Silver Nitrate Catalyzed Oxidation of Sulfides

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Abstract: A variety of sulfides were converted into the corresponding sulfoxide derivatives with 70% *tert*-butyl hydroperoxide in water as the oxidant in the presence of catalytic quantity of silver nitrate. The method described has a wide range of application, does not involve cumbersome workup, exhibits chemoselectivity, and proceeds under mild reaction conditions, and the resulting products are obtained in good yields within a reasonable time.

Key words: oxidation, sulfide, sulfoxide, silver nitrate, *tert*-butyl hydroperoxide

Catalytic oxidation processes play a key role in the manufacture of bulk and fine chemicals.[1] Sulfides may be considered as important intermediates in organic chemistry owing to their versatile usage in fundamental research;[2] especially chiral sulfoxides serve as important intermediates in the synthesis of biologically and medicinally important compounds.[3] They are also employed in the large-scale separation of radioactive and less-common metals.[4] They often play an important role as antiulcer,[5] anti-atherosclerotic,[6] anthelmintic,[7] antihypertensive,[8] and cardiotonic agents,[9] as well as psychotonics[10] and vasodilators.[11] The most popular and widely used method for the preparation of sulfoxides is the oxidation of the corresponding sulfides. Literature cites several important methods for this transformation.[12] The use of traditional oxidants such as trifluoroperacetic acid,[13] HNO_3/H_2SO_4 solution in nitromethane,[14] and iodic acid[15] and other hypervalent iodides[16] are well established for this transformation. However, most of these reagents show unsatisfactory performance on a medium-to-large scale because of low effective oxygen content and also because they have to be used in large quantities. Moreover these methods have high costs and often lead to the generation of environmentally unfavorable byproducts. Some interesting transition-metal-catalyzed transformations have been reported recently, which include the use of vanadium,[17] rhenium,[18] iron,[19] manganese,[20] and titanium[21] for the selective oxidation of sulfides to sulfoxides in the presence of a suitable oxidant. A recent efficient methodology for the transformation of sulfides to sulfoxides employs a vanadium-based catalytic process along with hydrogen peroxide in the presence of ionic liquids as solvent.[22] However, the high cost and the viscosity associated with ionic liquids hampered the commercialization of this process. Recently, self-catalyzed sulfoxidation reaction at high temperature (i.e., 70 °C) with hydrogen peroxide has been reported.[23] Although it is a green process, it does not work well for low volatile sulfides. It is highly desirable to find simple, less expensive, safe, and high efficiency sulfoxidation methods that will selectively oxidize sulfides to sulfoxides and not sulfones. The capability of silver(I) as an oxidant is documented through the synthesis of vanillic[24] and 3-theonic acids[25] where stoichiometric amounts of silver oxide and sodium hydroxide are reacted. Another popular example to access the scope of silver(I) in oxidation reactions is the Tollens reagent test for aldehydes. These reports prompted us to employ silver nitrate catalytically in the presence of hydrogen peroxide as oxidant to convert aldehydes into carboxylic acids.[26] Our success further inspired us to examine the capability of silver nitrate in the presence of a suitable oxidant to convert sulfides into sulfoxides/sulfones. The employment of silver nitrate is obvious because of its stability under ambient conditions, inexpensive nature, and ease of availability.

Initial attempts to optimize the reaction conditions for the oxidation of sulfides were performed with methyl phenyl sulfide as a suitable substrate in the presence of different solvents, oxidants, and 5 mol% of different silver salts (Table 1). The conversion of methyl phenyl sulfide to (methylsulfinyl)benzene is extremely facile in the presence of 5 mol% silver nitrate and 5 equivalents 70% *tert*-butyl hydroperoxide in water as the oxidant in acetonitrile under reflux conditions. This conversion is almost negligible (<5%) in the absence of silver nitrate. The reaction took 17 hours to go to completion with 2 mol% silver nitrate and 5 equivalents 70% *tert*-butyl hydroperoxide in water with 80% isolated yield of the product under these conditions. With 30% hydrogen peroxide as the oxidant, the reaction reached completion in 13.5 hours with 82% isolated yield of the product. The same reaction went to completion in 12 hours with 5 equivalents 5 M *tert*-butyl hydroperoxide in decane with 90% yield of the product. Among the different solvents used in this study (entries 1–7), acetonitrile yielded best results. The other silver(I) salts (entries 9–11) were not as good with respect to silver nitrate. It is pertinent to highlight here that the GC-MS of the crude product did not reveal the presence of sulfone during this entire optimization, even in the presence of 10 mol% silver nitrate and 20 equivalents *tert*-butyl hydroperoxide in water, making this conversion 100% selective.

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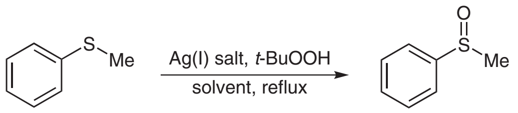
Table 1 Optimization of Reaction Conditions for the Conversion of Methyl Phenyl Sulfide to (Methylsulfinyl)benzene with Different Solvents[a]



Entry	Catalyst	Solvent	Time (h)[b]	Yield (%)[c]
1	$AgNO_3$	MeCN	10	96[d,e,f]
2	$AgNO_3$	DMF	12	75
3	$AgNO_3$	DMSO	13	65
4	$AgNO_3$	toluene	12	60
5	$AgNO_3$	EtOAc	11	90
6	$AgNO_3$	EtOH	10.5	88
7	$AgNO_3$	$MeNO_2$	15	86
8	AgI	MeCN	16	89
9	AgCl	MeCN	24	60
10	AgOTf	MeCN	24	80
11	AgOAc	MeCN	12	90

[a] 70% *t*-BuOOH (5 equiv) (H_2O) and Ag(I) (5 mol%) salts.

[b] Monitored using TLC technique.

[c] Isolated yield after column chromatography of crude.

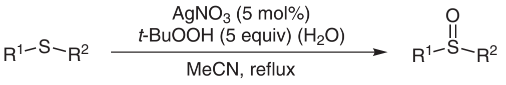
[d] Conversion <5% in the absence of $AgNO_3$.

[e] With 30% H_2O_2, the reaction went to completion in 13.5 h with 82% isolated yield.

[f] With 5 M *t*-BuOOH (decane), the reaction went to completion in 12 h with 90% isolated yield.

Having realized the correct conditions for sulfoxidation, we continued our quest with a variety of substrates as depicted in Table 2. A variety of substituted and unsubstituted alkyl aryl sulfides (entries 1–11), diaryl sulfide (entry 12), aryl benzyl sulfides (entries 4, 7 and 10), and dialkyl sulfide (entry 18) were successfully and selectively oxidized to the corresponding sulfoxides in high yields and purity. Sulfides with additional functionalities susceptible to oxidation or deprotection such as alkenes (entries 13 and 19), alkynes (entry 14), phenol (entry 15), nitrile (entry 16), and oxime (entry 17) were found to yield sulfoxides without affecting the sensitive functional groups. It is interesting to note that no epoxidation was observed during the oxidation of allyl phenyl sulfide (entry 13). Phenyl propargyl sulfide was oxidized to the sulfoxide in good yields (entry 14) without any dimerization. Again, it is very important to note that not a trace of sulfone was ever seen in the GC-MS spectra of crude products. Our catalytic system has the capability of transforming disulfides to disulfoxides under similar reaction conditions. The results are depicted in Table 3. This reaction reveals the same general trends as seen for sulfides (Table 2). It is noteworthy that neither monosulfoxide nor monosulfone were obtained in this reaction.

Table 2 Silver Nitrate Catalyzed Selective Oxidation of Sulfides to Sulfoxides[a]



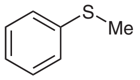
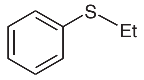
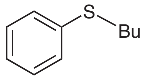
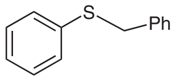
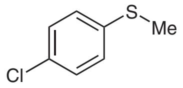
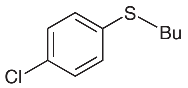
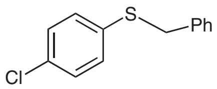
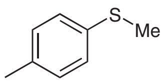
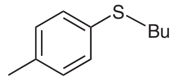
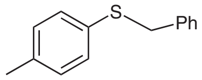
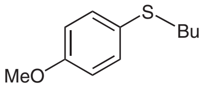
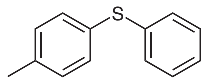
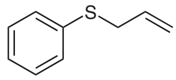
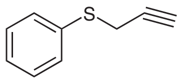
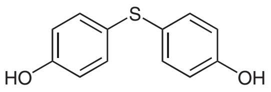
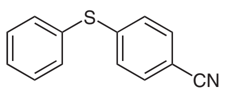
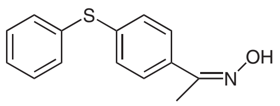
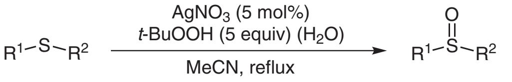
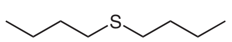
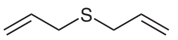
Entry	Sulfide	Time[b] (h)	Yield[c] (%)
1		10	96
2		20	91
3		14	90
4		18	89
5		21	88
6		20	92
7		22	93
8		16	95
9		17	92
10		17	91
11		3	94
12		16	90
13		8	91
14		5	93
15		6	92
16		20	87
17		22	85

Table 2 Silver Nitrate Catalyzed Selective Oxidation of Sulfides to Sulfoxides[a] (continued)



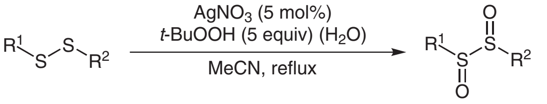
Entry	Sulfide	Time[b] (h)	Yield[c] (%)
18		6	92
19		2	94

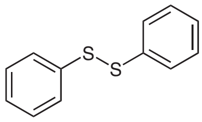
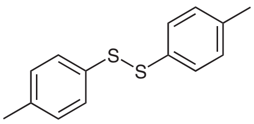
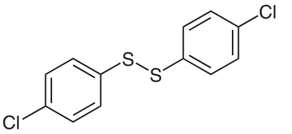
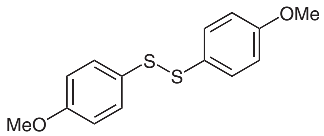
[a] Reactions performed in MeCN with $AgNO_3$ (5 mol%) and 70% *t*-BuOOH (5 equiv) under reflux conditions.

[b] Monitored using TLC until all the sulfide was found consumed.

[c] Isolated yield after column chromatography of the crude product.

Table 3 Silver Nitrate Catalyzed Selective Oxidation of Disulfides to Disulfoxides[a]



Entry	Disulfide	Time[b] (h)	Yield[c] (%)
1		22	92
2		13	91
3		24	90
4		4	93

[a] Reactions performed in MeCN with $AgNO_3$ (5 mol%) and 70% *t*-BuOOH (5 equiv) under reflux conditions.

[b] Monitored using TLC until all the disulfide was found consumed.

[c] Isolated yield after column chromatography of the crude product.

The kinetic studies of the sulfoxidation with methyl phenyl sulfide, bis(4-hydroxyphenyl) sulfide, and bis(4-methoxyphenyl) disulfide were explored next. High-pressure liquid chromatography (HPLC) was used to determine the various starting materials and products present as a function of time. The concentration of reactant and product for the oxidation of methyl phenyl sulfide is shown in Figure 1. The concentration of the sulfide decreases steadily while that of the sulfoxide increases. We have calculated the rate of such reactions. As an example let us consider the conversion of methyl phenyl sulfide to (methylsulfinyl)benzene. Van't Hoff differential method was used to determine the order (n) and rate constant (k) (Figure 2). From Figure 1, the rate of the reaction at different concentrations can be estimated by evaluating the slope of the tangent at each point on the curve corresponding to that of methyl phenyl sulfide. With these data, $\log_{10}$(rate) versus $\log_{10}$(concentration) is plotted. The order (n) and rate constant (k) is given by the slope of the line and its intercept on the $\log_{10}$(rate) axis. From Figure 2, it is clear that this reaction proceeds with second-order kinetics ($n = 2.07$) and the rate constant $k = 4.78 \times 10^{-5}$ L mol^{-1} s^{-1}. For the other substrates namely bis(4-hydroxyphenyl) sulfide and 4-methoxydilsulfide, the order of the reaction $n \approx 2$ with rate constants (k) 1.14×10^{-3} L mol^{-1} s^{-1} and 2.35×10^{-2} L mol^{-1} s^{-1}, respectively (see Supporting Information for details).

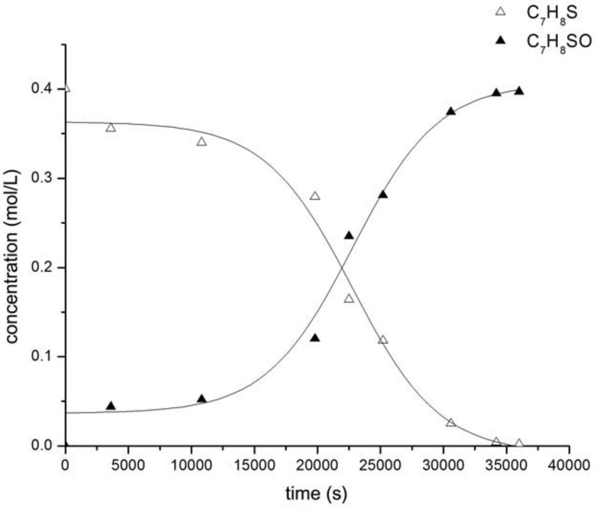


Figure 1 Concentration versus time in the oxidation of methyl phenyl sulfide [$AgNO_3$ (5 mol%), *t*-BuOOH (5 equiv), MeCN, reflux]

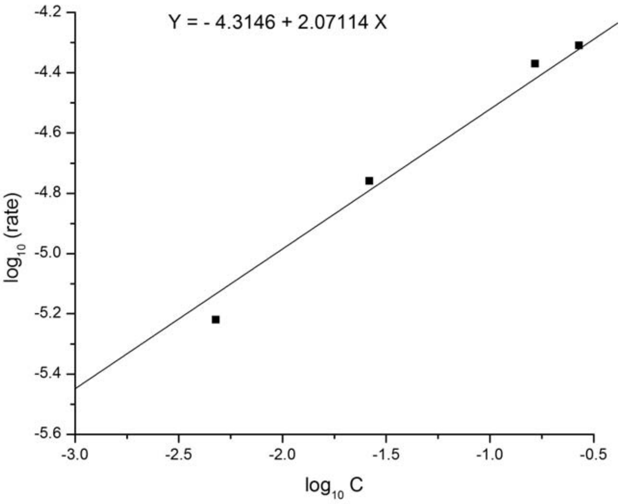


Figure 2 Van't Hoff differential plot for the oxidation of methyl phenyl sulfide [$AgNO_3$ (5 mol%), *t*-BuOOH (5 equiv), MeCN, reflux]

In summary, we have developed a simple, efficient, chemoselective and inexpensive catalytic method for the oxidation of sulfides to sulfoxides with a table top reagent such as silver nitrate. It is noteworthy to mention that this method does not use ligands and other additives.

All the substrates used in this study were purchased from Aldrich and used as received. The solvents used were purchased from Ranchem, India and purified using standard methods. ^{1}H and ^{13}C spectra were recorded with a Bruker Avance 400 instrument. Chemical shifts were referenced to residual solvent resonances and are reported as parts per million relative to $SiMe_4$. $CDCl_3$ was used for NMR spectral measurements. GC-MS were recorded using Jeol JMS GC-Mate II instrument. HPLC analysis was done with Waters HPLC instrument fitted with Waters 515 pump and Waters 2487 dual-wavelength absorbance detector.

Sulfoxides; Typical Procedure

To a stirred soln of $AgNO_3$ (8.05 mg, 0.05 mmol) and sulfide/disulfide (1 mmol) in MeCN (2.5 mL) was added 70% aq *t*-BuOOH (0.64 mL, 5 mmol). The mixture was heated to reflux and the progress was monitored by TLC until all sulfide/disulfide was found consumed. After completion, MeCN was evaporated and the crude mixture was washed with $NaHCO_3$ and extracted with EtOAc. The EtOAc was evaporated followed by flash column purification to obtain the pure sulfoxides. The product was characterized using ^{1}H, ^{13}C NMR spectroscopy, ESI-MS and IR spectroscopy. The data were found to be in accord with the literature (see Supporting Information).

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

Acknowledgment

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References

(1) Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidation of Organic Compounds*; Academic Press: New York, **1981**.

(2) (a) Cremlyn, R. J. *An Introduction to Organosulfur Chemistry*; John Wiley and Sons: Chichester, **1996**. (b) Drabowski, J.; Kielbasinski, P.; Mikolajczyk, M. *Synthesis of Sulfoxides*; John Wiley and Sons: New York, **1994**. (c) *The Synthesis of Sulphones, Sulphoxides, and Cyclic Sulphides*; Capozzi, G.; Patai, S.; Rappoport, Z., Eds.; John Wiley and Sons: New York, **1994**.

(3) (a) Legros, J.; Dehli, J.; Bolm, C. *Adv. Synth. Catal.* **2005**, *347*, 19. (b) Carreno, M. C. *Chem. Rev.* **1995**, *95*, 1717. (c) Fernández, N.; Khiar, I. *Chem. Rev.* **2003**, *103*, 3651.

(4) (a) Khan, M. H.; Hussany, S. M.; Khan, M. A.; Ali, A. *Radiochim. Acta* **1994**, *65*, 239. (b) Shukla, J. P.; Singh, R. K.; Sawant, S. R.; Varadarajan, N. *Anal. Chim. Acta* **1993**, *276*, 181.

(5) (a) Salas, M.; Ward, A.; Caro, J. *BMC Gastroenterol.* **2002**, *2*, 17; http://www.biomedcentral.com/bmcgastroenterol/. (b) Spencer, C. M.; Faulds, D. *Drugs* **2000**, *60*, 321.

(6) Perez-Giraldo, C.; Cruz-Villalon, G.; Sanchez-Silos, R.; Martinez-Rubio, R.; Blanco, M. T.; Gomez-Garcia, A. C. *J. Appl. Microbiol.* **2003**, *95*, 709.

(7) Merino, G.; Molina, A. J.; Garcia, J. L.; Pulido, M. M.; Prieto, J. G.; Alverez, A. I. *J. Pharm. Pharmacol.* **2003**, *55*, 757.

(8) Kotelanski, B.; Grozmann, R. J.; Cohn, J. N. *Clin. Pharmacol. Ther.* **1973**, *14*, 427.

(9) Scimied, R.; Wang, G. X.; Korth, M. *Circ. Res.* **1991**, *68*, 597.

(10) Lechin, F.; Van der Dijis, B.; Pardey-Maldonado, B.; John, E.; Jimenez, V.; Orozco, B.; Baez, S.; Lechin, M. E. *J. Med.* **2000**, *31*, 333.

(11) Padmanabhan, S.; Lavin, R. C.; Durant, G. J. *Tetrahedron: Asymmetry* **2000**, *11*, 3455.

(12) (a) Bagherzadeh, M.; Latifi, R.; Tahsini, L.; Amini, M. *Catal. Commun.* **2008**, *10*, 196. (b) Karimi, B.; Nezhad, M. G.; Clark, J. H. *Org. Lett.* **2005**, *7*, 625. (c) Hajipour, A. R.; Ruoho, A. E. *Sulfur Lett.* **2003**, *26*, 83. (d) Bravo, A.; Dordi, B.; Fontana, F.; Minisci, F. *J. Org. Chem.* **2001**, *66*, 3232.

(13) Venier, C. G.; Squires, T. G.; Chen, Y. Y.; Hussmann, G. P.; Shei, J. C.; Smith, B. F. *J. Org. Chem.* **1982**, *47*, 3773.

(14) Gasparrini, F.; Giovannoli, M.; Maresca, L.; Natile, G.; Palmieri, G. *Synth. Commun.* **1984**, *14*, 1111.

(15) Lakouraj, M. M.; Tajbakhsh, M.; Shirini, F.; Asady Tamani, M. V. *Synth. Commun.* **2005**, *35*, 775.

(16) (a) Shukla, V. G.; Salgaonkar, P. D.; Akamanchi, K. G. *J. Org. Chem.* **2003**, *68*, 5422. (b) Tohama, H.; Takizawa, S.; Watanabe, H.; Kita, Y. *Tetrahedron Lett.* **1998**, *39*, 4547. (c) Xia, M.; Chen, Z. C. *Synth. Commun.* **1997**, *27*, 1315.

(17) (a) Romanelli, G. P.; Bennardi, D. O.; Palermo, V.; Vázquez, P. G.; Tundo, P. *Lett. Org. Chem.* **2007**, *4*, 544. (b) Trivedi, R.; Lalitha, P. *Synth. Commun.* **2006**, *36*, 3777. (c) Di Furia, F.; Modena, G.; Curci, R. *Tetrahedron Lett.* **1976**, *17*, 4637.

(18) Stanger, K. J.; Wiench, J. W.; Pruski, M.; Espenson, J. H.; Kraus, G. A.; Angelici, R. J. *J. Mol. Catal. A: Chem.* **2006**, *243*, 158.

(19) (a) Egami, H.; Katsuk, T. *J. Am. Chem. Soc.* **2007**, *129*, 8940. (b) Baciocchi, E.; Gerini, M. F.; Lapi, A. *J. Org. Chem.* **2004**, *69*, 3586. (c) Legros, J.; Bolm, C. *Angew. Chem. Int. Ed.* **2003**, *42*, 5487. (d) Marques, A.; Marin, M.; Ruasse, M. F. *J. Org. Chem.* **2001**, *66*, 7588.

(20) (a) Barker, J. E.; Ren, T. *Tetrahedron Lett.* **2005**, *46*, 6805. (b) Xie, F.; Fu, Z. H.; Zhong, S.; Ye, Z. P.; Zhou, X. P.; Liu, F. L.; Rong, C. Y.; Mao, L. Q.; Yin, D. L. *J. Mol. Catal. A: Chem.* **2009**, *307*, 93.

(21) Iwamoto, M.; Tanaka, Y.; Hirosumi, J.; Kita, N.; Triwahyono, S. *Microporous Mesoporous Mater.* **2001**, *48*, 271.

(22) Conte, V.; Fabbianesi, F.; Floris, B.; Galloni, P.; Sordi, D.; Arends, I. C. W. E.; Bonchio, M.; Rehder, D.; Bogdal, D. *Pure Appl. Chem.* **2009**, *81*, 1265.

(23) Shi, F.; Tse, M. K.; Kaiser, H. M.; Beller, M. *Adv. Synth. Catal.* **2007**, *349*, 2425.

(24) Pearl, I. A. *Org. Synth.* **1963**, *4*, 972.

(25) Campaigne, E.; LeSuer, W. M. *Org. Synth.* **1963**, *4*, 919.

(26) Chakraborty, D.; Gowda, R. R.; Malik, P. *Tetrahedron Lett.* **2009**, *50*, 6553.