Mild, Selective Sulfoxidation with Molybdenum(VI) cis-dioxo Catalysts

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Experimental

All NMR and kinetics experiments were performed on a Bruker ARX400 NMR. Elemental analyses were performed by Atlantic Microlab, Inc. Mass spectrometry was performed at the interdepartmental mass spectrometry facility at Purdue University. UV-vis experiments were performed in DMSO with an Agilent Technologies Cary 60 UV-vis instrument, coupled with a Quantum Northwest Temperature control unit, and using a 1 cm quartz cell. IR measurements were taken using a Thermo Nicolet Nexus FT-IR.

Sulfoxidation Procedure
To a 20 mL vial was added Mo(O)\(_2\)L (1 mg, 0.01 equivalents), sulfide (1 equivalent), CDCl\(_3\) (1 mL), and diphenylmethane as an internal NMR standard. To this stirred suspension, tBuOOH (5M, 1 equivalent) was added. The reaction was capped and stirred at room temperature under normal atmosphere for 30 minutes, at which time the reaction solution was analyzed by NMR.

Ligand Synthesis\(^1\)
The appropriate salicylaldehyde (1 eq) and 2-aminoethanethiol (1 eq) were stirred in MeOH (1.3M) for three days at room temperature. The reaction was allowed to sit in the freezer until the precipitate had formed. The product was filtered, washing with cold MeOH, and dried. The product was used without further purification.

Salicylaldehyde (1.4 mL, 13.138 mmol); 2-aminoethanethiol (1.013 g, 13.138 mmol); isolated 2.38 g (64%), including cyclized side product.

5-bromosalicylaldehyde (2.606 g, 12.962 mmol); 2-aminoethanethiol (1.0 g, 12.962 mmol); isolated 1.50 g (44%), including cyclized side product.
3,5-dichlorosalicylaldehyde (2.476 g, 12.962 mmol); 2-aminoethanethiol (1.0 g, 12.962 mmol); isolated 2.75 g (85%), including cyclized side product.

**Synthesis of (cyclohexylmethyl)(phenyl)sulfane**

Small pieces of sodium metal (21 mg, 0.91 mmol) was stirred in ethanol at room temperature to form NaOEt. Once the sodium metal had dissolved, thiophenol was added and allowed to stir 30 minutes at room temperature for full deprotonation. Then, (bomomethyl)cyclohexane (127 μL, 0.91 mmol) was added and the reaction was stirred overnight at room temperature. The reaction was quenched by the addition of water. The crude product was extracted with dichloromethane, and the combined extracts were dried over Na₂SO₄, and concentrated. The crude product was purified via column chromatography to give the target product as a colorless oil (146 mg, 78%). Compound matched literature records.

**Synthesis of 4-(phenylthio)azetidin-2-one**

Thiophenol (334 μL, 3.253 mmol) and 4-acetoxy-2-azetidinone (200 mg, 1.549 mmol) were dissolved in an acetone:water mixture (10 mL, 3:2). To this solution was added NaHCO₃ (521 mg, 6.196 mmol). The reaction was stirred vigorously overnight at room temperature. The product was isolated through sequential recrystallization from dichloromethane/hexane (125 mg, 45%). Compound matched literature records.

**Synthesis of methyl (tert-butoxycarbonyl)-L-methioninate (17)**

L-methionine methyl ester hydrochloride was purchased from Sigma Aldrich and used without further purification.

A biphasic solution of L-methionine methyl ester hydrochloride (0.5 g, 2.504 mmol) and sodium bicarbonate (1.052 g, 12.519 mmol) was prepared in water (5 mL) and EtOAc (12.5 mL). The solution was cooled to 0°C and benzyl chloroformate (391.5 µL, 2.754 mmol) was added dropwise to the stirring reaction. The reaction was stirred at 0°C for 1 hour, then at ambient temperature for 18 hours. The organic layer was isolated, washed with 1M HCl, then washed with water. The organic layer was dried over Na₂SO₄ and concentrated to afford a colorless oil (730 mg, 2.455 mmol, 98%). If desired, this oil can be crystallized from petroleum ether by layering the petroleum ether on the oil and allowing it to sit in the refrigerator for approximately 2 weeks. However, this is unnecessary as the oil is pure by NMR. The ¹H NMR spectrum agreed with the reported literature.
## Crystallographic Information Summary

|                  | 8a                  | 9                  | 10                  |
|------------------|---------------------|--------------------|---------------------|
| formula          | C12H6MoN2O4S        | C12H15BrMoN2O4S    | C12H13Cl2MoN2O4S    |
| MW               | 380.27              | 459.17             | 448.14              |
| crystal system   | triclinic           | triclinic          | triclinic           |
| space group      | -P 1 (No. 2)        | -P 1 (No. 2)       | -P 1 (No. 2)        |
| a (Å)            | 9.2142(5)           | 6.6747(7)          | 6.6342(2)           |
| b (Å)            | 9.4436(5)           | 10.323(2)          | 10.2260(3)          |
| c (Å)            | 9.6497(6)           | 12.4535(12)        | 13.0152(4)          |
| α (deg)          | 71.315(4)           | 71.815(12)         | 104.8790(10)        |
| β (deg)          | 71.902(3)           | 75.447(6)          | 103.6770(10)        |
| γ (deg)          | 72.655(4)           | 85.030(10)         | 95.779(2)           |
| V (Å³)           | 737.44(8)           | 789.1(2)           | 816.90(4)           |
| T (K)            | 295                 | 150                | 150                 |
| λ (Å)            | 0.71073             | 1.54178            | 0.71073             |
| ρ (g cm⁻³)       | 1.713               | 1.933              | 1.822               |
| μ (mm⁻¹)         | 1.044               | 11.158             | 1.822               |
| transm coeff     | 0.111- 0.829        | 0.017- 0.410       | 0.063- 0.700        |
| R (Fo a)         | 0.024               | 0.042              | 0.026               |
| Rw (Fo2 b)       | 0.0845              | 0.1354             | 0.0747              |

\[ R = \frac{\sum ||F_0|| - ||F_e||}{\sum ||F_0||} \text{ for } F_0 > 2\sigma(F_0^2) \]
\[ R_w = \left[ \frac{\sum w(||F_0|| - ||F_e||)^2}{\sum w||F_0||^2} \right]^{1/2} \]
NMR spectra

**Figure S1. cis-Mo^{VI} (O)_{2}(H_{2} sal-eta) (8) in DMSO-d6**

KC-01-114.1.fid — H1 standard parameters, CDC3, QNP probe.
Figure S2. cis-Mo\textsuperscript{VI} (O\textsubscript{2})(\textsubscript{H\textsubscript{2}}sal-eta-\textit{p}-Br) (9) in DMSO-d\textsubscript{6}
Figure S3. *cis*-MoVI (O)₂(H₂sal-eta-o,p-Cl) (10) in DMSO-d6

KC-01-200/rspc.1.1d — H1 standard parameters, CDCl₃, QNP probe.
Figure S4. Sample experimental crude reaction NMR

\[ \text{Mo(O)}_2(\text{H}_2\text{sal-eta}) (1 \text{ mol\%}) \]
\[ \text{r-BuOOH, CDCl}_3, \text{ RT, 30 min} \]

Diphenylmethane internal standard

KC-01-257.1.fid
H1 standard parameters, CDCl3, QNP probe.
**Figure S5.** methyl (2S)-2-((tert-butoxycarbonyl)amino)-4-(methylsulfinyl)butanoate (17)

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