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Enantioselective Vanadium-Catalyzed Oxidation of 1,3-Dithianes from Aldehydes and Ketones using β-Amino Alcohol Derived Schiff Base Ligands

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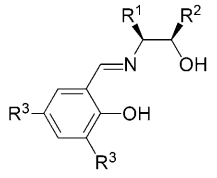
Abstract: The asymmetric vanadium-catalyzed oxidation of 1,3-dithianes from aldehydes and ketones by β-amino alcohol-derived Schiff base ligands with two stereogenic centers was investigated. Using aqueous hydrogen peroxide as the oxidant and the Schiff base **3b** as a chiral ligand, a variety of 1,3-dithianes derived from aldehydes were easily converted into the corresponding mono-sulfoxides in good yields (81–88%) with excellent enantioselectivities (up to 99% *ee*). Additionally, 99% *ee* was obtained for the enantioselective vanadium-catalyzed oxidation of the 1,3-dithianes derived from ketones. We found a slight kinetic resolution when using a higher ratio of hydrogen peroxide during the oxidation of the aldehyde-derived 1,3-dithianes but not in the ketone-derived 1,3-dithianes.

Keywords: asymmetric catalysis; chiral sulfoxides; 1,3-dithianes; Schiff base ligands; vanadium

Over the past two decades, the enantioselective oxidation of sulfides to sulfoxides has been of great interest because sulfoxides are useful synthetic intermediates for the asymmetric synthesis of various chemically and biologically significant molecules[1] and chiral auxiliaries.[1f,2] Among the methods used for the preparation of optically active sulfoxides, the titanium,[3] aluminum,[4] manganese[5] and vanadium[6] complex-catalyzed asymmetric oxidation of sulfides has been widely studied. Vanadium-catalyzed asymmetric oxidation of sulfides is one of the most attractive routes because of its high enantioselectivity, low catalyst loading, the use of inexpensive aqueous hydrogen peroxide as the oxidant and mild reaction conditions. Bolm first reported the famous vanadium catalyst system prepared *in situ* from $VO(acac)_2$ and substituted with the salicylidene derivative (*S*)-*tert*-leucinol in 1995, which effectively catalyzed the oxidation of sulfides to sulfoxides using hydrogen peroxide as the oxidant with good enantioselectivity (up to 80% *ee*).[7] Since then many optimizations have been carried out on the basis of this protocol including: (i) the use of other amino alcohols for the preparation of Schiff bases as chiral ligands,[8] (ii) (*S*)-*tert*-leucinol-based Schiff bases modified with various aromatic aldehydes,[6,8a,9] (iii) the manner of H_2O_2 addition and the use of additives,[10] (iv) the method of oxidation/kinetic resolution.[11]

By comparison with the well studied simple sulfides, the catalytic asymmetric oxidation of dithioacetals and dithioketals has had limited success. Bolm[12] used a vanadium catalyst system for the enantioselective oxidation of dithioacetals and dithioketals with 30% aqueous H_2O_2 and obtained the corresponding mono-sulfoxides with enantioselectivities of up to 85% *ee*. In addition, Di Furia et al. reported the efficient asymmetric oxidation of cyclic dithioacetals and dithioketals with $Ti(OCHMe_2)_4$.[13] Corich and coworkers introduced the use of [Ti(*i*-PrO)$_4$/DET/*t*-BuOOH] for the oxidation of thioethers[14] and Page used the modified Sharpless procedure for the enantioselective sulfoxidation of a wide range of *Z*-substituted-1,3-dithianes.[15] Aggarwal et al. used the Modena asymmetric oxidation of 2-benzyloxymethyl-1,3-dithiolane to obtain a *trans* bis-sulfoxide.[16] Roland reported a preparative scale enantioselective oxidation of prochiral dithioacetals and dithioketals to their corresponding sulfoxides using whole-cell cultures of microorganisms.[17] Katsuki[18] reported the asymmetric oxidation of 2-substituted 1,3-dithianes using Ti(salen) as the catalyst by UHP with high enantioselectivity to afford the corresponding mono-sulfoxides.



2a: R^1 = *t*-Bu, R^2 = H, R^3 = *t*-Bu
2b: R^1 = *t*-Bu, R^2 = H, R^3 = I
2c: R^1 = *t*-Bu, R^2 = Me, R^3 = *t*-Bu

1a: R^1 = Bn, R^2 = Et, R^3 = I
1b: R^1 = Bn, R^2 = H, R^3 = *t*-Bu
1c: R^1 = Bn, R^2 = Me, R^3 = *t*-Bu
1d: R^1 = Bn, R^2 = Et, R^3 = *t*-Bu
1e: R^1 = Bn, R^2 = *n*-Pr, R^3 = *t*-Bu
1f: R^1 = Bn, R^2 = *n*-Bu, R^3 = *t*-Bu

3a: R^1 = *i*-Pr, R^2 = H, R^3 = *t*-Bu
3b: R^1 = *i*-Pr, R^2 = Me, R^3 = *t*-Bu
3c: R^1 = *i*-Pr, R^2 = Et, R^3 = *t*-Bu
3d: R^1 = *i*-Pr, R^2 = *n*-Pr, R^3 = *t*-Bu
3e: R^1 = *i*-Pr, R^2 = *n*-Bu, R^3 = *t*-Bu
3f: R^1 = *i*-Pr, R^2 = *n*-Pen, R^3 = *t*-Bu

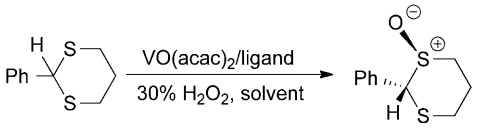
Scheme 1. Chiral Schiff base ligands for screening the vanadium-catalyzed oxidation of sulfides.

The dithioacetal mono-oxides have reversed polarity to carbonyl compounds and serve as stereocontrol elements in a variety of reactions to improve the reactivity of carbonyl groups such as in intramolecular enolate alkylation,[19a] amination,[19b] nucleophilic addition,[19c] reduction,[19d] conjugate addition,[19e] cycloaddition,[19f] and the Mannich reaction.[19g] Therefore, from both fundamental and practical standpoints, it is still desirable to develop a highly effective catalyst system for the preparation of these useful compounds.

In our study, to investigate the structural influence of the β-amino alcohol moiety on Schiff bases and especially those with two stereogenic centers, we used a series of Schiff base ligands derived from phenylalanine to screen the vanadium-catalyzed oxidation of sulfides and found that some had excellent activity and enantioselectivity.[20] In this paper, we report on the results of the catalytic asymmetric oxidation of 1,3-dithianes derived from aldehydes and ketones using aqueous hydrogen peroxide as the oxidant and upon catalysis by a system that consists of $VO(acac)_2$ and β-amino alcohol-derived Schiff bases with two stereogenic centers.

Among the series of Schiff base ligands that we used for the vanadium-catalyzed oxidation of methyl phenyl sulfide, ligand **1a** (Scheme 1) afforded the best results.[20] However, upon screening the vanadium-catalyzed oxidation of the 1,3-dithiane derived from benzaldehyde in CH_2Cl_2 with H_2O_2 as the oxidant at 25 °C, we found that this ligand only gave 52% *ee* (Table 1, entry 1). On the other hand, ligands **1b** and **1c**, which possess *tert*-butyl groups on the aldehyde moieities, gave good results (Table 1, entries 2 and 3: ligand **1b**, 80% *ee*; ligand **1c**, 85% *ee*). The other ligands that were derived from phenylalanine such as **1d** to **1f** also gave moderate to good enantioselectivities (Table 1, entries 4–6). To investigate the effect of the stereochemistry of the Schiff base ligands on the enantioselectivity of the product and develop a more effective catalyst system for the oxidation of the different substituted 1,3-dithianes, we prepared the

Table 1. Influence of chiral ligands on the enantioselectivity of the asymmetric oxidation of the 1,3-dithiane derived from benzaldehyde.[a]



Entry	Ligand	Solvent	Yield [%][b]	*ee* [%][c]
1	**1a**	CH_2Cl_2	81 (77)[b]	52 (*R*,*R*)[d]
2	**1b**	CH_2Cl_2	95 (90)	80 (*R*,*R*)
3	**1c**	CH_2Cl_2	94 (88)	85 (*R*,*R*)
4	**1d**	CH_2Cl_2	93 (90)	85 (*R*,*R*)
5	**1e**	CH_2Cl_2	91 (86)	64 (*R*,*R*)
6	**1f**	CH_2Cl_2	94 (90)	55 (*R*,*R*)
7	**2a**	CH_2Cl_2	93 (87)	85 (*R*,*R*) (85%)[e]
8	**2b**	CH_2Cl_2	78 (71)	38 (*R*,*R*)
9	**2c**	CH_2Cl_2	87 (82)	69 (*R*,*R*)
10	**3a**	CH_2Cl_2	98 (94)	81 (*R*,*R*)
11	**3b**	CH_2Cl_2	97 (94)	96 (*R*,*R*)
12	**3c**	CH_2Cl_2	97 (93)	93 (*R*,*R*)
13	**3d**	CH_2Cl_2	94 (89)	81 (*R*,*R*)
14	**3e**	CH_2Cl_2	90 (85)	78 (*R*,*R*)
15	**3f**	CH_2Cl_2	91 (88)	77 (*R*,*R*)
16	**3b**	$CHCl_3$	88 (82)	81 (*R*,*R*)

[a] All reactions were carried out with 1.1 equiv of 30% H_2O_2 and a catalyst (1 mol%) for 16 h at 25 °C.
[b] The conversion was determined by ^{1}H NMR spectroscopic analysis. The value in parenthesis is the isolated yield after purification on a silica column.
[c] Determined by HPLC analysis with a Chiralcel OD-H column. The optical rotation was obtained in acetone. Details are given in the Supporting Information.
[d] The absolutely configuration was determined from the HPLC retention times reported in the literature.[23]
[e] The value in parenthesis is the catalysis result of ligand **2a** as reported previously.[12]

Schiff base ligands **2** and **3** (Scheme 1) that were derived from (*S*)-*tert*-leucine and (*S*)-valine according to the procedure in the literature[7] and that which we reported previously.[20]

A preliminary study into the enantioselective vanadium-catalyzed oxidation of 1,3-dithiane was undertaken with these Schiff bases as chiral ligands and with 1.1 equivalents of 30% H_2O_2 as the oxidant. Ligands **2a** and **2b**, which Bolm[7] and Anson[6a] first introduced independently in the asymmetric oxidation of sulfides to sulfoxides, gave 85% and 38% *ee*, respectively. This indicates that the *tert*-butyl groups in the salicylidene moiety of the ligand give better results than the iodo group. Ligand **3a**, which was derived from valine and has a similar structure to ligand **2a** gave 81% *ee* under the same reaction conditions. On the other hand, ligand **3b**, which possesses two stereogenic centers at the β-amino alcohol moiety gave 96% *ee* (Table 1, entry 11). However, ligands **3c**,

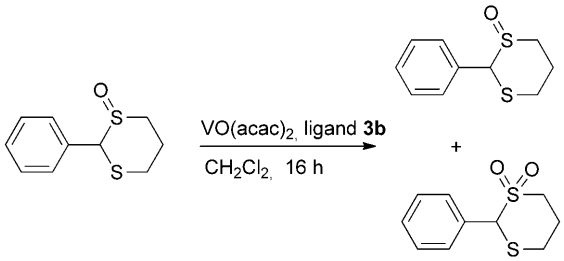
3d, **3e** and **3f** where the R^1 groups range from ethyl to *n*-pentyl gave *ee* values from 93% to 77% (Table 1, entries 12–15). These results imply that a suitable steric effect is an important factor in obtaining high enantioselectivity. We also performed the reaction using chloroform as the solvent, however, the *ee* was much lower than that using dichloromethane (Table 1, entry 15). Additionally, only *trans* isomers were obtained in all cases as evident from a comparison of the ^{13}C NMR shifts of with C-6 signal with those previously reported.[21]

The asymmetric oxidation of simple sulfides is sometimes accompanied by kinetic resolution. A process has been developed for the preparation of enantiomerically pure sulfoxides by several groups in recent years.[11] For vanadium-catalyzed sulfide oxidation, Jackson et al. successfully developed a tandem procedure using oxidation/kinetic resolution for the synthesis of chiral sulfoxides in chloroform.[11b] Zeng et al. combined enantioselective sulfoxidation with concomitant kinetic resolution to produce chiral sulfoxides with vanadium-Schiff base complexes derived from *(S)*-phenylalaninol or *(S)*-leucinol as the catalyst. Moderate yields (40.6%) and up to 99% *ee* were obtained using H_2O_2 (2.0 equiv.) as the oxidant.[11c] In our previous study, we used Schiff base ligands derived from amino alcohols with two stereogenic centers for the vanadium-catalyzed oxidation of sulfides,[20] and we found that kinetic resolution was present following a highly efficient asymmetric oxidation in chloroform when excess oxidant was used. To investigate the kinetic resolution process in enantioselective oxidation, a racemic sulfoxide derived from 1,3-dithiane was used with different equivalents of H_2O_2 as the oxidant in CH_2Cl_2 at room temperature. The results (Table 2) show that the selectivity factor *S*, a measure of the effectiveness of the kinetic resolution process, remains about 5 under these conditions (the selectivity factor *S* varied from 7 to 30 for the kinetic resolution of alkyl aryl sulfoxides[22]).

We then adjusted the ratio of hydrogen peroxide/sulfide in the oxidation/kinetic resolution procedure to obtain sulfoxides with high *ee* and yield. Good enantioselectivity and chemical yield (91% yield with 97.2% *ee*) were obtained when the ratio was adjusted to 1.20 and 88% yield was obtained with excellent enantioselectivity (up to 99% *ee*) with 1.3 equivalents of H_2O_2 as the oxidant. These results indicate that the kinetic resolution of the sulfoxides is indeed favorable for high *ee* values. Chloroform was also evaluated as a solvent for the oxidation/kinetic resolution process and the results (Table 3, entries 4–7) indicate that it is not such an efficient solvent as CH_2Cl_2 for the asymmetric oxidation/kinetic resolution of 1,3-dithiane.

The results of the enantioselective oxidation of a series of 1,3-dithianes that were derived from aldehydes catalyzed by the $VO(acac)_2$/ligand **3b** under the optimal reaction conditions are listed in Table 4. All 19 substrates gave high yields and excellent enantioselectives in most cases. All the 1,3-dithianes that were derived from 2-, 3-, and 4-methyl-substituted benzaldehyde gave 99% *ee* (Table 4, entries 3–5). However, 2-(4′-methoxyphenyl)-1,3-dithiane gave only 87% *ee* in contrast to the 99% *ee* for its two other isomers; 2-

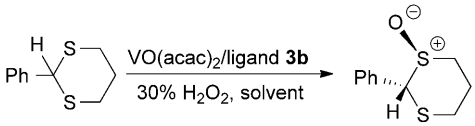
Table 2. Kinetic resolution of the racemic sulfoxides.[a]



Entry	H_2O_2 [equiv.]	Conversion [%][b]	*ee* [%][c]	*S*[d]
1	0.2	20.7	16.8	5.42
2	0.3	30.9	27.1	5.28
3	0.4	38.8	37.1	5.44
4	0.5	46.8	47.9	5.35

[a] All reactions were carried out with 1.1 equiv. of 30% H_2O_2 and a catalyst (1 mol%) for 16 h at 25 °C.
[b] The conversion was determined by ^1H NMR spectroscopic analysis .
[c] Determined by HPLC analysis with a Chiralcel OD-H column.
[d] $S = k_{re(fast/slow)} = \ln[(1-C)(1-ee)]/\ln[(1-C)(1+ee)]$.

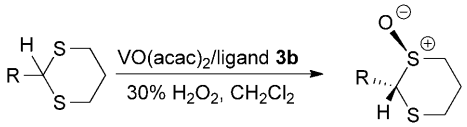
Table 3. The oxidation/kinetic resolution of 1,3-dithianes derived from aldehydes.[a]



Entry	Solvent	*T* [°C]	H_2O_2 [equiv.]	Yield [%][b]	*ee* [%][c]
1	CH_2Cl_2	r.t.	1.1	97 (94)	96.4[d]
2	CH_2Cl_2	r.t.	1.2	91 (88)	97.2
3	CH_2Cl_2	r.t.	1.3	88 (83)	>99.9
4	$CHCl_3$	0	1.1	88 (84)	81
5	$CHCl_3$	0	1.2	86 (81)	87
6	$CHCl_3$	0	1.3	83 (80)	92
7	$CHCl_3$	0	1.4	79 (75)	96

[a] All reactions were carried out with 30% H_2O_2 and a catalyst (1 mol%) for 16 h at 25 °C.
[b] The conversion was determined by ^1H NMR spectroscopic analysis .The value in parenthesis is the isolated yield after purification on a silica column.
[c] Determined by HPLC analysis with a Chiralcel OD-H column.
[d] The optical rotation was obtained in acetone. Details are given in the Supporting Information.

Table 4. Asymmetric oxidation of various 1,3-dithiane derived from aldehydes with $VO(acac)_2$/**3b.**[a]



Entry	R	Yield [%][b]	*ee* [%][c,d]
1	1-naphthyl	88	96
2	2-naphthyl	84	99
3	2-Me-C_6H_4	86	99
4	3-Me-C_6H_4	86	99
5	4-Me-C_6H_4	83	99 (*S,S*)[d]
6	2-MeO-C_6H_4	80	99
7	3-MeO-C_6H_4	81	99
8	4-MeO-C_6H_4	81	87 (*S,S*)[d]
9	2,5-di-MeO-C_6H_3	84	88
10	2-Cl-C_6H_4	87	99
11	4-Cl-C_6H_4	82	98 (*S,S*)[d]
12	2-Br-C_6H_4	83	94
13	4-Br-C_6H_4	86	99
14	2-F-C_6H_4	86	96
15	4-F-C_6H_4	81	99
16	2-NO_2-C_6H_4	85	85
17	3-NO_2-C_6H_4	88	99
18	4-NO_2-C_6H_4	83	85
19	cyclohexane	89	35

[a] All reactions were carried out with 1.3 equiv. of 30% H_2O_2 and a catalyst (1 mol%) for 16 h at 25 °C.
[b] Isolated yield after purification on a silica column.
[c] Determined by HPLC analysis with a Chiralcel OD-H column. The optical rotation was obtained in acetone. Details are given in the Supporting Information.
[d] The absolutely configuration was determined from the HPLC retention times reported in the literature.[23]

(2′-methoxyphenyl)- and 2-(3′-methoxyphenyl)-1,3-dithiane (Table 4, entries 6 and 7). Steric hindrance by the substituted groups also affects the enantioselectivity. 2-(2′-Methoxyphenyl)-1,3-dithiane gave 99% *ee* and by comparison 2-(2′,5′-dimethoxyphenyl)-1,3-dithiane gave 88% *ee* under the same conditions. Other substrates containing electron-withdrawing groups such as halogens and the nitro group were also examined. Apart from 2-(2′-nitrophenyl)- and 2-(4′-nitrophenyl)-1,3-dithiane (Table 4, entries 16 and 18, 85% *ee*), all these substrates gave very good results. We also investigated the 1,3-dithiane derived from cyclohexanal using **3b** as the chiral ligand. Unlike the aromatic aldehydes, which provided very good results, cyclohexanal gave a poor *ee* under the same reaction conditions (Table 4, entry 19, 89% yield with 35% *ee*).

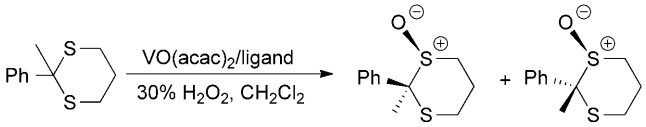
Using 2-methyl-2-phenyl-1,3-dithiane as a substrate the Schiff base ligands **1, 2** and **3** were also screened for the vanadium-catalyzed enantioselective oxidation of 1,3-dithianes that were derived from ketones and the results are listed in Table 5. It was evident that **3b** was still the best chiral ligand for the reaction in CH_2Cl_2 with H_2O_2 as the oxidant, which gave a moderate diastereoselectivity and enantioselectivity (Table 5, entry 8, 74:26 for *cis*:*trans* and 73% *ee* for the *cis* isomers). Much lower *ee*s were obtained for the *trans* sulfoxides. This behavior may be related to a stabilization of the aromatic interactions between the substrate and the active peroxo complex. The *trans* sulfoxides expose the methyl group to the activated peroxo vanadium complex.[24] Additionally, the *cis* isomers are the main products, which is different to other catalyst systems.[18]

Unlike the asymmetric oxidation of the 1,3-dithianes derived from aldehydes, kinetic resolution may coexist under a higher ratio of hydrogen peroxide and this phenomenon was not found during the vanadium-catalyzed enantioselective oxidation of the 1,3-dithianes derived from acetophenone. This was also confirmed by a kinetic resolution experiment using a racemic sulfoxide derived from 2-methyl-2-phenyl-1,3-dithiane.

The enantioselectivity of the vanadium/**3b** complex was also examined with a variety of 1,3-dithianes derived from ketones under the optimized conditions, and the results are summarized in Table 6. Most of the substituted groups on the phenyl group of the aromatic ketones of 1,3-dithiane resulted in higher enantioselectivities. For example, all halogen (including chlorine, bromine and fluorine) substituted 1,3-dithianes gave higher enantioselectivities than the unsubstituted substrate [Table 6, entry 1, 2-(2′-chlorophenyl)-2-methyl-1,3-dithiane, 94% *ee*; entry 2, 2-(3′-chlorophenyl)-2-methyl-1,3-dithiane, 97% *ee*; entry 3, 2-(3′-chlorophenyl)-2-methyl-1,3-dithiane, 75% *ee*; bromine substituted substrates gave similar results]. Similar to the oxidation of 1,3-dithianes derived from aldehydes, electron-donating groups lead to higher *ee*s [Table 6, entries 7–9, 99%, 99% and 97% *ee* for 2-, 3-, and 4-methyl-substituted substrates; entry 10, 85% *ee* for 2-(3-methoxyphenyl)-2-methyl-1,3-dithiane] except for 4-methoxy-substituted dithioketal, which only gave 27% *ee*. On the other hand, 1,3-dithianes containing electron-withdrawing groups such as fluorine and nitro groups also give good to excellent results [Table 6, entry 12, 98% *ee* for 2-(4′-nitrophenyl)-2-methyl-1,3-dithiane; entry 13, 78% *ee* for 2-(4′-fluorophenyl)-2-methyl-1,3-dithiane]. However, the dithioketals derived from other ketones such as 1-(naphthalen-1-yl)ethanone did not give very good results (Table 6, entries 14–16).

In summary, we have developed a highly efficient catalyst system for the enantioselective vanadium-catalyzed oxidation of 1, 3-dithianes derived from aldehydes and ketones. All the substrates were easily converted into the corresponding sulfoxides in high chemical yields and with moderate to excellent enantioselectivities when using 30% aqueous hydrogen

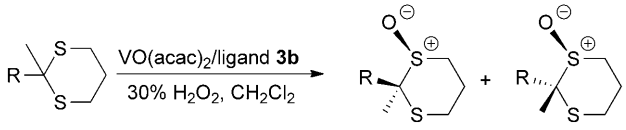
Table 5. Influence of chiral ligands on the enantioselectivity of asymmetric oxidation of 1,3-dithiane derived from acetophenone.[a]



Entry	Ligand	Conversion [%][b]	*dr* (*cis:trans*)[b]	*ee*[d] (yield[e] [%]) *cis*	*trans*
1	**1a**	100	65:35	52 (60)	9 (33)
2	**1b**	100	81:19	12 (78)	1 (16)
3	**1c**	100	68:32	61 (61)	9 (29)
4	**2a**	100	60:40	68 (55)	12 (37)
5	**2b**	82	43:39	39 (38)	8 (36)
6	**2c**	100	58:42	61 (50)	10 (40)
7	**3a**	100	70:30	68 (65)	15 (28)
8	**3b**	100	74:26	73 (70)	27 (23)

[a] All reactions were carried out with 1.1 equiv. 30% H_2O_2 and catalyst (1 mol%) for 16 h at 25 °C.
[b] Determined by ^{1}H NMR spectroscopic analysis.
[c] Determined by HPLC analysis with a chiralcel OD-H column.
[d] The *ee* value for each isomer.
[e] The isolated yield after purification on a silica column.

Table 6. Asymmetric oxidation of various 1,3-dithianes derived from ketones with $VO(acac)_2$/**3b**.[a]



Entry	R	*dr* (*cis:trans*)[b]	*cis* Yield [%][c]	*cis* *ee* [%][d]	*trans* Yield [%][c]	*trans* *ee* [%][d]
1	2-Cl-C_6H_4	72:28	65	94[d]	25	27[e]
2	3-Cl-C_6H_4	83:17	78	97	10	–
3	4-Cl-C_6H_4	82:18	75	75	10	–
4	2-Br-C_6H_4	78:22	71	92	18	23
5	3-Br-C_6H_4	70:30	64	99	27	31
6	4-Br-C_6H_4	66:34	63	74	31	27
7	2-Me-C_6H_4	76:24	73	99	20	7
8	3-Me-C_6H_4	75:25	71	99	21	21
9	4-Me-C_6H_4	75:25	72	97	19	5
10	3-MeO-C_6H_4	60:40	57	85	37	–
11	4-MeO-C_6H_4	62:38	59	27	33	32
12	4-NO_2-C_6H_4	70:30	66	98	19	–
13	4-F-C_6H_4	68:32	61	78	27	29
14	1-naphthyl	51:49	47	65	43	18
15	1-indanone	100:0	93	50	–	–
16	2-phenylethyl	73:27	70	60	22	61

[a] All reactions were carried out with 1.1 equiv. 30% H_2O_2 and catalyst (1 mol%) for 16 h at 25 °C.
[b] Determined by ^{1}H NMR spectroscopic analysis and the conversion is 100%.
[c] Isolated yield after purification on the silica column.
[d] Determined by HPLC analysis with a chiralcel OD-H column.
[e] The optical rotation was tested in acetone, Details are reported in the Supporting Information.

peroxide as the oxidant and a chiral vanadium-Schiff base complex as the catalyst. The easy preparation of the ligands from natural valine and their excellent performance make them good candidates for practical applications. Further studies on the scope of this reaction are underway.

Experimental Section

General Procedure for the Asymmetric Oxidation of 1,3-Dithianes Derived from Aldehydes and Ketones

To a solution of $VO(acac)_2$ (0.01 mmol) in CH_2Cl_2 (2 mL), a chiral ligand (0.015 mmol) was added at room temperature. The mixture was stirred for 10 min and then the sulfide substrate (1 mmol) was added. After the solution was stirred for another 2 min and cooled to 0 °C, 30% H_2O_2 (1.1 equiv.) was slowly added. The mixture was stirred smoothly (200 rpm) at 25 °C for 16 h. After the reaction was complete (monitored by TLC), the organic layer was separated, washed with brine and dried over Na_2SO_4. The solvent was removed under reduced pressure to afford the crude product which was purified by flash column chromatography on silica gel to give the desired product.

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