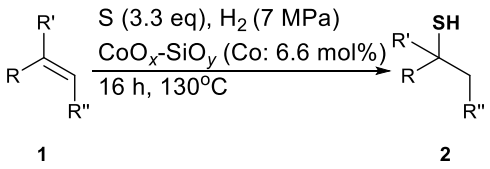
2.4.6 General procedure for optimization of the reaction conditions



Scheme 2.10 Catalysts screening for alkenes **1a** and **2a**.

To a 40 mL autoclave with a magnetic stir bar, 3-methyl-3buten-1-ol **1a** or tetradecene **1b** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq), MS4A (100 mg), and Co or Ni cat. (Co or Ni: 6 mol%) was added, then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane was added as the internal standard, then the mixture was washed with acetic ethyl ester and transformed into a 10 mL centrifuge tube. The residue including catalyst, zeolite, and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol **2a** or **2b**.

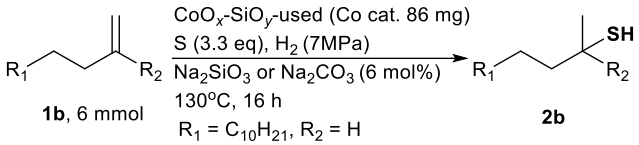
2.4.7 General procedure for catalytic thiol synthesis from H_2, S and alkenes



Scheme 2.11 Alkene substrates analysis.

To a 40 mL autoclave with a magnetic stir bar, alkene **1** (6 mmol, 1.0 eq), sulfur (640.4 mg, 20 mmol, 3.3 eq), and CoO_x-SiO_y (95.0 mg, Co: 25 wt%, Co: 6.6 mol%) was added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130℃ while stirring at 800 rpm for 16 hours. After the reaction was complete, the autoclave was cooled with ice water then open the valve to place under air atmospheric pressure to distill off the residual gas. Decane, tridecane, or tetradecane was added as the internal standard, and then the mixture was washed with solvents such as hexane, acetic ethyl ester, or diethyl ether and transformed into a 10 mL centrifuge tube. The black residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol **2**. The solvent of the organic layer was removed by an evaporator. The resulting mixture was purified by distillation under reduced pressure to give a colorless liquid.

2.4.8 General procedure for the effect of bases in the thiol synthesis



Scheme 2.12 The effect of weak base in the thiol synthesis.

To a 40 mL autoclave with a magnetic stir bar, tetradecene **1b** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq), Na_2SiO_3 or Na_2CO_3 (6 mol%) and recovered cobalt silicate catalyst (CoO_x-SiO_y-used, Co: 86.0 mg) was added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual gas. Tridecane was added as the internal standard, then the mixture was washed with ethyl acetate and transformed into a 10 mL centrifuge tube. The residue including catalyst, bases and unreacted sulfur was removed by centrifugal separation and the organic layer was analyzed by GC to calculate the yield of thiol **2b**.

2.4.9 Leaching analysis for the thiol synthesis of tetradecene **1b**

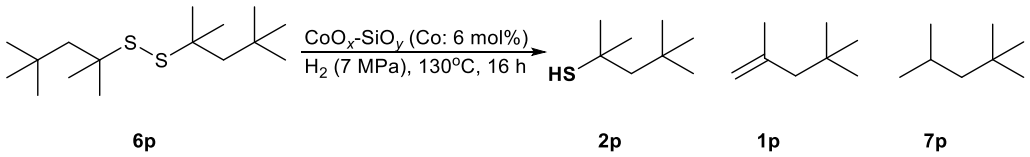
To a 40 mL autoclave with a magnetic stir bar, tetradecene **1b** (6 mmol, 1.0 eq), sulfur (640.4 mg, 20 mmol, 3.3 eq), and CoO_x-SiO_y (86.1 mg, Co: 25wt%, Co: 6 mol%) were added. Then, the

autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130℃ while stirring at 800 rpm for 16 hours. After the reaction is complete, open the valve under 130℃ to place it under air atmospheric pressure to distill off the residual gas, then undergo a hot filtration to remove the residue. To oxidize the organic layer, it was refluxed aqua regia until gave a clear aqueous solution, and MP-AES evaluated the cobalt content of the solution in less than 5.7 ppb.

2.4.10 Mass spectrometer for the gas analysis

To a 40 mL autoclave with a magnetic stir bar, sulfur (640.8 mg, 20 mmol) and CoO_x-SiO_y (95.0 mg, Co: 25 wt%, Co: 6.6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130℃ while stirring at 800 rpm for 16 hours. After the reaction was complete, the autoclave was cooled with ice water, then open the valve to collect the gas into a balloon. The balloon was connected to the mass spectrometer to detect H_2S gas.

2.4.11 The reduction of disulfane **6p**



Scheme 2.13 Reduction of disulfane **6p** using CoO_x-SiO_y as the catalyst.

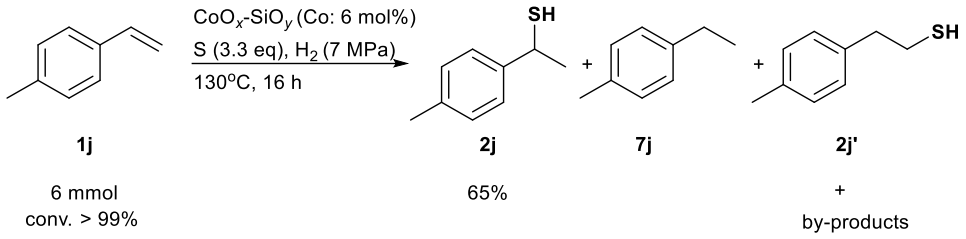
To a 40 mL autoclave with a magnetic stir bar, disulfane **6p** (6 mmol, 1.0 eq), sulfur (0 or 640.4 mg, 0 or 20 mmol, 0 or 3.3 eq), and CoO_x-SiO_y (86.1 mg, Co: 25wt%, Co: 6 mol%) was added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130℃ while stirring at 800 rpm for 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane was added as the internal standard, then the mixture was washed with hexane and transformed into a 10 mL centrifuge tube. The black residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of

thiol **2p**.

2.4.12 Assessment of the purity of products **2j**, **2s** by ^{1}H NMR analysis

The quantitative NMR (qNMR) was measured at a relaxation delay of 60 seconds, 1,3,5-trioxane (99%, TCI) as the internal standard and the purity of 1-(p-Tolyl)ethane-1-thiol and 1-Phenoxypropane-2-thiol was calculated.

1. 1-(p-Tolyl)ethane-1-thiol **2j**



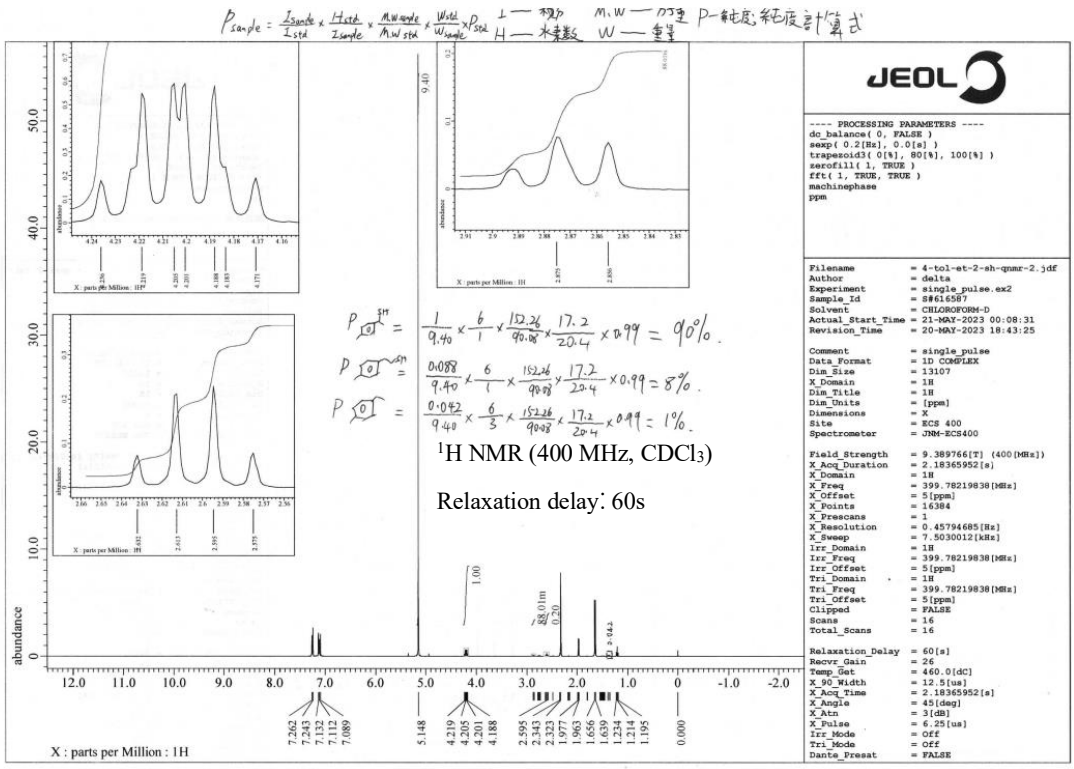
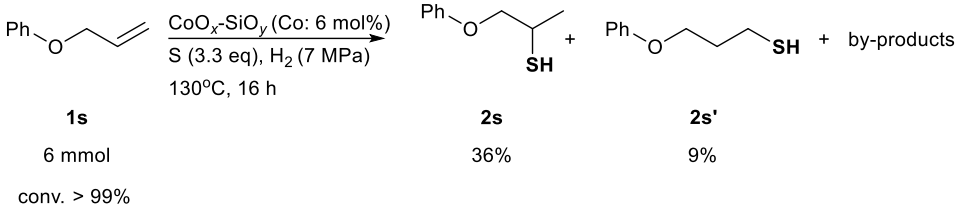


Figure 2.8 NMR purity analysis for 1-(p-tolyl)ethane-1-thiol: 1-(p-tolyl)ethane-1-thiol 90%, 2-(p-tolyl)ethane-1-thiol 8%, 4-ethyltoluene 1%.

2. 1-Phenoxypropane-2-thiol **2s**



1s 6 mmol conv. > 99%

2s 36%

2s' 9%

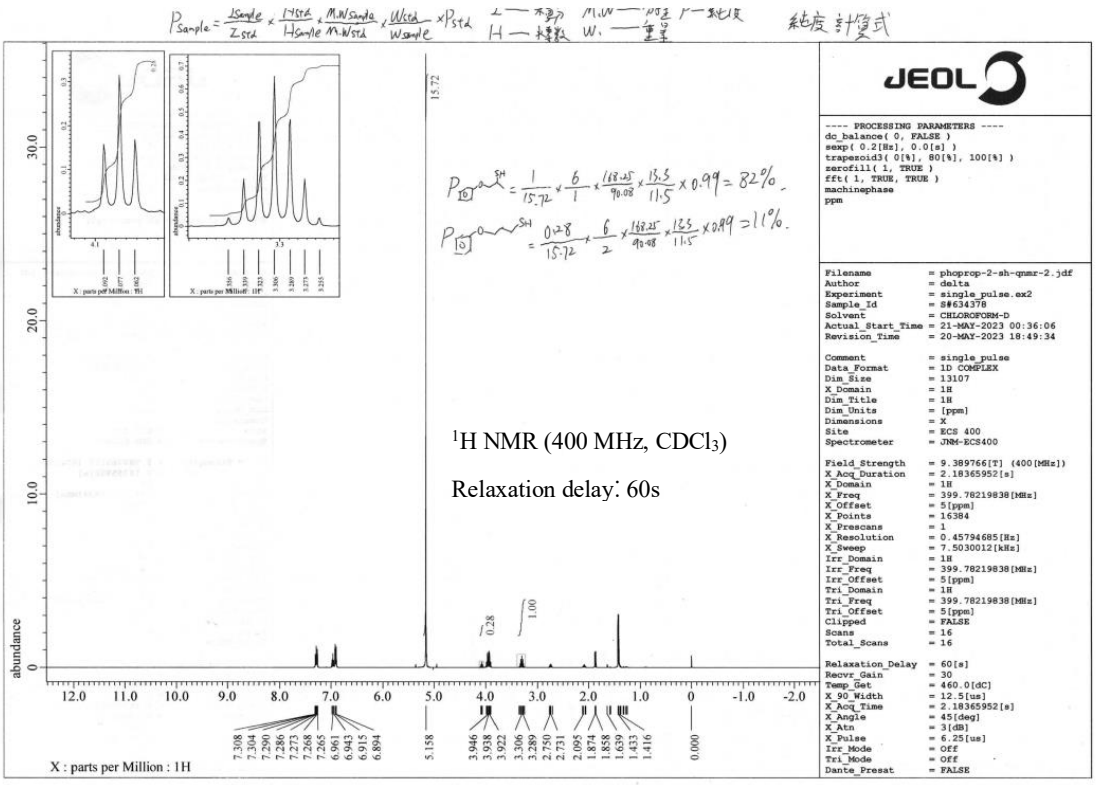
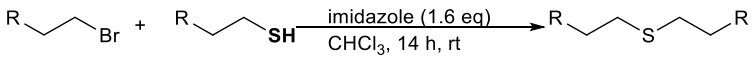


Figure 2.9 NMR purity analysis for 1-phenoxypropane-2-thiol: 1-phenoxypropane-2-thiol 82%, 3-phenoxypropane-1-thiol 11%.

2.4.13 Synthesis of **3b**, **4b**, **5b** and 1,2-di(tetradecan-2-yl)disulfane



1 mmol R= $C_{12}H_{25}$

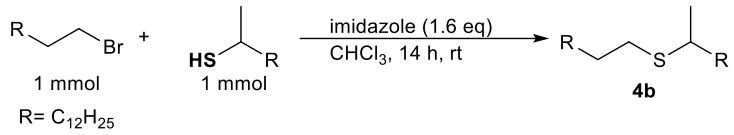
1 mmol

3b

Scheme 2.14 Synthesis of dialkylmonosulfane **3b**.

To a 25 mL of flask tetradecane-2-thiol **2b** (230.0 mg, 1.0 mmol, 1 eq), which was obtained

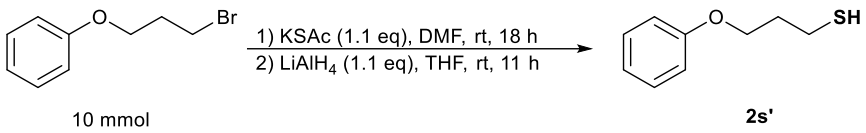
from the General Procedure for **1b**, and imidazole (110.6 mg, 1.6 mmol, 1.6 eq) was added. Then the flask was replaced with N_2. Tetradecyl bromide (277.3 mg, 1.0 mmol, 1 eq) in 3 mL of $CHCl_3$ was added to the flask under an N_2 atmosphere and reacted for 14 hours. After the reaction, the solvent of the reaction mixture was removed under reduced pressure. The resulting crude mixture was purified by silica gel column chromatography (hexane: ethyl acetate = 49:1) to give ditetradecylsulfane **3b** (300 mg, 0.7 mmol, 70% yield) as a white solid.



Scheme 2.15 Synthesis of dialkylmonosulfane **4b**.

To a 25 mL of flask tetradecane-2-thiol **2b** (232.0 mg, 1.0 mmol, 1 eq), which was obtained from the General Procedure for **1b**, and imidazole (110.6 mg, 1.6 mmol, 1.6 eq) was added. Then the flask was replaced with N_2. Tetradecyl bromide (283.6 mg, 1.0 mmol, 1 eq) in 3 mL of $CHCl_3$ was added to the flask under an N_2 atmosphere and reacted for 14 hours. After the reaction, the solvent of the reaction mixture was removed under reduced pressure. The resulting crude mixture was purified by a silica gel column chromatography (hexane: ethyl acetate = 49:1) to give the tetradecan-2-yl(tetradecyl)sulfane **4b** (300 mg, 0.7 mmol, 70% yield) as a white solid.
The ditetradecanedisulfane was obtained by a reported method.[54] Moreover, the resulting disulfane was measured by NMR and elemental analysis, which was compared with the crude dialkylmonosulfane **5b**.

2.4.14 Synthesis of 3-phenoxypropane-1-thiol **2s'**



Scheme 2.16 Synthesis of 3-phenoxypropane-1-thiol via S_N2 reaction.

3-Bromopropoxybenzene (2.14 g, 10 mmol, 1 eq, TCI) and KSAc (1.26 g, 11 mmol, 1.1 eq, TCI) were placed in a 50 mL of the flask with a stirrer bar. Then, the mixture was dissolved in 2 mL of DMF and stirred for 18 hours. After the reaction, the mixture was washed with water, extracted with ethyl acetate 3×5 mL, and dried with $MgSO_4$. Then the resulting mixture was filtrated to remove the residue and the organic layer was concentrated by an evaporator to give the crude thioester as a yellow oil. The crude oil was purified by silica gel column chromatography

eluting with hexane: ethyl acetate (9:1) to give the 3-phenoxypropyl ethanethioate (1. 62 g, 7.7 mmol, 77% yield) as a light-yellow oil. The oil was dissolved in 5 mL of THF and used in the next step. To 100 mL of the flask, $LiAlH_4$ (0.32 g, 8.4 mmol, 1.1 eq) was added. Then the flask was replaced with N_2 and THF 5 mL was added into the flask under N_2 atmosphere. The thioester solvation was added into the flask and stirred for 11 hours. The reaction was quenched with ice, extracted with ethyl acetate 3 × 5 mL, and dried with $MgSO_4$. Then the resulting mixture was filtrated to remove the residue and the organic layer was concentrated by an evaporator to give the crude thiol. The crude thiol was purified by silica gel column chromatography eluting with hexane: ethyl acetate (49:1). After the column chromatography, the solvent was removed and gave a light-yellow oil. The oil was distilled under reduced pressure to obtain the 3-phenoxypropane-1-thiol **2s'** (0.31 g, 1.8 mmol, 24% yield).

2.4.15 General procedure for recycling run

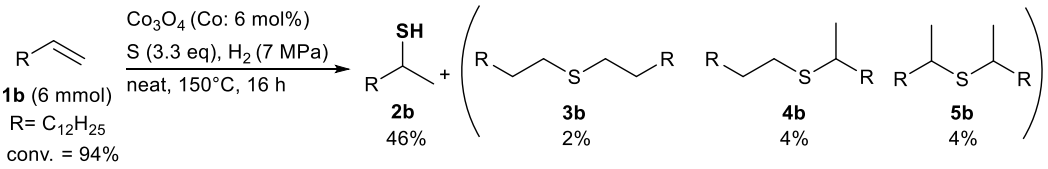
Sulfur powder (640.4 mg, 20 mmol, 3.3 eq), alkene **1b** (6 mmol, 1.0 eq), and CoO_x-SiO_y-used (86.0 mg) or Co_xS_y-SiO_z /MS4A (186.0 mg) and a magnetic stirrer bar were placed in a 40 mL autoclave. Then, the autoclave was evacuated and charged with H_2 gas three times. After that, the autoclave was heated to 130°C and stirred at 800 rpm for 16 h. After 16 h, the autoclave was cooled with ice water. tridecane was added as an internal standard, then the resulting mixture was centrifuged and filtered to remove the catalysts. The supernatant of the centrifuged mixture was analyzed by GC.

Sulfur powder (640.4 mg, 20 mmol, 3.3 eq), alkene **1b** (6 mmol, 1.0 eq), and CoO_x-SiO_y (86.0 mg, Co: 25 wt%, 6 mmol) and a magnetic stirrer bar were placed in a 40 mL autoclave. Then, the mixture was carried out in General procedure for thiol synthesis. After the thiol synthesis, the organic layer was removed, and the resulting residue was washed with CS_2 (3×3 mL) and ethyl acetate (3×3 mL). Then, the solid was placed under reduced pressure and dried at room temperature overnight to obtain the recovered catalyst (CoO_x-SiO_y-used) as a black powder (S_{BET} = 30.0 m^2/g).

2.4.16 Control experiments in the effect of cobalt catalyst, reaction time, temperature and reaction intermediate study

To a 40 mL autoclave with a magnetic stir bar, tetradecene **1b** (1178.6 mg, 6 mmol, 1.0 eq) and sulfur (640.4 mg, 20 mmol, 3.3 eq) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 150°C while stirring at 800 rpm

for 16 hours. After the reaction was complete, the autoclave was cooled with ice water then open the valve to place under air atmospheric pressure to distill off the residual gas. The mixture was washed with Et_2O 3×5 mL and transformed into a 50 mL flask. The organic layer was concentrated by an evaporator to give the product (1410.8 mg), including polysulfanes (Figure 2.10A, ca. 81% NMR yield), thiol **2b** and dialkylmonosulfanes (**3b**, **4b** and **5b**). The NMR yield of polysulfanes was calculated by ^1H NMR (Sample: 13.3 mg, 1,3,5-trioxane: 12.8 mg, Figure 2. 10A) and the ^{13}C NMR, DEPT and HMQC spectrum was also investigated (Figure 2. 11, 2. 12 and 2. 13). Tridecane (26.4 mg) was added as the internal standard then the resulting mixture was dissolved in 10 mL of Et_2O. The solution was analyzed by GC to calculate the yield of thiol **2b** (5%), and dialkylmonosulfanes (**3b**, **4b** and **5b**, 4%). Then, the resulting solution was dropped into a solution of $LiAlH_4$ (0.761 g, 20 mmol, 3.3 eq) at room temperature under an N_2 atmosphere. After 14 hours, the reaction was quenched with ice and extracted with Et_2O 3×5 mL and dried with Na_2SO_4. Then the resulting mixture was filtrated to remove the residue and the organic layer was concentrated by an evaporator to give the crude product. To calculate the NMR yield, 1,3,5-trioxane (22.4 mg) was added to the product (12.2 mg), which was used to calculate the yield of thiol **2b** (65%) and dialkylmonosulfanes (**3b**, **4b** and **5b**, 31%). The NMR yield of thiol and dialkylmonosulfanes was measured at a relaxation delay of 60 seconds, 1,3,5-trioxane as the internal standard and the yield of polysulfane was calculated at ca. 81%.



Scheme 2.17 16 hours reaction between tetradecane **1b**, sulfur and Co_3O_4

To a 40 mL autoclave with a magnetic stir bar, alkene **1b** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq), and Co_3O_4 (Co: 6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 150℃ while stirring at 800 rpm for 16 hours. After the reaction was complete, the autoclave was cooled with ice water then open the valve to place under air atmospheric pressure to distill off the residual gas. Tridecane was added as the internal standard, and then the mixture was washed with hexane and transformed into a 10 mL centrifuge tube. The black residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol **2b** (46%) and dialkylmonosulfanes (**3b**, **4b** and **5b**, 10%).

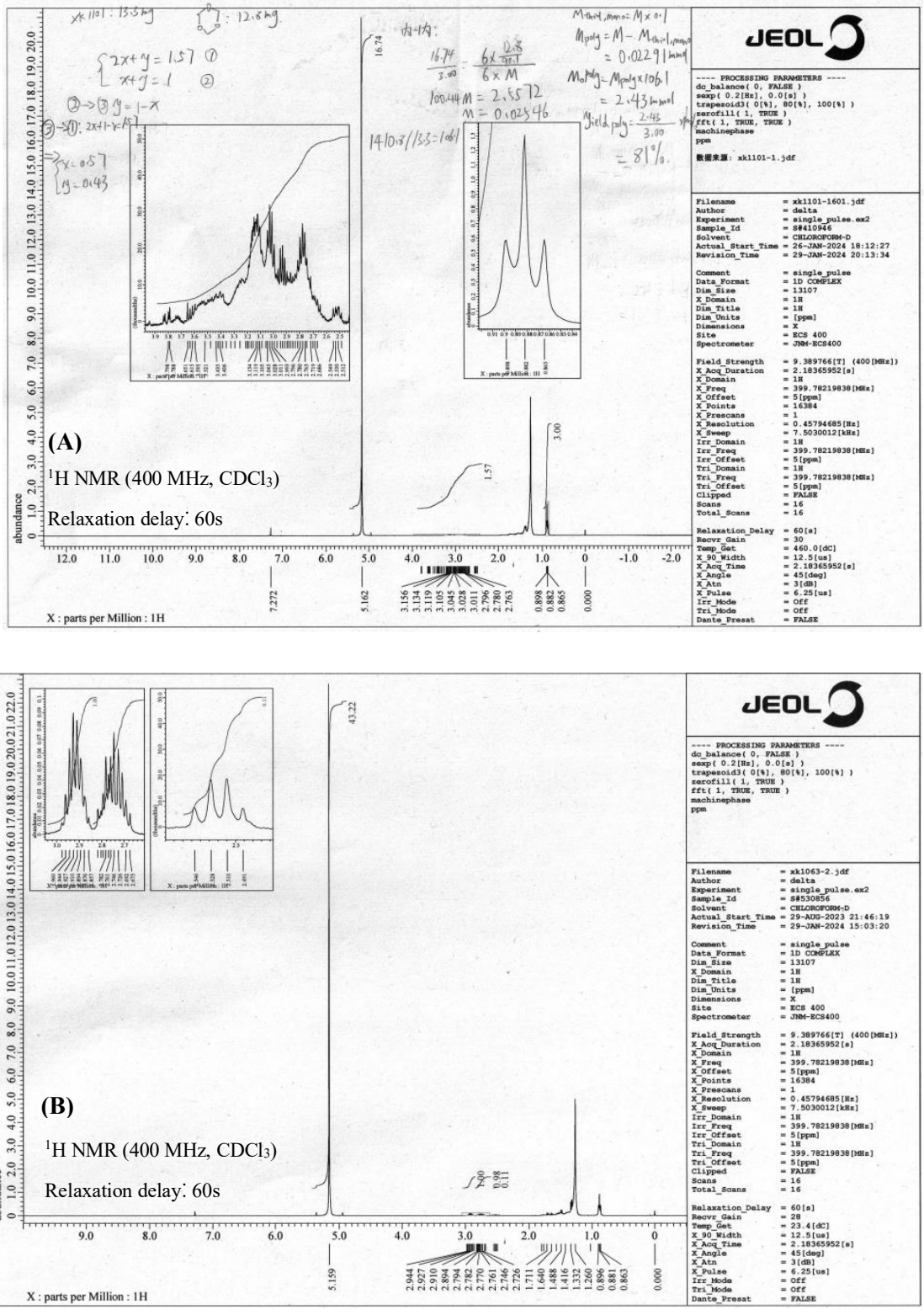


Figure 2.10 NMR analysis for the thiol synthesis before and after hydride reduction: (A) Before the reduction. (B) After the reduction.

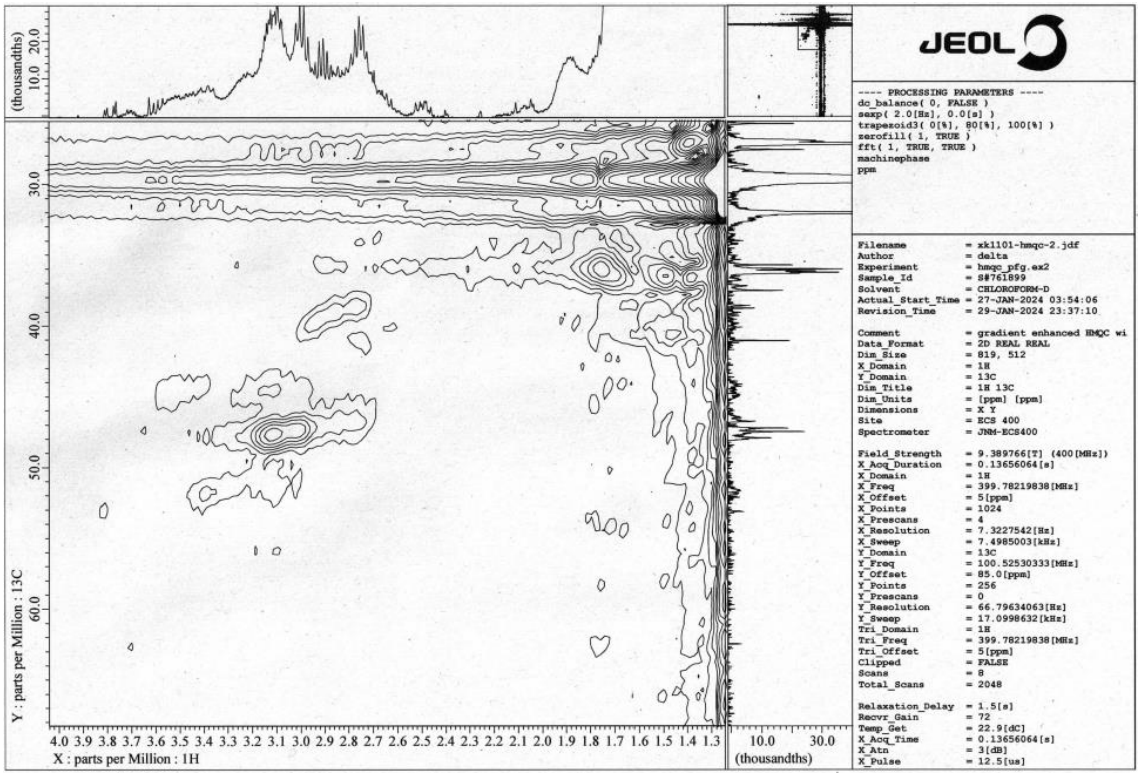


Figure 2.11 HMQC spectrum of the polysulfanes.

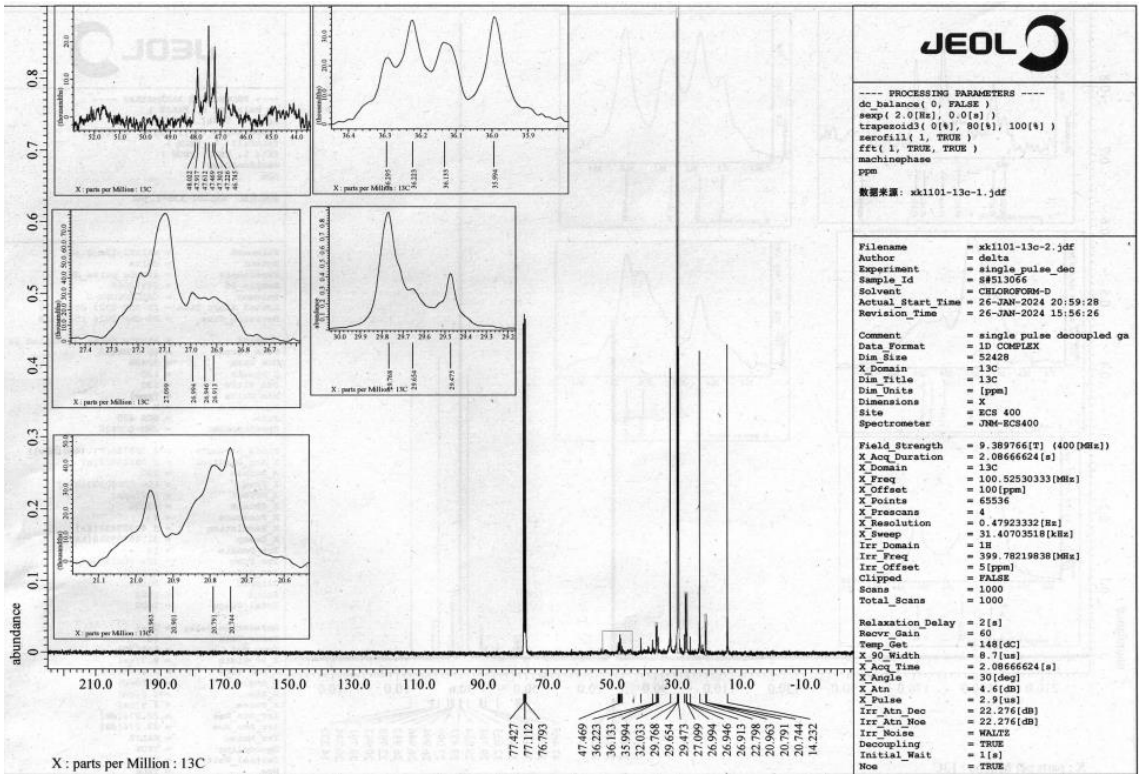
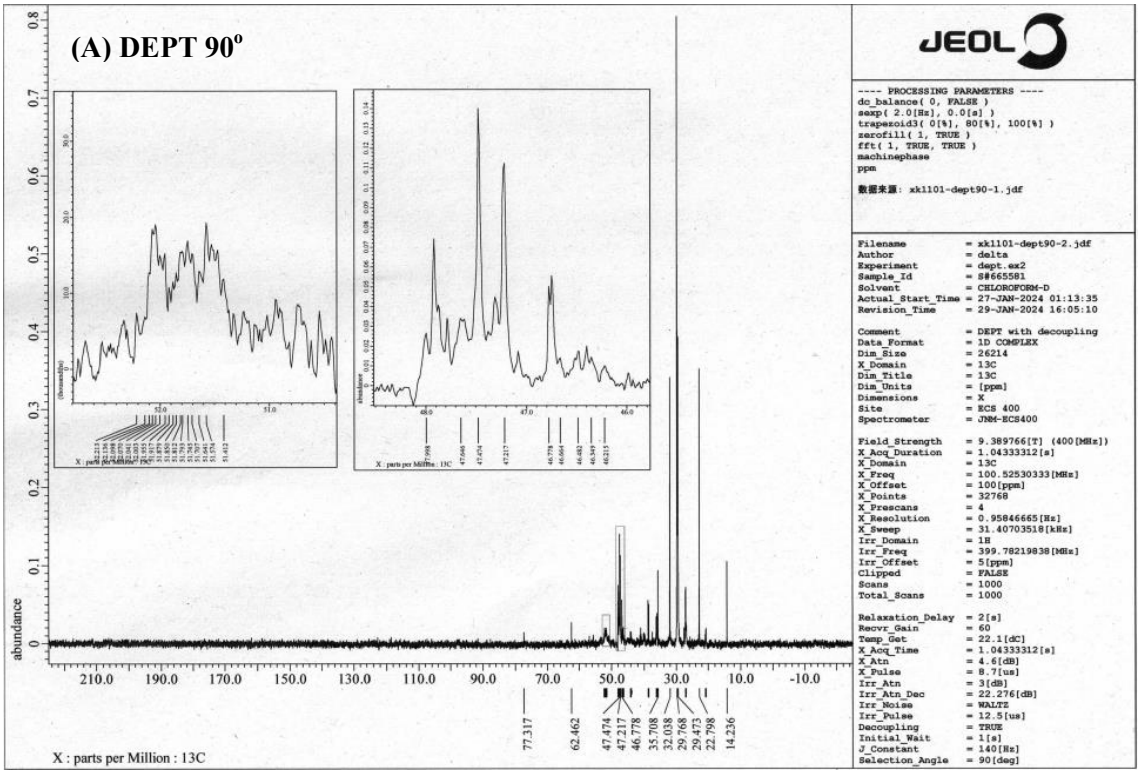


Figure 2.12 ^{13}C NMR spectrum of the polysulfanes.



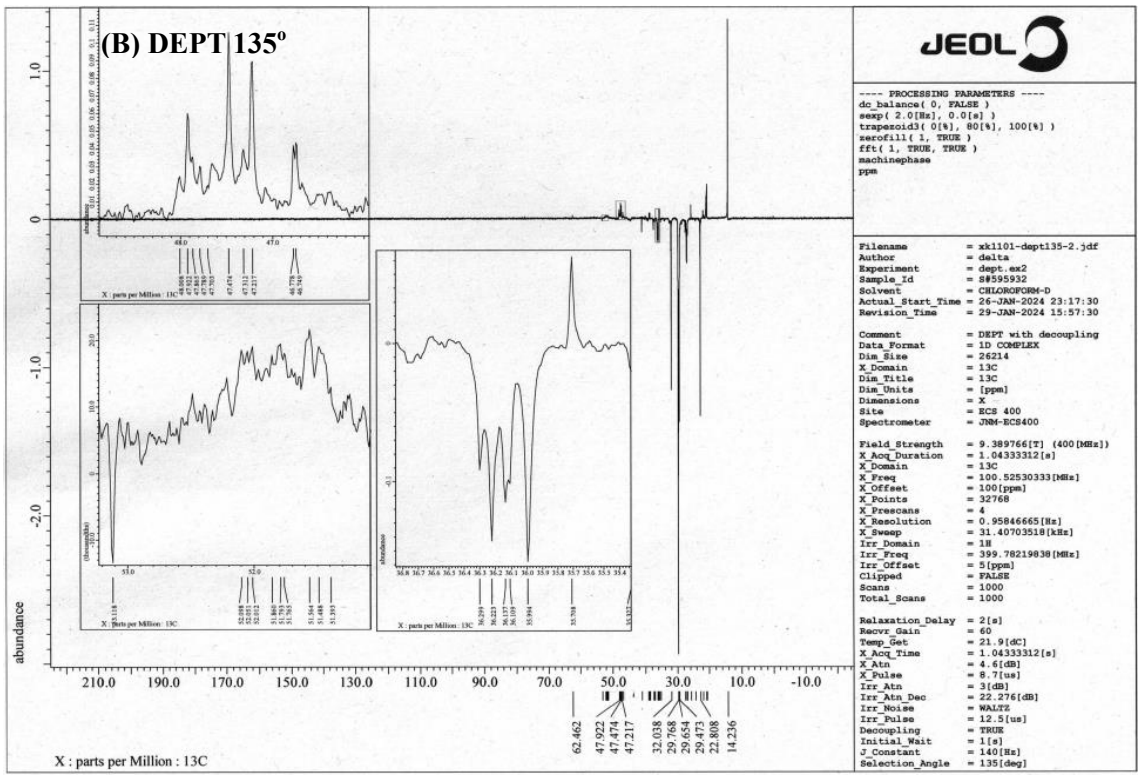
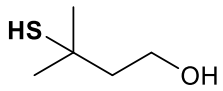


Figure 2.13 DEPT spectra of the polysulfanes: (**A**) DEPT 90° and (**B**) DEPT 135°.

2.4.17 ^{1}H, ^{13}C NMR data and elemental Analysis

3-Methyl-3-sulfanylbutan-1-ol (**2a**)



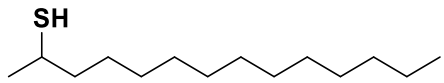
Title thiol (137 mg, 1.1 mmol, 18%) was synthesized from 3-methyl-3-buten-1-ol **1a** (516.0 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: diethyl ether, internal standard: tridecane, distilled conditions: 1.5 Torr, 100°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 3.87 (t, *J* = 6.8 Hz, 2H), 1.89 (t, *J* = 6.8 Hz, 2H), 1.81 (s, 1H), 1.64 (br, 1H), 1.43 (s, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 60.5 (CH_2), 48.4(CH_2), 43.5(C), 33.4(CH_3, 2C).

Elemental Analysis: Calcd for $C_5H_{12}OS$: H 10.06, C 49.96, O 13.31, S 26.67%. Found: H 10.11, C 49.75.

Tetradecane-2-thiol (**2b**)



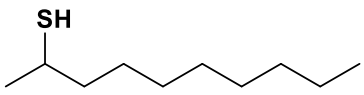
Title thiol (734 mg, 3.2 mmol, 53%) was synthesized from tetradecene **1b** (1189.4 mg, 6.05 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 200°C).

^{1}H NMR (600 MHz, $CDCl_3$): δ 2.93 (sep, 6.6 Hz, 1H), 1.48 (d, *J* = 6.6 Hz, 1H), 1.44–1.34(m, 2H), 1.32 (d, *J* = 7.2 Hz, 3H), 1.29–1.21 (m, 20H), 0.88 (t, *J* = 7.8 Hz, 3H).

^{13}C NMR (150 MHz, $CDCl_3$): δ 41.1 (CH_2), 35.8 (CH), 32.1 (CH_2), 29.81 (CH_2), 29.79 (CH_2, 2C), 29.75 (CH_2), 29.7 (CH_2), 29.5 (CH_2), 29.49 (CH_2), 27.60 (CH_2), 25.8 (CH_3), 22.84 (CH_2), 14.3 (CH_3).

Elemental Analysis: Calcd for $C_{14}H_{30}S$: H 13.12, C 72.97, S 13.91. Found: H 13.21, C 73.15.

Decane-2-thiol (**2c**)



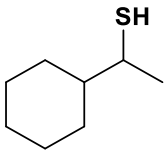
Title thiol (421 mg, 2.4 mmol, 40%) was synthesized from decene **1c** (843.3 mg, 6.01 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 120°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.93 (sep, *J* = 7.2 Hz, 1H), 1.48 (d, *J* = 6 Hz, 1H), 1.45–1.35(m, 2H), 1.32 (d, J = 7.2 Hz, 3H), 1.31–1.19 (m, 12H), 0.88 (t, *J* = 6.4 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 41.1 (CH_2), 35.8 (CH), 32.0 (CH_2), 29.7 (CH_2), 29.5 (CH_2), 29.4 (CH_2), 27.6 (CH_2), 25.8 (CH_3), 22.8 (CH_2), 14.3 (CH_3).

Elemental Analysis: Calcd for $C_{10}H_{22}S$: H 12.72, C 68.89, S 18.39. Found: H 12.76, C 69.11.

1-Cyclohexylethane-1-thiol (**2d**)



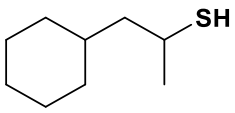
Title thiol (358 mg, 2.5 mmol, 42%) was synthesized from vinylcyclohexane **1d** (668.6 mg, 6.06 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 100°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.92-2.80 (m, 1H), 1.96–1.61 (m, 5H), 1.41–1.00 (m, 10H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 45.5 (*C*H), 41.4 (*C*H), 30.0 (CH_2), 29.6 (CH_2), 26.54 (CH_2), 26.5 (CH_2), 26.48 (CH_2), 26.45 (CH_2), 22.8 (CH_3).

Elemental Analysis: Calcd for $C_8H_{16}S$: H 11.18, C 68.89, S 18.39. Found: H 11.19, C 66.72.

1-Cyclohexylpropane-2-thiol (**2e**)



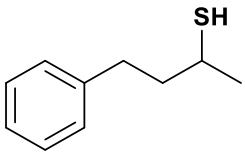
Title thiol (438 mg, 2.8 mmol, 47%) was synthesized from allylcyclohexane **1e** (756.5 mg, 6.08 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 120°C).

1H NMR (400 MHz, $CDCl_3$): δ 3.04 (sep, J = 6.4 Hz, 1H), 1.77–1.60 (m, 6H), 1.50-1.37 (m, 4H), 1.33–1.10 (m, 5H), 0.97–0.77 (m, 2H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 48.9 (CH_2), 35.6 (*C*H), 33.6 (CH_2), 32.91 (CH_2), 32.9 (*C*H), 26.7 (CH_2), 26.4 (CH_2), 26.3 (CH_2), 26.2 (CH_3).

Elemental Analysis: Calcd for $C_9H_{18}S$: H 11.46, C 68.29, S 20.25. Found: H 11.48, C 68.37.

4-Phenylbutane-2-thiol (**2f**)



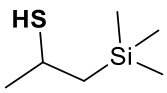
Title thiol (447 mg, 2.7 mmol, 45%) was synthesized from but-3-en-1-ylbenzene **1f** (798.7 mg, 6.04 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tetradecane, distilled conditions: 1.5 Torr, 120°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.11 (m, 5H), 2.96-2.86 (m, 1H), 2.82–2.65 (m, 2H), 1.95–1.76 (m, 2H), 1.51 (d, *J* = 4 Hz, 1H), 1.37 (d, *J* = 4.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 141.7 (*C*), 128.6 (*C*H, 4C), 126.1 (*C*H), 42.7 (CH_2), 35.1 (*C*H), 33.8 (CH_2), 25.9 (CH_3).

Elemental Analysis: Calcd for $C_{10}H_{14}S$: H 8.49, C 72.23, S 19.28. Found: H 8.56, C 72.12.

1-(Trimethylsilyl)propane-2-thiol (**2g**)



Title thiol (226 mg, 1.5 mmol, 25%) was synthesized from allyltrimethylsilane **1g** (685.5 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: diethyl ether, internal standard: tridecane, distilled conditions: 1.5

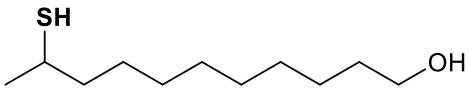
Torr, 36°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 3.20 (m, 1H), 1.68 (d, *J* = 5.6 Hz, 1H), 1.39 (d, *J* = 6.4 Hz, 1H), 0.99 (dd, *J* = 7.2 Hz, 1H), 0.05 (s, 9H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 33.1 (*C*H), 30.4 (*C*H_2), 29.5 (*C*H_3), -0.7 (*C*H_3, 3C).

Elemental Analysis: Calcd for $C_6H_{16}SSi$: H 10.87, C 48.58, S 21.61, Si 18.93. Found: H 10.77, C 48.68.

10-Mercaptoundecan-1-ol (**2h**)



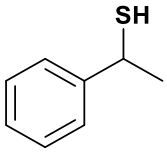
Title thiol (748 mg, 3.7 mmol, 62%) was synthesized from undec-10-en-1-ol **1h** (1025.3 mg, 6.02 mmol) according to General Procedure (Solvent for extraction: acetic ethyl ester, internal standard: tridecane, distilled conditions: 1.5 Torr, 200°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 3.64 (t, *J* = 6.8 Hz, 2H), 2.93 (sep, *J* = 6.8 Hz, 1H), 1.70–1.25 (m, 21H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 63.2 (*C*H_2), 41.1 (*C*H_2), 35.8 (*C*H), 32.9 (*C*H_2), 29.7 (*C*H_2), 29.6 (*C*H_2), 29.5 (*C*H_2), 29.4 (*C*H_2), 27.6 (*C*H_2), 25.9 (*C*H_2), 25.8 (*C*H_3).

Elemental Analysis: Calcd for $C_{11}H_{24}OS$: H 11.84, C 64.65, O 7.83, S 15.69. Found: H 11.88, C 64.69.

1-Phenylethane-1-thiol (**2i**)



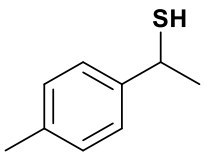
Title thiol (270 mg, 2.0 mmol, 33%) was synthesized from styrene **1i** (617.3 mg, 5.93 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 85°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41–7.17 (m, 5H), 4.24 (dq, *J* = 6.8 Hz, 5.2 Hz, 1H), 1.99 (d, *J* = 5.2 Hz, 1H), 1.67 (d, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 146.0 (*C*), 128.8 (*C*H, 2C), 127.3 (*C*H), 126.5 (*C*H, 2C), 38.9 (*C*H), 26.2 (*C*H_3).

Elemental Analysis: Calcd for $C_8H_{10}S$: H 7.29, C 69.51, S 23.19. Found: H 7.26, C 69.61.

1-(p-Tolyl)ethane-1-thiol (**2j**)



Title thiol (216 mg, 1.4 mmol, 24%) was synthesized from 1-methyl-4-vinylbenzene **1j** (708.2 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 110°C).

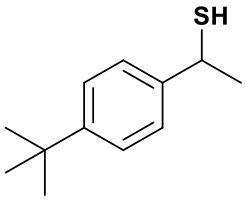
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26 (d, *J* = 8 Hz, 2H), 7.13 (d, *J* = 8.4 Hz, 2H), 4.21 (dq, *J* = 6.8

Hz, 6.8 Hz, 1H), 1.97 (d, *J* = 5.2 Hz, 1H), 1.66 (d, *J* = 7.6 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 142.0 (*C*), 135.9 (*C*), 128.4 (*C*H, 2C), 125.4 (*C*H, 2C), 37.6 (*C*H), 25.3 (*C*H_3), 20.2 (*C*H_3).

Elemental Analysis: Calcd for $C_9H_{12}S$: H 7.94, C 71.00, S 21.06. Found: H 7.95, C 71.16.

1-(4-(tert-Butyl)phenyl)ethane-1-thiol (**2k**)



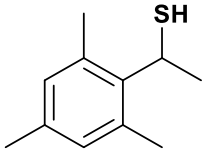
Title thiol (444 mg, 2.3 mmol, 38%) was synthesized from 1-(tert-butyl)-4-vinylbenzene **1k** (961.2 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 140°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32 (m, 4H), 4.22 (dq, *J* = 6.4 Hz, 6.4 Hz, 1H), 1.99 (d, *J* = 5.2 Hz, 1H), 1.67 (d, *J* = 6.8 Hz, 3H), 1.31 (s, 9H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 149.2 (*C*), 141.9 (*C*), 125.1 (*C*H, 2C), 124.6 (*C*H, 2C), 37.5 (*C*H, C), 33.6 (*C*), 30.5 (*C*H_3, 3C), 25.2 (*C*H_3).

Elemental Analysis: Calcd for $C_{12}H_{18}S$: H 9.34, C 74.17, S 16.50. Found: H 9.30, C 74.52.

1-Mesitylethane-1-thiol (**2l**)



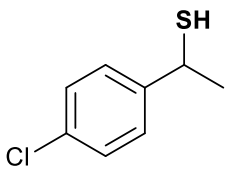
Title thiol (610 mg, 3.4 mmol, 56%) was synthesized from 1,3,5-trimethyl-2-vinylbenzene **1l** (875.5 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 140°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 6.81 (s, 2H), 4.78 (dq, *J* = 7.2 Hz, 5.6 Hz, 1H), 2.80-2.10 (br s, 9H), 1.97 (d, *J* = 5.6 Hz, 1H), 1.70 (d, *J* = 7.6 Hz, 1H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 137.9 (*C*H), 137.0 (*C*), 136.4 (*C*H), 134.9 (*C*), 131.7 (*C*), 129.2 (*C*), 33.4 (*C*H), 23.6 (*C*H_3, 2C), 21.2 (*C*H_3), 20.8 (*C*H_3).

Elemental Analysis: Calcd for $C_{11}H_{16}S$: H 8.94, C 73.27, S 17.78. Found: H 8.93, C 73.28.

1-(4-Chlorophenyl)ethane-1-thiol (**2m**)



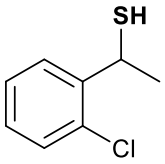
Title thiol (301 mg, 1.7 mmol, 28%) was synthesized from 1-chloro-4-vinylbenzene **1m** (831.4 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: decane, distilled conditions: 1.5 Torr, 80°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.26 (m, 4H), 4.20 (dq, *J* = 6.8 Hz, 5.2 Hz, 1H), 1.65 (d, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 144.5 (*C*), 132.9 (*C*), 128.9 (*C*H, 2C), 127.9 (*C*H, 2C), 38.2 (*C*H), 26.1 (CH_3).

Elemental Analysis: Calcd for C_8H_9ClS: H 5.25, C 55.65, Cl 20.53, S 18.57. Found: H 5.28, C 55.83.

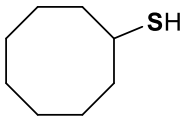
1-(2-Chlorophenyl)ethane-1-thiol (**2n**)



Title thiol (175 mg, 1.0 mmol, 17%) was synthesized from 1-chloro-2-vinylbenzene **1n** (833.2 mg, 6.01 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: decane, distilled conditions: 1.5 Torr, 80°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.58–7.51 (m, 1H), 7.37–7.27 (m, 2H), 7.20–7.12 (m, 1H), 6.69 (dq, *J* = 6.4 Hz, 6.4 Hz, 1H), 2.11 (d, *J* = 5.2 Hz, 1H), 1.67 (d, *J* = 6.8 Hz, 1H)
^{13}C NMR (100 MHz, $CDCl_3$): δ 142.2 (C), 131.6 (C), 128.8 (CH), 127.3 (CH), 126.5 (CH), 126.3 (CH), 33.6 (CH), 23.6 (CH3).
Elemental Analysis: Calcd for C_8H_9ClS: H 5.25, C 55.65, Cl 20.53, S 18.57. Found: H 5.29, C 55.72.

Cyclooctanethiol (**2o**)

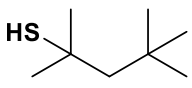


Title thiol (491 mg, 3.4 mmol, 56%) was synthesized from cyclooctene **1o** (657.3 mg, 5.96 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 110°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 3.16 (m, *J* = 5.2 Hz, 1H), 2.10–1.90 (m, H), 1.85–1.40 (m, 14H).
^{13}C NMR (100 MHz, $CDCl_3$): δ 40.1 (*C*H), 36.1 (CH_2, 2C), 27.4 (CH_2, 2C), 25.6 (CH_2), 25.0 (CH_2, 2C).

Elemental Analysis: Calcd for $C_8H_{16}S$: H 11.18, C 66.60, S 22.22. Found: H 11.24, C 66.63.

2,4,4-Trimethylpentane-2-thiol (**2p**)

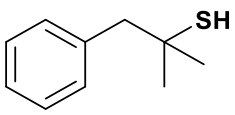


Title thiol (231 mg, 1.6 mmol, 26%) was synthesized from 2,4,4-trimethylpent-1-ene **1p** (672.4 mg, 5.99 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 80°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.85 (s, 1H), 1.70 (s, 2H), 1.57 (s, 3H), 1.04 (s, 9H).
^{13}C NMR (100 MHz, $CDCl_3$): δ 58.2 (CH_2), 46.0 (*C*), 35.8 (CH_3, 2C), 32.9 (*C*), 31.7 (CH_3, 3C).

Elemental Analysis: Calcd for $C_8H_{18}S$: H 12.40, C 65.68, S 21.92. Found: H 12.38, C 65.54.

2-Methyl-1-phenylpropane-2-thiol (**2q**)



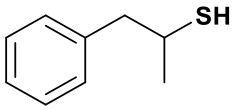
Title thiol (558 mg, 3.4 mmol, 57%) was synthesized from (2-methylallyl)benzene **1q** (788.3 mg, 5.96 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tetradecane, distilled conditions: 1.5 Torr, 120°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.21 (m, 5H), 2.90 (s, 1H), 1.71 (s, 1H), 1.39 (s, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 138.0 (*C*), 130.9 (*C*H, 2C), 128.0 (*C*H, 2C), 126.7 (*C*H), 52.6 (CH_2), 45.0 (*C*), 32.5 (CH_3, 2C).

Elemental Analysis: Calcd for $C_{10}H_{14}S$: H 8.49, C 72.23, S 19.28. Found: H 8.42, C 72.39.

1-Phenylpropane-2-thiol (**2r**)



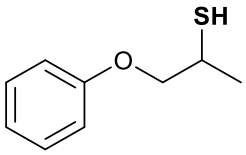
Title thiol (249 mg, 1.8 mmol, 27%) was synthesized from allylbenzene **1r** (704.6 mg, 5.96 mmol) according to General Procedure (Solvent for extraction: hexane, internal standard: tridecane, distilled conditions: 1.5 Torr, 110°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.14 (m, 5H), 3.23 (sep, J = 6.8 Hz, 1H), 2.85 (m, 2H), 1.56 (d, J = 5.2 Hz, 1H), 1.34 (d, J = 6 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 139.5 (*C*), 129.4 (*C*H, 2C), 128.5 (*C*H, 2C), 126.7 (*C*H), 47.5 (CH_2), 36.9 (*C*H), 24.5 (CH_3).

Elemental Analysis: Calcd for $C_9H_{12}S$: H 7.94, C 71.00, S 21.06. Found: H 7.99, C 71.05.

1-Phenoxypropane-2-thiol (**2s**)



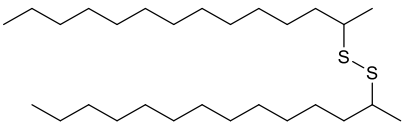
Title thiol (307 mg, 1.8 mmol, 30%) was synthesized from (allyloxy)benzene **1s** (803.6 mg, 5.98 mmol) according to General Procedure (Solvent for extraction: diethyl ether, internal standard: decane, distilled conditions: 1.5 Torr, 110°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32–7.27 (m, 2H), 6.96 (t, J = 6.4 Hz, 1H), 6.91 (d, J = 8 Hz, 2H), 3.95 (dq, J = 3.6, 6.4 Hz, 2H), 3.31 (sep, J = 7.2Hz, 1H), 1.86 (d, J = 6.4 Hz, 1H), 1.43 (d, J = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 158.6 (*C*), 129.7 (*C*H, 2C), 121.2 (*C*H), 114.8 (*C*H, 2C), 74.6 (CH_2), 34.2 (*C*H), 21.2 (CH_3).

Elemental Analysis: Calcd for $C_9H_{12}OS$: H 7.19, C 64.25, O 9.51, S 19.05. Found: H 7.21, C 64.34.

1,2-di(tetradecan-2-yl)disulfane



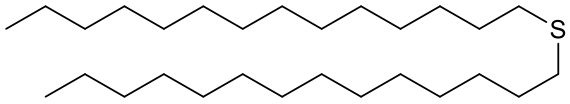
Title disulfane (188 mg, 0.41 mmol, 75%), which was synthesized from thiol **2b** (252.7 mg, 1.1 mmol) according to Procedure 2.4.13.

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.77 (sext, *J* = 6.0 Hz, 2H), 1.74-1.60 (m, 2H), 1.43–1.19 (m, 48H), 0.88 (t, *J* = 6.4 Hz, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 46.8 (*C*H, 2C), 36.4 (*C*H_2, 2C), 32.1 (*C*H_2, 2C), 29.8 (*C*H_2, 2C), 29.8 (*C*H_2, 2C), 29.8 (*C*H_2, 2C), 29.7 (*C*H_2, 2C), 29.6 (*C*H_2, 2C), 29.5 (*C*H_2, 2C), 27.3 (*C*H_2, 2C), 22.9 (*C*H_2, 2C), 20.9 (*C*H_2, 2C), 20.8 (*C*H_3, 2C), 14.3 (*C*H_3, 2C).

Elemental Analysis: Calcd for $C_{28}H_{58}S_2$: H 12.74, C 73.29, S 13.97. Found: H 12.80, C 73.53.

Ditetradecylsulfane (**3b**)



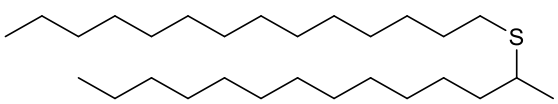
Title monosulfane (300 mg, 0.7 mmol, 70%) was synthesized from tetradecane-1-thiol (230.0 mg, 1.0 mmol, 1 eq) according to Procedure 2.4.13.

^{1}H NMR (600 MHz, $CDCl_3$): δ 2.50 (t, *J* = 7.2 Hz, 4H), 1.60–1.56 (m, 4H), 1.55–1.10 (m, 44H), 0.88 (t, *J* = 6.6 Hz, 6H).

^{13}C NMR (150 MHz, $CDCl_3$): δ 32.3 (*C*H_2, 2C), 32.1 (*C*H_2, 2C), 29.9 (*C*H_2, 2C), 29.84 (*C*H_2, 2C), 29.83 (*C*H_2, 2C), 29.81 (*C*H_2, 4C), 29.77 (*C*H_2, 2C), 29.7 (*C*H_2, 2C), 29.5 (*C*H_2, 2C), 29.4 (*C*H_2, 2C), 29.1 (*C*H_2, 2C), 22.9 (*C*H_2, 2C), 14.3 (*C*H_3, 2C).

Elemental Analysis: Calcd for $C_{28}H_{58}S$: H 13.70, C 78.79, S 7.51. Found: H 13.68, C 78.68.

Tetradecan-2-yl(tetradecyl)sulfane (**4b**)



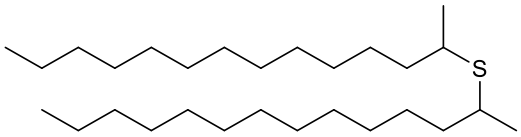
Title monosulfane (300 mg, 0.7 mmol, 70%) was synthesized from thiol **2b** (232.0 mg, 1.0 mmol) according to Procedure 2.4.13.

^{1}H NMR (600 MHz, $CDCl_3$): δ 2.73 (sext, *J* = 6.0 Hz, 1H), 2.51 (t, *J* = 7.2 Hz, 1H), 1.60–1.51 (m, 4H), 1.46–1.10 (m, 45H), 0.88 (t, *J* = 6.6 Hz, 6H).

^{13}C NMR (150 MHz, $CDCl_3$): δ 40.1 (*C*H), 37.2 (*C*H_2), 32.1 (*C*H_2, 2C), 30.5 (*C*H_2), 30.1 (*C*H_2), 29.83 (*C*H_2, 2C), 29.81 (*C*H_2, 3C), 29.78 (*C*H_2, 2C), 29.77 (*C*H_2, 2C), 29.73 (*C*H_2, 2C), 29.69 (*C*H_2), 29.5 (*C*H_2, 2C), 29.4 (*C*H_2), 29.2 (*C*H_2), 27.2 (*C*H_2), 22.9 (*C*H_2, 2C), 21.5 (*C*H_3), 14.3 (*C*H_3, 2C).

Elemental Analysis: Calcd for $C_{28}H_{58}S$: H 13.70, C 78.79, S 7.51. Found: H 13.58, C 78.54.

Di(tetradecan-2-yl)sulfane (**5b**)



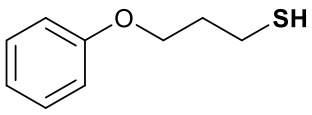
Title crude monosulfane **5b** (282 mg) was a mixture, including **3b**, **4b** and the other organosulfur compounds.

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.76 (sext, *J* = 6.4 Hz, 2H), 1.80–1.10 (m, 50H), 0.88 (t, *J* = 5.6 Hz, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 38.8 (*C*H, 2C), 38.6 (*C*H_2, 2C), 37.6 (*C*H_2, 2C), 32.1 (*C*H_2, 2C), 29.81 (*C*H_2, 4C), 29.80 (*C*H_2, 2C), 29.5 (*C*H_2, 2C), 27.2 (*C*H_2, 2C), 27.1 (*C*H_2, 2C), 22.9 (*C*H_2, 2C), 22.0 (*C*H_2, 2C), 21.9 (*C*H_3, 2C), 14.3 (*C*H_3, 2C).

HRMS-EI (*m*/*z*): $[M]^+$ Calcd for $C_{28}H_{58}S^+$: 426.4259; Found: 426.4258.

3-Phenoxypropane-1-thiol[55]



Title thiol (0.31 g, 1.8 mmol, 24%) was synthesized from 3-bromopropoxybenzene (2.14 g, 10 mmol) according to Procedure 2.4.14.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.25 (m, 2H), 7.00–6.85 (m, 3H), 4.08 (t, *J* = 6 Hz, 2H), 2.74 (q, *J* = 6.8 Hz, 2H), 2.08 (quin, *J* = 6 Hz, 2H), 1.40 (t, *J* = 8 Hz, 3H).

^{13}C NMR (150 MHz, $CDCl_3$): δ 158.9 (*C*), 129.6 (*C*H, 2C), 120.9 (*C*H), 114.6 (*C*H, 2C), 65.6 (*C*H_2), 33.5 (*C*H_2), 21.4 (*C*H_2).

2.5 Reference

[1] H. R. Duffey, R. D. Snow and D. B. Keyes, *Ind. Eng. Chem.*, **1934**, 26, 91–93.

[2] S. O. Jone and E. E. Reid, *J. Am. Chem. Soc.*, **1938**, 60, 2452–2455.

[3] V. N. Ipatieff and B. S. Friedman, *J. Am. Chem. Soc.*, **1939**, 60, 2731–2734.

[4] W. A. Schulze, J. P., Lyon and G. H. Short, *Ind. Eng. Chem.*, **1948**, 40, 2308–2313.

[5] W. E. Vaughan and F. F. Rust, *J. Org. Chem.*, **1942**, 07, 477–490.

[6] S. Kenichi, A. Wataru and O. Shigeru, *Bull. Chem. Soc. Jpn.*, **1965**, 38, 221–223.

[7] E. V. Shinkar, D. A. Kudryavtsev, K. P. Pashchenko, N. T. Berberova and A. V. Okhlobystina, *Mendeleev Commun.*, **2017**, 27, 180–182.

[8] T. B. Nguyen, *Adv. Synth. Catal.*, **2017**, 359, 1066–1130.

[9] M. W. Farlow, W. A. Lazier and F. K. Signaigo, *Ind. Eng. Chem.*, **1950**, 42,2547–2549.

[10] Y. Nishiyama, Y. Ohtori, S. Hamanaka, A. Ogawa, S. Murai and N. Sonoda, *J. Ceram.*, **1987**, 7, 1502–1504.

[11] E. Yamamoto, Y. Takaki, Y. kawai, K. Takakura, M. Kimura, H. Murayama, T. Nagao, T. Kamachi, H. Matsueda, S. Otsuki, H. Sakata and M. Tokunaga, *ACS Catal.*, **2023**, 13, 14121–14130.

[12] M. D. Curtis and S. H. Druker, *J. Am. Chem. Soc.*, **1997**, 119, 1027–1036.

[13] T. H. Lim, S. J. Cho, H. S. Yang, M.H. Engelhard and D. H. Kim, *Appl. Catal.*, A **2015**, 505, 62–69.

[14] Y. Liu, S. Wen and W. Shi, *Mater. Lett.*, **2018**, 214, 194–197.

[15] Y. Li, X. Han, T. Yi, Y. He and X. Li, *J. Energy Chem*., **2019**, 31, 54–78.

[16] F. Mueller, D. Bresser, N. Minderjahn, J. Kalhoff, S. Menne, S. Krueger, M. Winter and S. Passerini, *Dalton Trans.*, **2014**, 43, 15013–15021.

[17] X. Hu, L. Wei, R. Chen, Q. Wu and J. Li, *ChemistrySelect*, **2020**, 5, 5268–5288.

[18] R. S. Kate, S. A. Khalate and R. J. Deokate, *J. Alloys Compd.*, **2018**, 734, 89–111.

[19] J. Ma, H. Wei, Y. Liu, X. Ren, Y. Li, F. Wang, X. Han, E. Xu, X. Cao, G. Wang, F. Ren and S. Wei, *Int. J. Hydrog. Energy*, **2020**, 45, 21205–21220.

[20] O. Tamada, K. Fujino and S. Sasaki, *Acta. Crystallogr.* B **1983**, 39, 692–697.

[21] S. Bayat, D. Ghanbari and M. Salavati-Niasari, *J. Mol. Liq.*, **2016**, 220, 223–231.

[22] H. Ming and B. G. Baker, *Appl. Catal.,* A **1995**, 123, 23–36.

[23] Y. Mu, Y. Zhang, X. Pei, X. Dong, Z. Kou, M. Cui and C. Meng, *J. Colloid Interface Sci.*, **2022**, 611, 235–245.

[24] X. Kong, Y. Zhu, H. Zheng, X. Li, Y. Zhu and Y. Li, *ACS Catal.*, **2015**, 5, 5914–5920.

[25] S. Escher, Y. Niclass, M. Waal and C. Starkenmann, *Chem. Biodivers*, **2006**, 3, 943–957.

[26] R. D. Bruycker, O. Herbinet, H. Carstensen, F. Battin-Leclerc and K. M. V. Geem, *Combust Flame*, **2016**, 171, 237–251.

[27] S. Bayat, A. Sobhani and M. S. Niasari, *J. Mater. Sci. Mater. Electron*, **2018**, 29, 7077–7089.

[28] P. Q. H. Nguyen, D. Zhang, R. Rapp, J. P. Bradley and P. Dera, *RSC Adv*., **2021**, 11, 20687–20690.

[29] Y. Cheng, Y. Zhang and C. Meng, *ACS Appl. Energy Mater.*, **2019**, 2, 3830–3839.

[30] J. Yatabe, T. Sugizaki, T. Ikawa and T. Kageyama, *Journal of the Chemical Society of Japan: chemistry and industrial chemistry*, **1997**, 105, 188–191.

[31] H. Taguchi, Y. Takeda and H. Shibahara, *Matter. Lett.*, **2002**, 52, 412–416.

[32] J. Xue, F. Cui, Z. Huang, J. Zuo, J. Chen and C. Xia, *Chin. J. Catal.*, **2012**, 33, 1642–1649.

[33] A. Mekki, D. Holland, C. F. McConville and M. Salim, *J. Non-Cryst. Solids*, **1996**, 208, 267–276.

[34] E. Merlen, J. Lynch, M. Bisiaux and F. Raatz, *Surf. Interface Anal.*, **1990**, 16, 364–368.

[35] Y. Foucaud, M. Badawi, L. O. Filippov, O. Barres, I. V. Filippova and S. Lebègue, *Chem. Sci.*, **2019**, 10, 9928–9940.

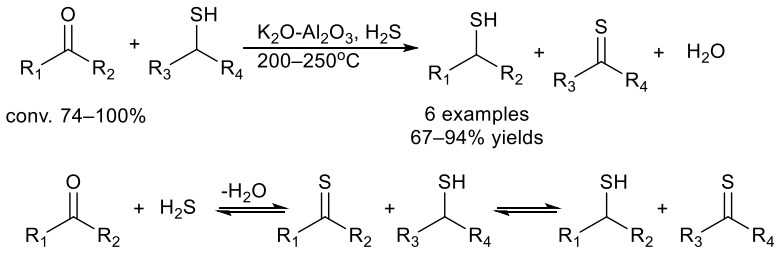
[36] T. L. Barr, *Appl. Surf. Sci.*, **1983**, 15, 1–35.
[37] X. R. Yu and H. Hantsche, *Surf. Interface Anal.*, **1993**, 20, 555–558.
[38] P. Blandin, K. A. Maximova, M. B. Gongalsky, J. F. Sanchez-Royo, V. S. Chirvony, M. Sentis, V. Y. Timoshenko and A. V. Kabashin, *J. Mater. Chem.* B **2013**, 1, 2489–2495.
[39] W. Tang, J. Weng, X. Lu, L. Wen, A. Suburamanian, C. Nam and P. Gao, *Appl. Catal.,* B **2019**, 256, 117859.
[40] S. Ju, Y. Liu, H. Chen, F. Tan, A. Yuan, X. Li and G. Zhu, *ACS Appl. Energy Mater.*, **2019**, 2, 4439–4449.
[41] R. G. Pearson, *J. Am. Chem. Soc.*, **1963**, 85, 3533–3539.
[42] Y. Takana, H. Hattori and K. Tanabe, *Bull. Chem. Soc. Jpn.*, **1978**, 51, 3641–3642.
[43] T. Matsuda, M. Sugimoto and H. Yoshihara, *Bull. Chem. Soc. Jpn.*, **1991**, 64, 552–558.
[44] L. Su, X. Chen, H. Wang, Y. Wang and Z. Lu, *J. Clean. Prod.*, **2022**, 336, 130376.
[45] R. Wischert, P. Laurent, C. Copéret, F. Delbecq and P. Sautet, *J. Am. Chem. Soc.*, **2012**, 134, 14430–14449.
[46] S. W. Benson, *Chem. Rev.*, **1978**, 78, 23–35.
[47] J. J. Griebel, R. Glass, S. K. Char, J. Pyun, *Prog. Polym. Sci.*, **2016**, 58, 90–125.
[48] R. Steudel, R. Strauss, L. Koch, *Angew. Chem. Int. Ed. Engl.*, **1985**, 24, 59–60.
[49] Y. Elsayed, M. Seredych, A. Dallas and T. J. Bandosz, *Chem. Eng. J.*, **2009**, 155, 594–602.
[50] H. Böhme and G. Zinner, *Ann.*, **1953**, 585, 142–149.
[51] N. Lau and M. D. Pluth, *Curr. Opin, Chem. Biol.*, **2019**, 49, 1–8.
[52] T. T. Trinh, A. P. J. Jansen and R. A. V. Santen, *J. Phys. Chem.* B **2006**, 110, 23099–23106.
[53] Y. Ma, S. Zhang, C. Chang, Z. Huang, J. C. Ho and Y. Qu, *Chem. Soc. Rev.*, **2018**, 47, 5541–5553.
[54] J. K. Vandavasi, W. P. Hu, C. Y. Chen and J. J. Wang, *Tetrahedron*, **2011**, 67, 8895–8901.
[55] C. K. Maurya, A. Mazumder and P. K. Gupta, *Beilstein J. Org. Chem.*, **2017**, 13, 1184–1188.

Chapter 3: Thiol Synthesis from Carbonyl Compounds Using Elemental Sulfur and Hydrogen with Heterogeneous Cobalt Catalysts

Chapter 3 Thiol Synthesis from Carbonyl Compounds Using Elemental Sulfur and Hydrogen with Heterogeneous Cobalt Catalysts

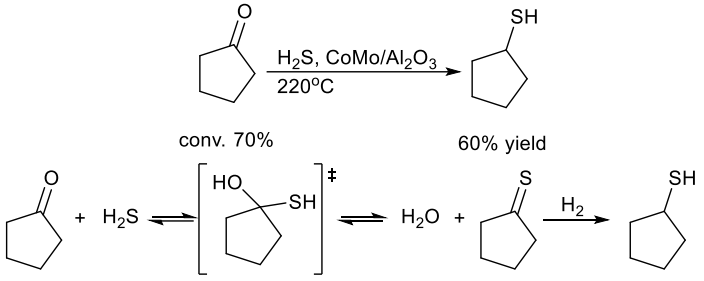
3.1 Introduction

The catalytic synthesis of thiol from carbonyl compounds and H_2S has been reported. Luclen *et al.* presented that potassium-alumina (K_2O-Al_2O_3) catalyzed thiol synthesis from carbonyl compounds and H_2S (Scheme 3.1).[1] The reaction gives thiol in acceptable yields of 67–94%. However, this method was carried out in high reaction temperature conditions.



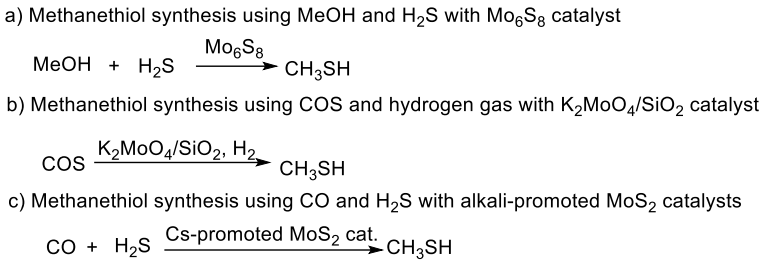
Scheme 3.1 K_2O-Al_2O_3-catalyzed thiol synthesis using H_2S from carbonyl compounds.

Wang *et al.* reported that cobalt-molybdenum/alumina ($CoMo/Al_2O_3$) catalyzed cyclopentanthiol synthesis from H_2S and carbonyl compounds (Scheme 3.2).[2] Cyclopentanone undergoes acetal reaction and hydrogenolysis to afford the thiol in 60% yield.



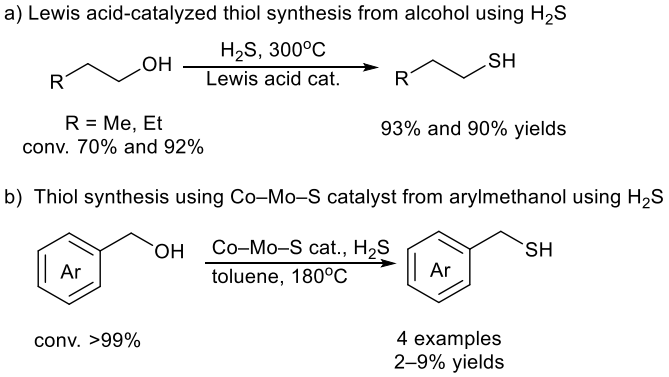
Scheme 3.2 $CoMo/Al_2O_3$-catalyzed cyclopentanone reductive thiolation using H_2S as a sulfur source.

Not only for ketone and aldehyde, methanol (MeOH), carbonyl sulfide (COS) and carbon monoxide (CO) can react with H_2S using heterogeneous catalysts to produce methanethiol (MeSH), which is an essential starting material in the industrial synthesis of cysteine (Scheme 3.3a–c).[3-5] Paskach and co-workers reported the Mo_6S_8-catalyzed MeSH synthesis from H_2S and MeOH.[3] This reaction gave MeSH a high selectivity of 80% (Scheme 3.3a).



Scheme 3.3 Methanethiol synthesis using heterogeneous catalysts.

Gutiérrez and co-workers reported a MeSH synthesis using COS as the starting material (Scheme 3.3b).[4] The H_2 was used to reduce COS on the molybdenum sulfide catalyst area to generate MeSH; however, this reaction showed a low yield of MeSH in only 31% and gave various gas by-products such as methane (CH_4), H_2S, CO and carbon dioxide (CO_2). Recently, Yu *et al.* reported methanethiol synthesis from CO and H_2S using alkali-promoted molybdenum sulfides as the catalyst (Scheme 3.3c).[5] Compared with other Mo-based catalysts, the cesium-promoted MoS_2 catalysts improved the selectivity of MeSH and no CH_4 was observed in this reaction. However, these reactions require high reaction temperatures (250–400°C) and only methanethiol can be synthesized.



Scheme 3.4 Thiol synthesis via H_2S reacted with alcohols.

The catalytic thiol synthesis from H_2S and alcohols is also reported as shown in Scheme 3.4. The Lewis acid catalyzed propanethiol or butanethiol synthesis using H_2S showed high alcohol conversion (70–92%) and the highest thiol yields in propanethiol (93%) and butanethiol (90%) (Scheme 3.4a).[6] Sorribes *et al.* reported the Co–Mo–S catalyst can transform the arylmethanols to dialkylmonosulfanes and thiols via hydrogen borrowing. However, this reaction gave thiols as the by-product, resulting in low yields (Scheme 3.4b, 2–9%).[7]

Indeed, cobalt polysulfide-catalyzed thiol synthesis from elemental sulfur, hydrogen and

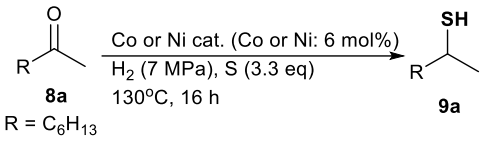
carbonyl compounds showed good conversion of carbonyl compounds and selectivity of thiols (Chapter 2, Scheme 2.5). This method appears to be a good idea in the industrial thiol synthetic process. However, the use of solvents and expensive organic bases increases the process cost of thiol synthesis.

Since the CoO_x-SiO_y catalyst showed great reductive activity in thiol synthesis from hydrogen gas, elemental sulfur and alkenes, the author also tries to use the CoO_x-SiO_y to innovate the reaction conditions of thiol synthesis from carbonyl compounds, elemental sulfur, and H_2 under solvents and organic bases-free conditions.

3.2 Results and discussion

3.2.1 Optimization of reaction conditions for synthesis of 2-octanethiol (**9a**)

Table 3.1 Catalysts screening for thiol synthesis from **8** using H_2 and elemental sulfur.



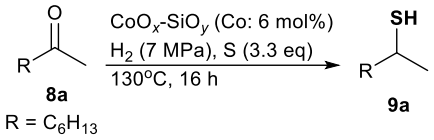
entry[a]	cobalt or nickel cat.	conv. (%)[b]	**9a** (%)[b]
1	CoO_x-SiO_y	80	65
2	$CoCO_3$	47	36
3	Co_3O_4	27	1
4	CoS	20	trace
5	CoS_2	–	–
6	NiO	41	2

[a]Reaction carried out under H_2 (7 MPa), octane-2-one **8** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), cobalt or nickel cat. (Co or Ni: 6 mol%), 130°C conditions. [b]Conv. and yield of ketone **8a** and thiol **9a** analyzed by GC using tridecane as internal standard. [c]GC yield less than 0.5%.

The initial reaction conditions using CoO_x-SiO_y (6 mol%) as the catalyst and ketone **8a** (6 mmol), elemental sulfur (20 mmol, 3.3 eq) was added into a 40 mL of autoclave, then the autoclave was placed under high-pressure hydrogen atmosphere (7 MPa). After 16 hours of reaction under 130℃, the ketone showed a low conversion in 80% and octane-2-thiol **9a** was observed in an acceptable yield of 65% (Table 3.1, entry 1). $CoCO_3$ as the catalyst used in this

reaction was also performed. However, the conversion of **8a** was decreased to 47% and the yield of **9a** was given in a yield of 36% (Table 3.1, entry 2). The catalytic activity of Co_3O_4, CoS, CoS_2 and NiO were also investigated (Table 3.1, entries 3–6). Nevertheless, all of the metal oxide or sulfide catalysts led to a decrease in the yield of thiol.

Table 3.2 Reaction condition screening for thiol synthesis from **8**



entry[a]	modifications	conv. (%)[b]	**9a** (%)[b]
1	none	80	65
2	sulfur 4.2 eq	79	66
3	sulfur 5.8 eq	93	78
4	sulfur 7.5 eq	91	66
5[c]	120°C	83	19
6[c]	150°C	100	88
7[c]	H_2 5 MPa	80	58
8[c]	H_2 3 MPa	78	3

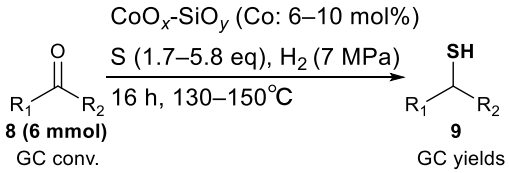
[a]Standard reaction carried out under H_2 (7 MPa), octane-2-one **8a** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), CoO_x-SiO_y (Co: 6 mol%), 130°C conditions. [b]Conv. and yield of ketone **8a** and thiol **9a** analyzed by GC using tridecane as internal standard. [c]Sulfur 5.8 eq was used.

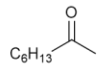
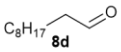
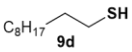
With the catalyst analysis in hand, the optimization of the reaction conditions was investigated. Firstly, since the conversion of **8a** was not 100%, the optimization of the equivalent of elemental sulfur was performed (Table 3.2, entries 2–4). When sulfur 5.8 eq was used, the reaction showed the highest conversion and yield (Table 3.2, entry 3, 93% and 78%). Next, the effect of the reaction temperature was investigated. When the reaction temperature was lowered to 120°C, the yield of thiol **9a** was decreased to 19% (Table 3.2, entry 5). Increasing the reaction temperature to 150°C showed that the yield of thiol was increased to 88% (Table 3.2, entry 6). Finally, when the hydrogen pressure was decreased to 5 MPa, the thiol still gave an acceptable

yield of 58% (Table 3.2, entry 7) and when the hydrogen pressure was decreased to 3 MPa, the reaction only gave thiol **9a** in the yield of 3% (Table 3.2, entry 8).

3.2.2 Substrate analysis for carbonyl compounds

Table 3.3 Carbonyl compound substrates are screening for this reaction.

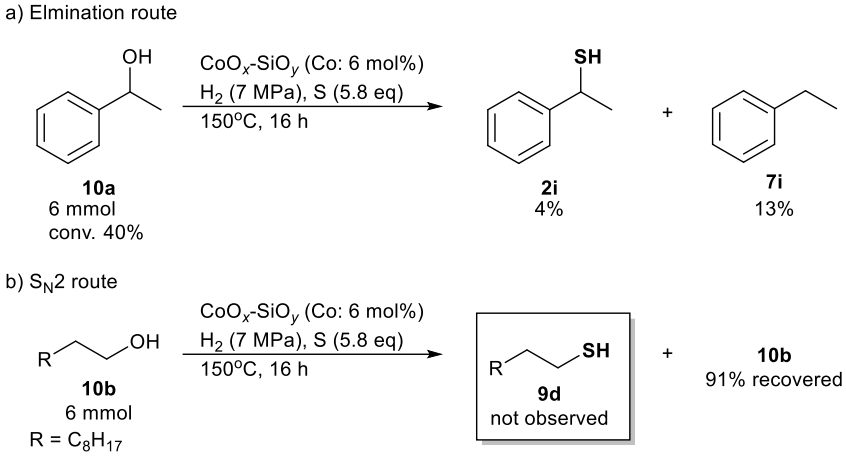


						conv. (%)	yield (%)
entry	substrates	products	CoO_x-SiO_y (mol%)	sulfur (mmol)	reaction temp.(°C)	**8**	**9**
1	 **8a**	 **9a**	6 mol%	35	150	94	74
2	 **8b**	 **9b**	6 mol%	35	150	100	64
3	 **8c**	 **2i**	6 mol%	20	150	92	11
4	 **8d**	 **9d**	10 mol%	35	150	100	59
5	 **8e**	 **9e**	6 mol%	10	130	100	33

Standard reaction conditions: H_2 7 MPa, CoO_x-SiO_y (Co: 6–10 mol%), carbonyl compounds **8** (6 mmol, 1 eq), sulfur (20–35 mmol, 3.3–5.8 eq), 130–150°C, 16 h. Conv. and yield of carbonyl compounds **8** and thiols **9** analyzed by GC using tridecane as an internal standard.

With the optimization of reaction conditions having been achieved, the author next investigated the possibility of substrates in this reaction. However, only three examples of thiols were successfully synthesized using this reaction system (Table 3.3). Cyclohexanone **8b** and decanal **8d** produced the corresponding thiols **9b** and **9d** in similar yields (Table 3.3, entries 2 and 4). Acetophenone **8c** and benzaldehyde **8e** afford the corresponding thiol **2i** and **9d**, resulting in low yields of 11% and 33% (Table 3.3, entries 3 and 5) and several by-products.

3.2.3 The reaction mechanism study



Scheme 3.5 Control experiment for the investigation of reaction pathways.

To investigate the reaction mechanism, a series of control experiments were investigated. Since carbonyl compounds may be reduced to alcohols,[8] which undergo S_N2 and/or elimination reactions[9,10] to form thiols. The author first checked the reactivity of 2-phenylethanol **10a** in this reaction system as shown in Scheme 3.5a. After 16 hours of reaction, 2-phenylethanol **10a** showed 40% conversion; however, thiol **2i** only resulted in 4% yield. Ethylbenzene was observed as the main product (13%) and acetophenone **8c** was not observed in this reaction. The reaction of decan-1-ol **10b** under the same reaction conditions was also performed (Scheme 3.5b). However, no thiol **9d** was observed and the **10b** was recovered in 91%. Indeed, alcohol can undergo C–S bond formation via the hydrogen borrowing route.[7] However, considering that the reaction occurs under strong reducing conditions, alcohols should be difficult to convert back to carbonyl compounds. Based on these observations, the mechanism of this reaction rules out the hydrogen borrowing, S_N2 and elimination routes.

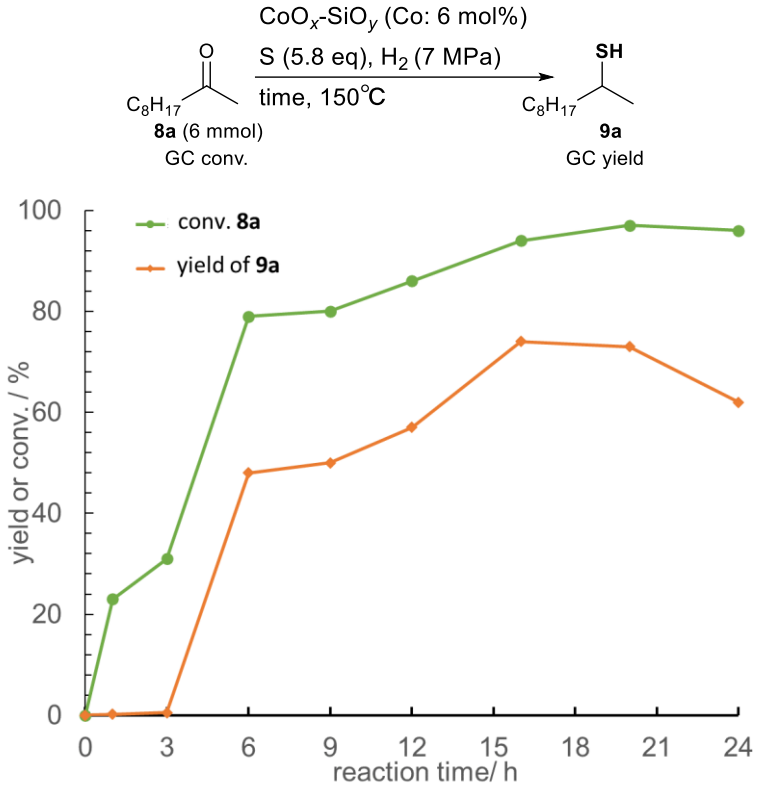
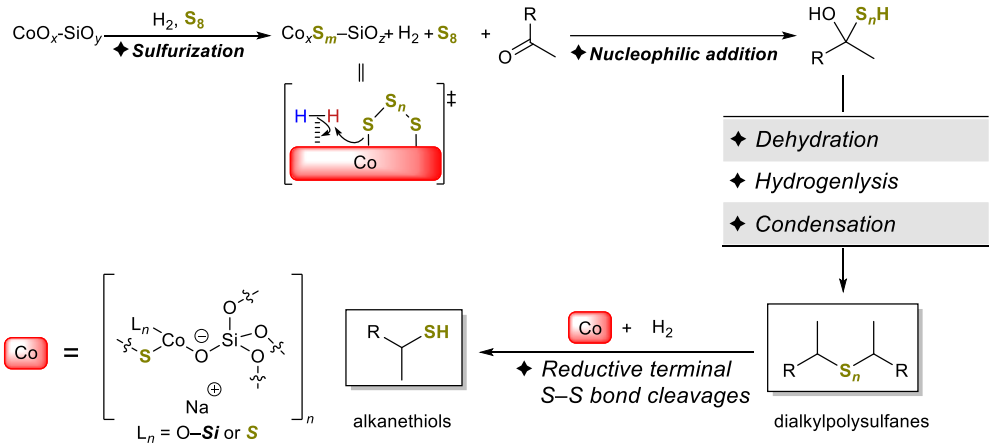


Figure 3.1 The time course of conversion of **8a** and yield of **9a**.

The time course in this reaction was investigated as shown in Figure 3.1. After 3 hours of reaction, the conversion of ketone **8a** was increased to 31%; however, the thiol **9a** was not observed. This result showed that the reaction intermediates could be formed in the initial period. The reaction between 6–12 hours showed that the reaction intermediates started to reduce and increased the yields of thiol **9a** in 48–57%. After 16 hours of the reaction, the highest yield of **9a** was observed at 74% and the conversion of **8a** was increased to 94%. After 24 hours of reaction, the yield of thiol **9a** was decreased to 62%. This result could be attributed to thiol **9a** underwent deprotonation on the catalyst surface and strongly adsorbed on the cobalt center.

Considering the above experiments and the relevant research, the author supposed a possible reaction mechanism as shown in Scheme 3.6. Firstly, CoO_x-SiO_y was subjected to sulfurization to form the Co_xS_m-SiO_z in the initial step. Then, the cleavage of the S–S bond in S_8 occurs followed by heterolytic H_2 activation with the Co_xS_m-SiO_z catalyst to generate the terminal SSH group. In addition, the SSH group in the surface of Co_xS_m-SiO_z undergoes the nucleophilic addition to ketone since the C=O bond is a better proton acceptor than the C=C bond[11] and gives the thioacetal as the reaction intermediates. Further dehydration, condensation, nucleophilic S–S bond exchange with RS_nH and reductive terminal S–S bond cleavage occur, yielding the thiol as the main product.

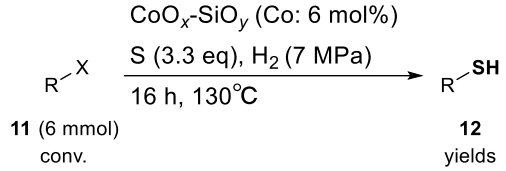


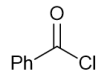
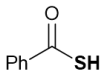
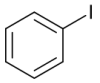
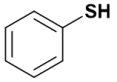
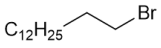
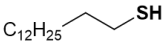
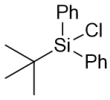
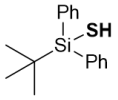
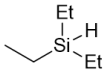
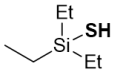
Scheme 3.6 Supposed the reaction mechanism.

3.2.4 Thiol synthesis from the other substrates

The author is also interested in the catalytic synthesis of organosulfur compounds from benzoic acid chloride, halides and silanes (Table 3.4). Benzoic acid chloride **11a** as the reaction substrate used in the reaction showed that thiobenzoic acid **12a** as the main product was observed (Table 3.4, entry 1, 23%) and benzyl thiol **9e** as the main by-product was generated in the yield of 18%. The reactivity of aryl halides was also investigated. Iodobenzene **11b** as the substrate in this reaction system resulted in a low conversion of 20% and gave thiophenol **12b** only a 12% yield (Table 3.4, entry 2) and 1-tetradecanbromide **11c** resulted in a similarly low yield and conversion in this reaction system (Table 3.4, entry 3). Finally, tert-butylchlorodiphenylsilane (TBDPSCl) **12d** and triethylsilane (Et_3SiH) **12e** as the substrates were used in this reaction system; however, TBDPSCl **12d** resulted in poor reactivity and no reaction occurred in this reaction system (Table 3.4, entry 4). When Et_3SiH **12e** was used as the substrate, the reaction showed a high conversion of 100%; however, no silanethiol was observed (Table 3.4, entry 5). Compared with the triethylsilanethiol[12] and 1,1,1,3,3,3-hexaethyldisilathiane,[13] this compound **13** showed different chemical shifts in ^1H and ^{13}C NMR and different *m/z* in GC-MS and HR-MS and the elemental analysis (H 12.12 and C 58.80). Based on these analyses, the author supposed that compound **13** may be bis(triethylsilyl)polysulfanes.

Table 3.4 Thiol synthesis from benzoic acid chloride, halides and silanes.



entry	substrates	products	conv. (%) **11**	yield (%) **12**
1	 **11a**	 **12a**	95	23
2	 **11b**	 **12b**	22	12
3	 **11c**	 **2b'**	25	21
4	 **11d**	 **12d**	0	0
5	 **11e**	 **12e**	100	0

Standard reaction conditions: H_2 7 MPa, CoO_x-SiO_y (Co: 6 mol%), halide compounds or organosilicon **11** (6 mmol, 1 eq), sulfur (20 mmol, 3.3 eq), 130°C, 16 h. Conv. and yield of carbonyl compounds **11** and organosulfur compounds **12** analyzed by GC or qNMR using tridecane or 1,3,5-trioxane as an internal standard.

3.3 Conclusion

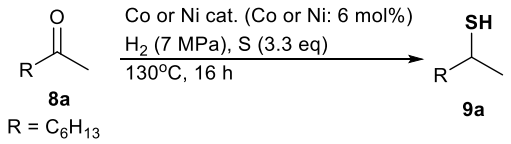
In summary, the improvement of the heterogeneous cobalt-catalyzed synthesis of thiols from carbonyl compounds using H_2 and elemental sulfur was achieved. The carbonyl compound substrates, including 2-octanone, cyclohexanone and decanal transformed to thiols in the yields of 53–88%. Acetophenone, benzaldehyde, 1-bromotetradecane, iodobenzene, benzoic acid chloride and 1-phenylethanol showed low reactivity and/or thiol selectivity in this reaction. Triethylsilane showed high conversion in the reaction conditions; however, the reaction gave an unknown compound as the main product, which is supposed to be bis(triethylsilyl)polysulfanes.

3.4 Experimental

3.4.1 General information for chemical materials and instruments

All starting materials including carbonyl compounds, iodobenzene, bromobenzene and 1-phenylethanol and the use of standards such as tridecane, phenylmathanethiol, thiophenol, benzene, ethylbenzene, cyclohexanethiol, decanethiol and styrene were available from TCI, FUJIFILM Wako Pure Chemical Corporation (Wako) and Sigma-Aldrich. The use of cobalt catalysts such as Co_3O_4, $CoCO_3$, CoS, CoS_2 and NiO was purchased from Sigma-Aldrich, Wako, Alfa Aesar and STREM CHEMICALS, INC. The use of reagent was purchased from Wako. The use of solvents such as $CHCl_3$, diethyl ether and hexane were all available from Wako. The use of 1-phenylethanethiol standard was obtained from alkene thiol synthesis and the preparation of CoO_x-SiO_y, which was introduced in Chapter 2. The purification of thiols was carried out with a glass tube oven GTO-2000. Conversion of alkenes and yield of thiols were measured with an Agilent Technologies gas chromatography 6850 GC system equipped with an HP-1 column (0.25 μm film, 0.32 mm diam., 30 m length). The heating program was maintained at 40°C for 5 minutes and then raised to 200°C for 20 minutes at 10 °C/min. It was then held for 15 min (total run time 40 min, average time 3 min). The use of a 40 mL autoclave was purchased from Toyo Kouatsu and the use of personal organic synthesizer PPV-5460 was purchased from EYELA. ^1H and ^{13}C NMR were measured with JEOL JNM-ECS-400 MHz or JNS-ECA-600 MHz at 20°C and the chemical shift of chloroform-d was reported and referenced in ^1H 7.26 ppm, ^{13}C 77.16 ppm and the internal standard of tetramethyl silane was referenced to 0.00 ppm. The NMR data were analyzed by Delta 6.1.0 software.

3.4.2 General procedure for optimization of the reaction conditions

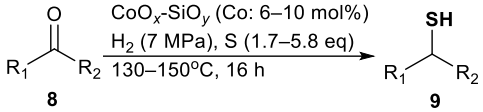


Scheme 3.7 Catalyst screening for octan-2one thiol synthesis.

To a 40 mL autoclave with a magnetic stir bar, 2-octanone **8a** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq) and Co or Ni cat. (Co or Ni: 6 mol%) was added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with

ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane was added as the internal standard, and then the mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol **9a**.

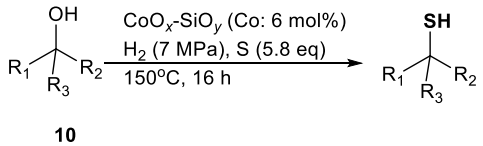
3.4.3 General procedure for carbonyl compound substrates analysis



Scheme 3.8 Carbonyl compounds screening in this thiol synthesis

To a 40 mL autoclave with a magnetic stir bar, carbonyl compound substrates (6 mmol, 1.0 eq), sulfur (10–34.8 mmol, 1.7–5.8 eq) and CoO_x-SiO_y (Co: 6–10 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130–150°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane or decane was added as the internal standard, and then the mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol.

3.4.4 Thiol synthesis from 1-phenylethanol

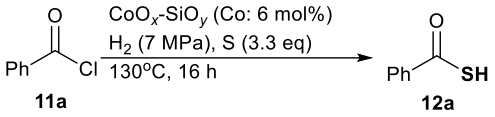


Scheme 3.9 Thiol synthesis using aliphatic alcohol.

To a 40 mL autoclave with a magnetic stir bar, alcohol **10** (6 mmol, 1.0 eq), sulfur (34.8 mmol, 5.8 eq) and CoO_x-SiO_y (Co: 6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 150°C while

stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane was added as the internal standard, and then the mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiol and alkane by-products.

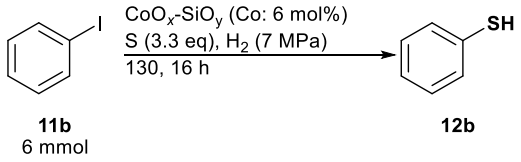
3.4.5 Synthesis of thiobenzoic acid from benzoic acid chloride, elemental sulfur, CoO_x-SiO_y and hydrogen gas



Scheme 3.10 Synthesis of thiobenzoic acid **12a** from **11a** and elemental sulfur.

To a 40 mL autoclave with a magnetic stir bar, benzoic acid chloride **11a** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq) and CoO_x-SiO_y (Co: 6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane or decane was added as the internal standard, and then the mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiobenzoic acid **12a**.

3.4.6 Thiophenol synthesis using iodobenzene, elemental sulfur, CoO_x-SiO_y and hydrogen gas

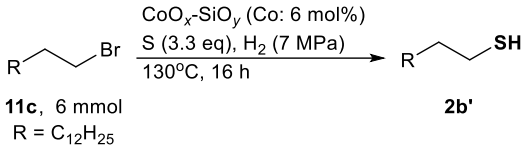


Scheme 3.11 Synthesis of thiophenol **12b** from **11b** and elemental sulfur.

To a 40 mL autoclave with a magnetic stir bar, iodobenzene **11b** (6 mmol, 1.0 eq), sulfur (20

mmol, 3.3 eq) and CoO_x-SiO_y (Co: 6 mol%), NEt_3 (0–1.5 eq) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. Tridecane was added as the internal standard, and then the mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was analyzed by GC to calculate the yield of thiophenol **12b**.

3.4.7 Thiol synthesis from 1-bromotetradecane



Scheme 3.12 Thiol synthesis from 1-bromotetradecane **11c** and elemental sulfur.

To a 40 mL autoclave with a magnetic stir bar, 1-bromotetradecane **11c** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq) and CoO_x-SiO_y (Co: 6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve to place under air atmospheric pressure to distill off the residual hydrogen sulfide. The mixture was washed with diethyl ether and transformed into a 10 mL centrifuge tube. The residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was distilled off under reduced pressure to obtain a clear oil. The oil 30.0 mg and 1,3,5-trioxane 30.0 mg was added to an NMR tube. The yield of tetradecane-1-thiol **2b'** was calculated by qNMR and given in 21% (Figure 3.2).

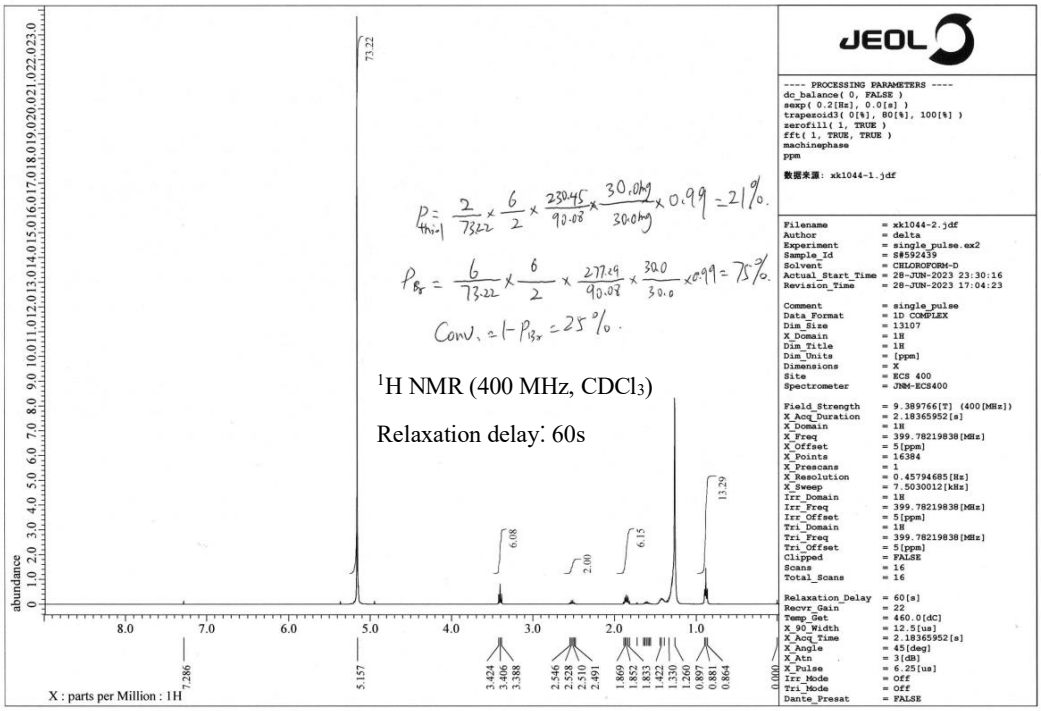
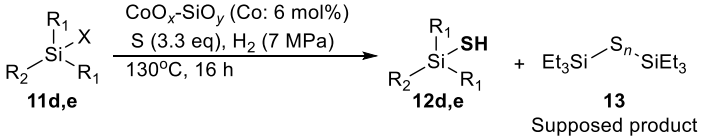


Figure 3.2 Yield of thiol **2b'** analysis by qNMR using 1,3,5-trioxane as the internal standard.

3.4.8 The reaction using organosilicon substrates.



Scheme 3.13 Synthesis of bis(triethylsilyl)polysulfane using CoO_x-SiO_y.

To a 40 mL autoclave with a magnetic stir bar, organosilicon compounds **11d** or **11e** (6 mmol, 1.0 eq), sulfur (20 mmol, 3.3 eq) and CoO_x-SiO_y (Co: 6 mol%) were added. Then the autoclave was pressurized to 7 MPa of hydrogen gas after being replaced with 2 MPa of hydrogen three times. The corresponding autoclave was equipped with an organic synthesizer and heated to 130°C while stirring at 800 rpm over 16 hours. After the reaction was complete, the autoclave was cooled with ice water, and then open the valve was placed under air atmospheric pressure to distill off the residual hydrogen sulfide. The mixture was transformed into a 10 mL centrifuge tube and the residue including catalyst and unreacted sulfur was removed by centrifugal separation and the clear organic layer was distilled off under reduced pressure (70–200°C) to obtain a colorless oil.

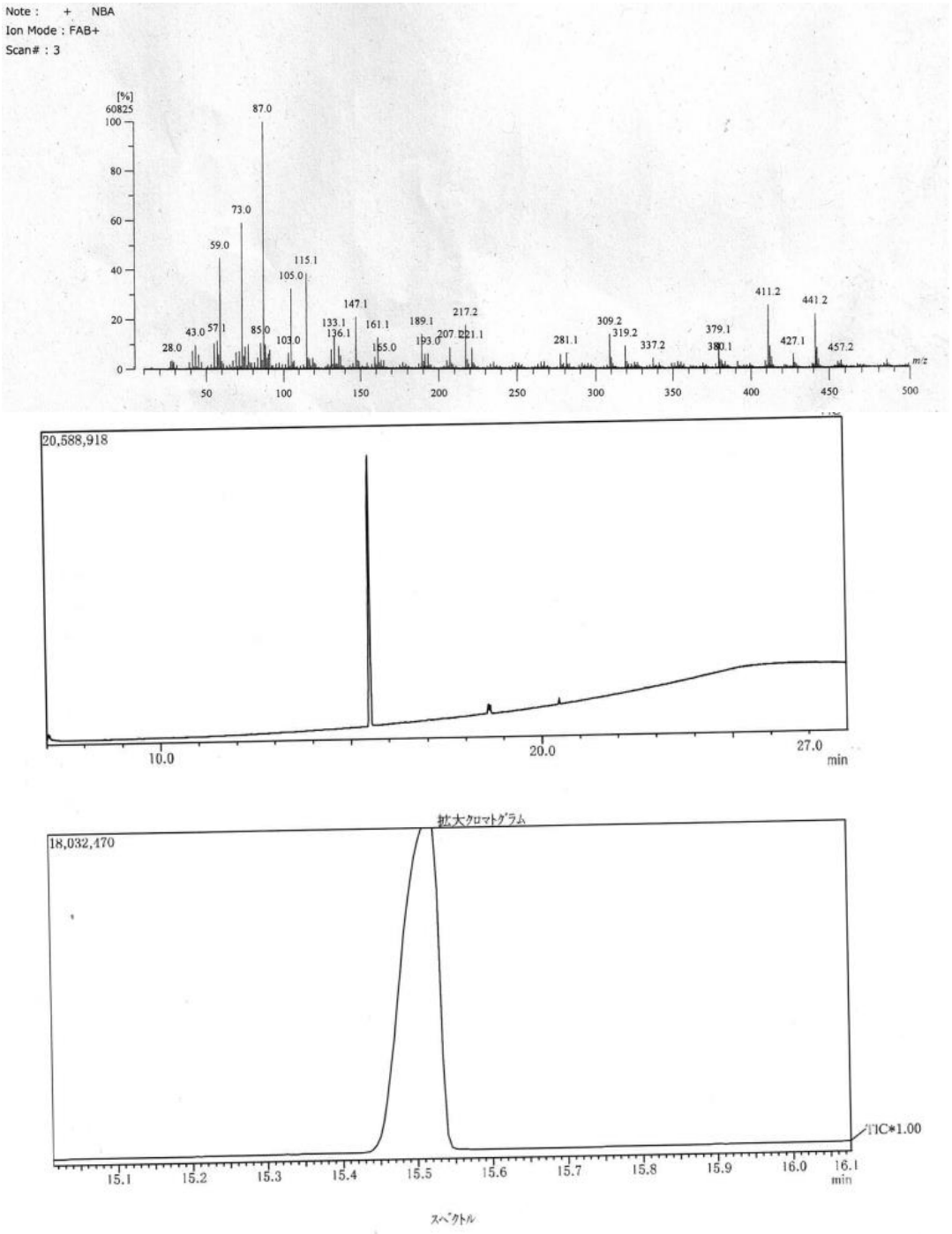
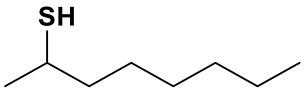


Figure 3.3 HR-MS and GC spectra for supposed compound **13**.

3.4.9 NMR data

Octane-2-thiol (**9a**)[14]



Title thiol was synthesized from 2-octanone **8a** (767.8 mg, 5.98 mmol) according to General Procedure (Solvent for extraction: diethyl ether, internal standard: tridecane, distilled conditions: 1.5 Torr, 110°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.93 (sep, *J* = 6.4 Hz, 1H), 1.75–1.18 (m, 14H), 0.86 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 41.1 (*C*H), 36.8 (*C*H_2), 31.9 (*C*H_2), 29.1 (*C*H_2), 27.6 (*C*H_2), 25.8 (*C*H_3), 22.8 (*C*H_2), 14.2 (*C*H_3).

Compound (**13**)

Title compound was synthesized from triethylsilane **12e** (697.1 mg, 6 mmol) according to Procedure 3.4.8 (distilled conditions: 1.5 Torr, 70°C then heated to 200°C).

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.93 (t, *J* = 7.6 Hz, R–CH_3), 0.52 (quin, *J* = 7.6 Hz, R–CH_2–R).

^{13}C NMR (100 MHz, $CDCl_3$): δ 6.9, 6.6.

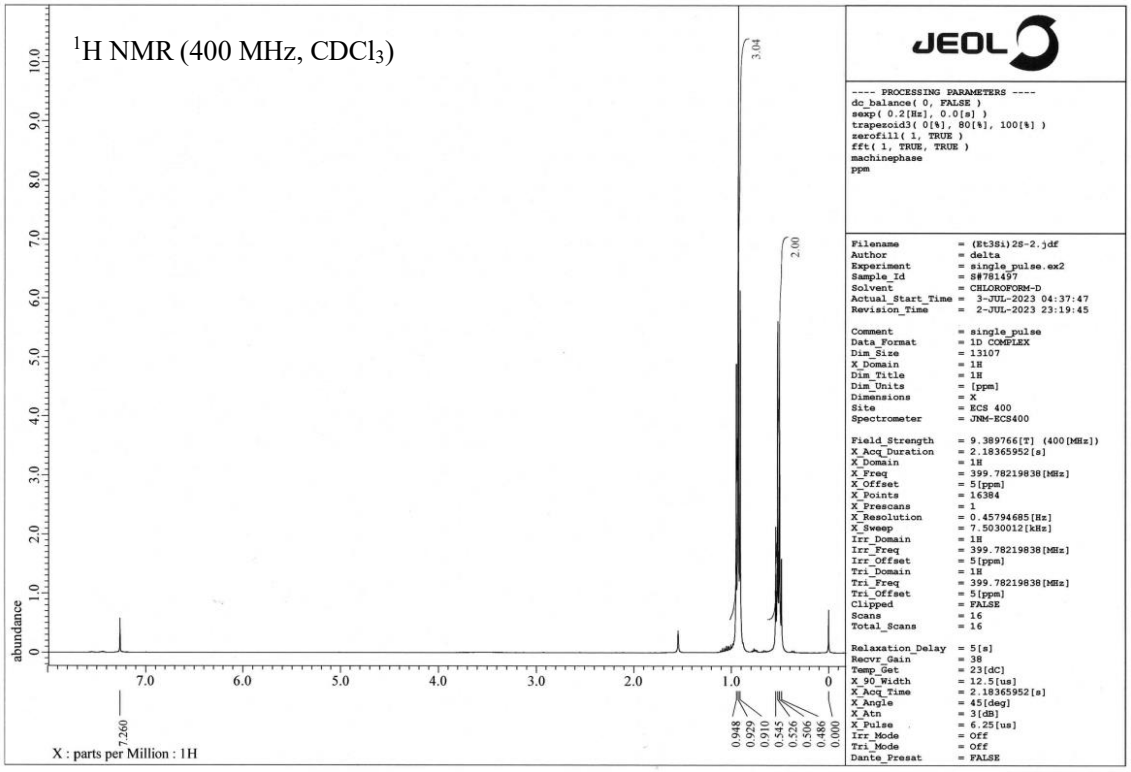


Figure 3.4 ^{1}H NMR spectrum for compound **13**.

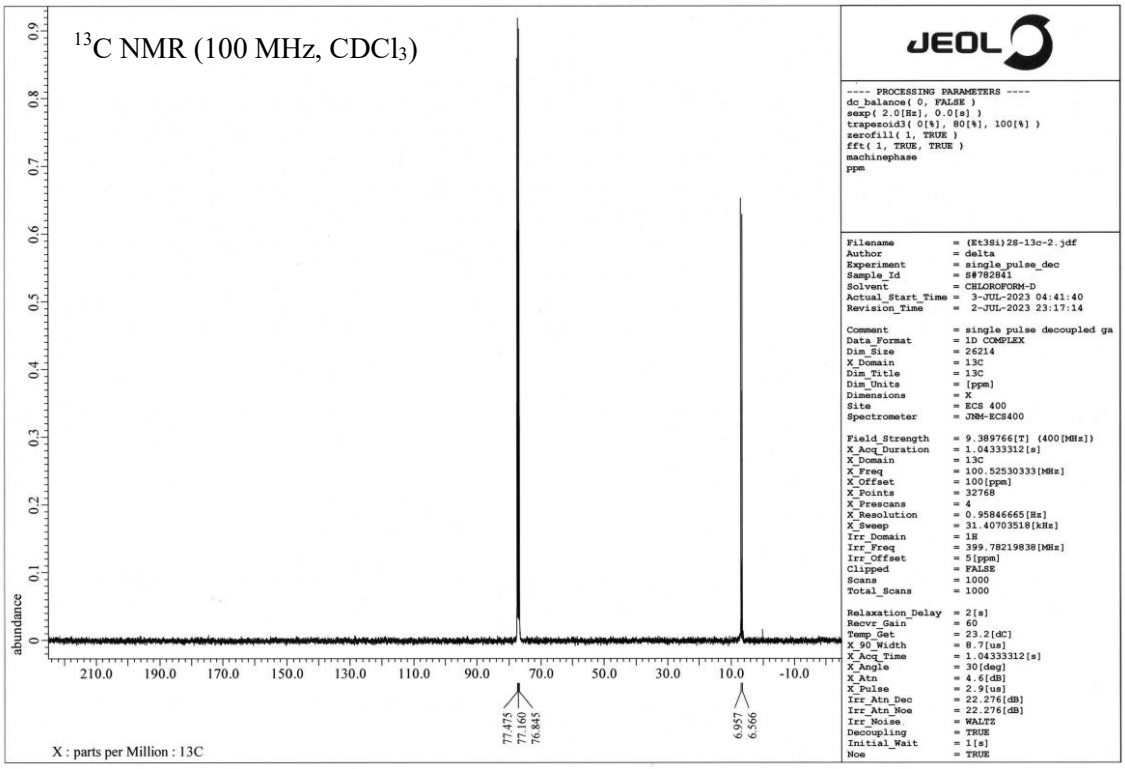


Figure 3.5 ^{13}C NMR spectrum for compound **13**.

3.5 Reference

[1] J. Luclen, J. Barrault, M. Gulsnet and R. Maurel, *Ind. Eng. Chem.*, **1978**, 17, 354–357.

[2] J. Wang, J. L. Lemnerton, W. Z. Li and G. Pérot, *Catal. Lett.*, **1996**, 42, 81–85.

[3] T. J. Paskach, G. L. Schrader and R. E. McCarley, *J. Catal.*, **2002**, 211, 285–295.

[4] O. Y. Gutiérrez, C. Kaufmann, A. Hrabar, Y. Zhu and J. A. Lercher, *J. Catal.*, **2011**, 280, 264–273.

[5] M. Yu, M. Chang, N. Kosinov and E. J. M. Hensen, *J. Catal.*, **2022**, 405, 116–128.

[6] A. V. Mashkina and L. N. Khairulina, *Kinet. Catal.*, **2002**, 43, 684–690.

[7] I. Sorribes and A. Corma, *Chem. Sci.*, **2019**, 10, 3130–3142.

[8] T. Mahdi and D. W. Stephan, *Angew. Chem. Int. Ed.*, **2015**, 54, 8511–8514.

[9] V. R. Madduluri, N. K. Katari, N. Peddinti, V. K. Velpula, D. R. Burri, S. R. R. Kamaraju and S. B. Jonnalagadda, *Res. Chem. Intermediat.*, **2018**, 44, 7619–7639.

[10] S. Chen, T. Wu and C. Zhao, *Green Chem.*, **2020**, 22, 7348–7354.

[11] D. R. Aireddy and K. Ding, *ACS Catal.*, **2022**, 12, 4707–4723.

[12] B. Becker, *Main Group Met. Chem.*, **1988**, 11, 75–90.

[13] R. Arias-Ugarte, H. K. Sharma, A. J. Metta-Magaña and K. H. Pannell, *Organometallics*, **2011**,

30, 6506–6509.
[14] J. Polster and P. Schieberle, *J. Agric. Food Chem.*, **2015**, 63, 1419–1432.

Acknowledgments

At the end of this anthology, the author sincerely thanks everyone who give him the bravery, light, power, confidence, energy and hope to insist his way. He is grateful to his parents, friends, and all those who supported his beliefs in accomplishing this research, anytime anywhere. He has mixed sentiments about this season. Anyone can condemn him based on one aspect of him, but only himself needs to accept all of that. He just does what he has to do and doesn't want to regret it again. This is the real him. However, anyway, he must be gone. And now he wakes up and says hello to face the asymmetry world.

The author would like to express our sincere gratitude to all those who have contributed to the completion of this thesis. The author extends special appreciation to Prof. Makoto Tokunaga, Prof. Haruno Murayama, Prof. Eiji Yamamoto and Mr. Hironobu Matsueda, who provided this chance to investigate this research field. The author would also like to thank Prof. Akina Yoshizawa, Prof. Ryoichi Kuwano, Prof. Takashi Kamachi, Prof. Yoshio Ito and Prof. Tatsuya Uchida for their excellent advice on this research. The authors would like to thank the funding agencies that supported the research funding of this project. The author wishes to acknowledge all organizations, which provided experimental instrumentals in this research. For example, the author thanks the Service Center of the Elementary Analysis of Organic Compounds (Faculty of Science, Kyushu University). Their support has been instrumental in the measurement of elemental analysis for organic sulfur compounds in our research. The author wishes to thank anyone in Tokunaga group. For example, the author would like to thank Mr. Yuta Takaki, Mr. Takeru Ishii and Mr. Yuta Shikama who are the members of this research region for their collaboration and insightful discussions.

It is my pleasure to study in Catalysis Organic Chemistry Laboratory and finish my Ph.D. project at the Graduate School of Science, Kyushu University.