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Synthesis of new chiral terpyridine mono-*N*-oxide and di-*N*-oxide ligands and their applications in copper-catalyzed asymmetric cyclopropanation

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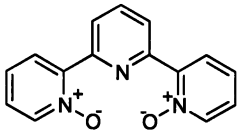
Abstract—New families of chiral terpyridine mono-*N*-oxides $\mathbf{L_1}$–$\mathbf{L_3}$ and di-*N*-oxides $\mathbf{L_4}$–$\mathbf{L_6}$, were synthesized in moderate to good yields by simple oxidation of their corresponding terpyridines with *m*-CPBA. The copper(II) triflate complexes of these ligands were found to be highly effective catalysts for asymmetric cyclopropanation of styrene with ethyl diazoacetate. The isolated yields of cyclopropane were excellent and the enantiomeric excesses of up to 83% were observed. Competition experiments with substituted styrenes showed good σ^+ correlations with $\rho = -0.70$ for mono-*N*-oxide $\mathbf{L_3}$ and $\rho = -0.69$ for di-*N*-oxide $\mathbf{L_6}$.

1. Introduction

Aromatic amine *N*-oxides[1] are known to be good ligands for transition metals and lanthanides[2–4] and as such, they have been used extensively in catalysis. Pyridine *N*-oxides, for examples, have been used as terminal oxidants for alkene epoxidation[5–7] and hydroxylation[8] and served as additives for rate enhancement in metal-catalyzed processes.[9–14] Useful applications of chiral pyridine *N*-oxides in asymmetric catalysis have also started to appear in the past few years. Among the most salient examples, Nakajima and co-workers reported the use of biquinoline *N*,*N*′-dioxides as catalytic ligands for asymmetric allylation of aldehydes[15] and conjugate additions of thiols;[16,17] Fu et al. demonstrated the utilization of planar-chiral pyridine *N*-oxides for desymmetrization of *meso*-epoxides[18] and Denmark's and Kočovsky's groups independently revealed the application of chiral bipyridine *N*-oxides in enantioselective Aldol additions to ketones[19] and allylation of aldehydes, respectively.[20]

Polydentate ligands containing the *N*-oxide moiety have been of great interest because of their coordination properties.[21–24] 2,2′:6′,2″-Terpyridine di-*N*-oxide **1** is one such multidentate ligand that can be prepared from terpyridine.[25] Recently, Nagata and co-workers employed this ligand for the study of its coordination chemistry with transition metals.[26]



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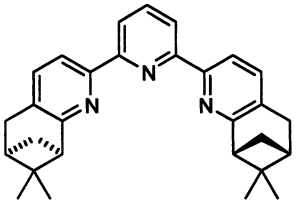
In our previous studies, we have developed a new class of chiral C_2-symmetric terpyridines, **2**–**4**, for copper-



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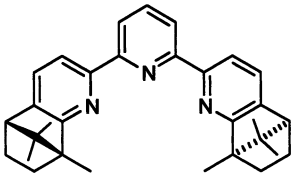

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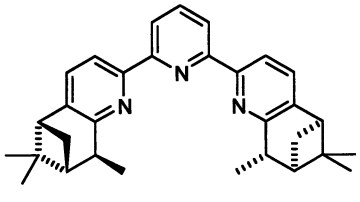

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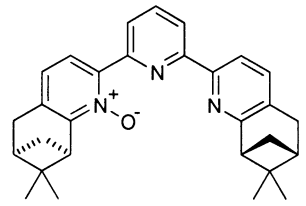
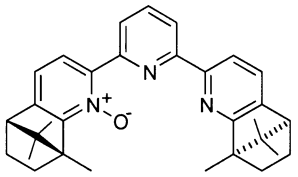
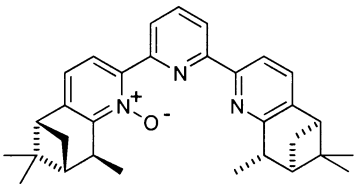


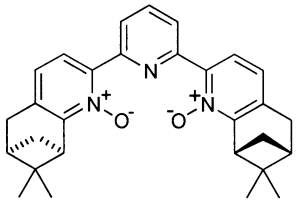
L_1



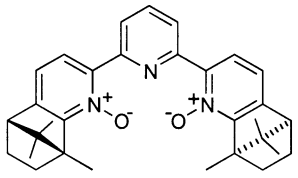
L_2



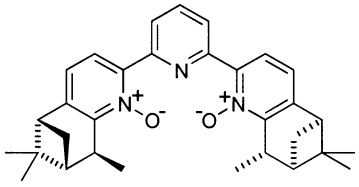
L_3



L_4



L_5



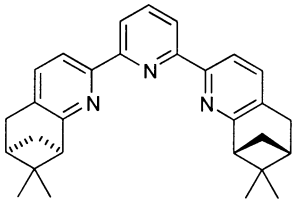
L_6

catalyzed asymmetric cyclopropanation.[27,28] These ligands can also be converted to the corresponding *N*-oxides by simple oxidation reaction. Herein, we describe the preparation of new chiral terpyridine mono- and di-*N*-oxide derivatives $\mathbf{L_1}$–$\mathbf{L_6}$ from terpyridines **2**–**4**. The use of these ligands in copper-catalyzed asymmetric cyclopropanation of styrene with ethyl diazoacetate was demonstrated.

2. Results and discussion

Syntheses of pyridine mono- and di-*N*-oxides through *N*-oxidation were reported previously by Thummel and co-workers.[25] With this simple procedure, terpyridine *N*-oxides can be synthesized using *m*-chloroperbenzoic acid (*m*-CPBA) as oxidizing agent. It was found that the formation of mono- and di-*N*-oxides can be controlled by using a suitable ratio of the oxidant and terpyridine, with an optimum reaction time.

In the first attempt, terpyridine mono-*N*-oxides $\mathbf{L_1}$–$\mathbf{L_3}$ were prepared by stirring terpyridines **2**–**4** with 1 equiv. of *m*-CPBA at room temperature for 8 h in dichloromethane. Surprisingly, less than 5% of the desired product was obtained using this procedure. In order to obtain better yields, the procedure was modified by increasing the amount of *m*-CPBA (1.3–2 equiv.) and reacting for 2–8 h (Scheme 1). If the reaction ran for over 8 h it led to serious oxidation of



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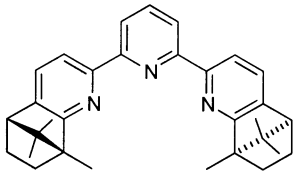

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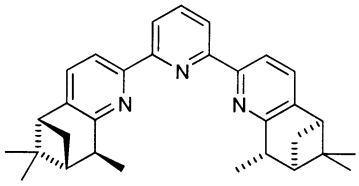
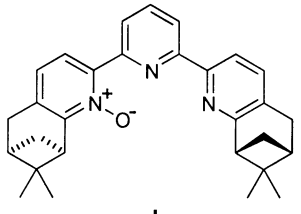


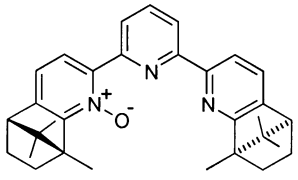
4

1.3-2 equivalents *m*-CPBA

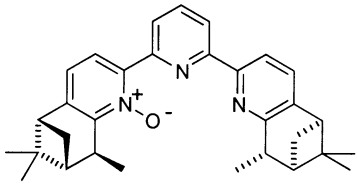
2-8 h, CH_2Cl_2, N_2



L_1



L_2



L_3

Scheme 1.

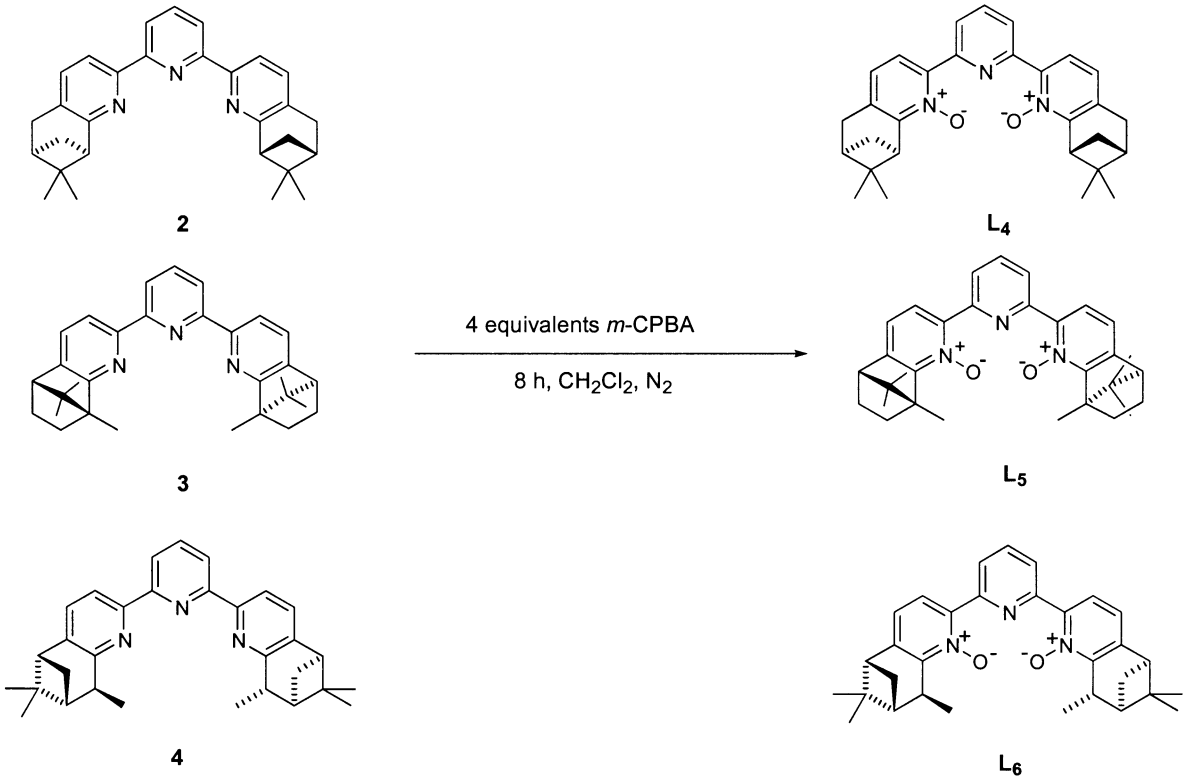
the mono-*N*-oxides to di-*N*-oxides. However, small amounts of starting terpyridines and di-*N*-oxides were still found in most of these reactions. After flash column chromatography, terpyridine *N*-oxides $\mathbf{L_1}$–$\mathbf{L_3}$ were obtained in moderate yields between 30 and 50%. Terpyridine di-*N*-oxides $\mathbf{L_4}$–$\mathbf{L_6}$ were prepared by stirring terpyridines **2**–**4** with excess *m*-CPBA (4 equiv.) at room temperature for 8 h in dichloromethane (Scheme 2). After work-up and recrystallization from diethyl ether, high purity products with isolated yields of 64–70% were obtained.

The isolated *N*-oxides $\mathbf{L_1}$–$\mathbf{L_6}$ were characterized by ^{1}H NMR analysis. Terpyridine mono- and di-*N*-oxides can be easily distinguished by the symmetry of their ^{1}H NMR spectra. By taking $\mathbf{L_3}$ and $\mathbf{L_6}$ as models for mono- and di-*N*-oxides, respectively, the seven protons of the terpyridine ring of $\mathbf{L_3}$ clearly show six sets of doublet signals at δ 7.00, 7.31, 8.07, 8.18, 8.49, 8.86 and one triplet at δ 7.91, while for $\mathbf{L_6}$, the seven protons of the terpyridine ring only show as three doublets at δ 6.98, 7.84, 8.72 and one triplet at δ 7.92 because of the molecular symmetry. Comparing the ^{1}H NMR of terpyridines[27] with the corresponding di-*N*-oxides, we found that their patterns are very similar and the only difference is the chemical shift of some of the aromatic protons.

The copper(II) chloride complexes of terpyridine *N*-oxides were prepared in good yields by reaction of the appropriate *N*-oxides with $CuCl_2$. However, because of difficulties in preparing some of these ligands in greater amounts, copper complexes $Cu(\mathbf{L_3})Cl_2$ and $Cu(\mathbf{L_6})Cl_2$ were the only two complexes that were chosen for detailed study. Elemental analysis indicated that these compounds are 1:1 ligand to copper complexes with two chloride ions. These green coloured complexes can be used directly as catalysts in cyclopropanation of styrene with diazoacetate but no enantioselectivity was observed with them.

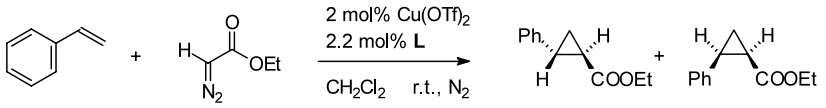
In contrast, when the complexes were generated in situ by stirring 2 mol% of $Cu(OTf)_2$ and 2.2 mol% of **L** in CH_2Cl_2 and stirring with 4 equiv. of ethyl diazoacetate for 30 minutes at 40°C, the catalysts induced some enantioselectivity. The experimental results are summarized in Table 1 and the results of **2**–**4** from our previous study are also included for comparison.[28] The yields of the isolated cyclopropane esters were excellent, ranging from 82 to 90% for terpyridine mono-*N*-oxides (entries 1–3) to 90–97% (entries 4–6) for the terpyridine di-*N*-oxides. Enantioselectivities of between 23 and 83% were obtained.

Of the terpyridine *N*-oxides, mono-*N*-oxide $\mathbf{L_3}$ gave the best result with 73% ee for *trans*-isomer and 83% ee for *cis*-isomer (entry 3). The *trans*/*cis* ratio of the cyclopropanes was determined by GC analysis of the reaction mixture. The isomer ratio was found between 66:34 to 76:24, favoring the *trans*-isomer over the *cis*-isomer. The absolute configurations of cyclopropane esters formed from styrene were found to be (1*R*,2*R*) for the *trans*-isomer and (1*R*,2*S*) for the *cis*-isomer. With respect to the absolute configuration of the products, the sense of asymmetric induction by these ligands was the same as those observed with the corresponding terpyridine ligands.[27,28]



Scheme 2.

Table 1. Asymmetric cyclopropanation of styrene with copper(II)-terpyridine mono-*N*-oxide and di-*N*-oxide complexes



Entry[a]	Ligand **L**	Yield (%)[b]	*trans*/*cis*	% ee (config.)[c]	
				trans	*cis*
1	$\mathbf{L_1}$	85	75:25	24 (1*S*,2*S*)	24 (1*S*,2*R*)
2	$\mathbf{L_2}$	82	76:24	31 (1*R*,2*R*)	27 (1*R*,2*S*)
3	$\mathbf{L_3}$	90	66:34	73 (1*R*,2*R*)	83 (1*R*,2*S*)
4	$\mathbf{L_4}$	92	74:26	20 (1*S*,2*S*)	20 (1*S*,2*R*)
5	$\mathbf{L_5}$	97	76:24	25 (1*R*,2*R*)	23 (1*R*,2*S*)
6	$\mathbf{L_6}$	90	70:30	31 (1*R*,2*R*)	43 (1*R*,2*S*)
7[d]	**2**	84	75:25	26 (1*S*,2*S*)	26 (1*S*,2*R*)
8[d]	**3**	88	76:24	32 (1*R*,2*R*)	30 (1*R*,2*S*)
9[d]	**4**	81	67:33	72 (1*R*,2*R*)	82 (1*R*,2*S*)

[a] Diazoacetate (0.2 equiv.) was used for the reduction of the Cu(II) catalysts before the start of the cyclopropanation reaction.
[b] Isolated yield after column chromatography.
[c] Enantiomeric excesses were determined by HPLC using a Daicel Chiralcel OJ column, and the absolute configurations were determined by comparing the order of elution with those of samples with known[29] configuration.
[d] Results obtained from Ref. 28.

If one compares ligands having the same chiral group, the terpyridine mono-*N*-oxide or di-*N*-oxide from **4** gave the best results, while those from **2** gave the worst results. Another interesting point to notice is that terpyridine mono-*N*-oxides always give better enantiomeric excess than that of their corresponding terpyridine di-*N*-oxides. Besides, all terpyridine mono-*N*-oxides gave similar diastereoselectivity and enantioselectivity when compared to the corresponding parent terpyridine ligands while terpyridine di-*N*-oxides gave very different and inferior enantioselectivity.

In order to obtain more information about the nature of the intermediates involved in the reaction, competition experiments using $\mathbf{L_3}$ and $\mathbf{L_6}$ as ligands in the cyclopropanation of four substituted styrenes were carried out. With ethyl diazoacetate (EDA), the rates of cyclopropanation of the substituted styrenes relative to that of styrene were measured by GC analysis. The plot of $\log(k_X/k_H)$ values versus Hammett constants σ^+ are shown in Figs. 1 and 2 for the mono-*N*-oxide $\mathbf{L_3}$ and the di-*N*-oxide $\mathbf{L_6}$, respectively. As expected, in both cases, electron-donating groups led to higher reaction rate, while an electron-withdrawing group resulted in lowered reaction rate. Good σ^+ correlations were obtained with $\rho = -0.70$ for mono-*N*-oxide $\mathbf{L_3}$ and $\rho = -0.69$ for di-*N*-oxide $\mathbf{L_6}$. The value for the chiral terpyridine ligand **4** was found to be $\rho = -0.76$ under the same reaction condition.[28] These small negative values of ρ indicated the formation of electrophilic metal–carbene complex intermediate and also a moderate positive charge built-up at the benzylic carbon in the transition state during the reaction. The different ρ values of $\mathbf{L_3}$ and **4**, however, suggests that even though the enantioselectivities of these two ligands are similar, the

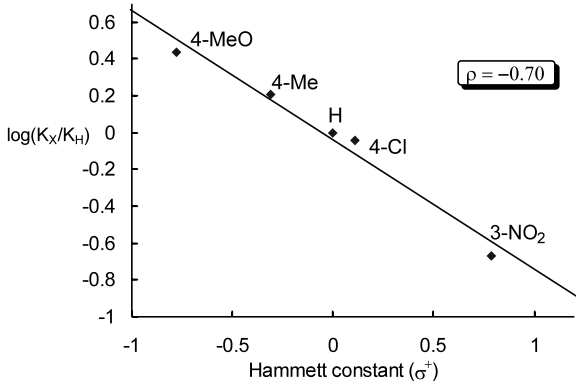


Figure 1. Hammett plot for the cyclopropanation of substituted styrenes with EDA using $Cu(\mathbf{L_3})(OTf)_2$ complex as catalyst.

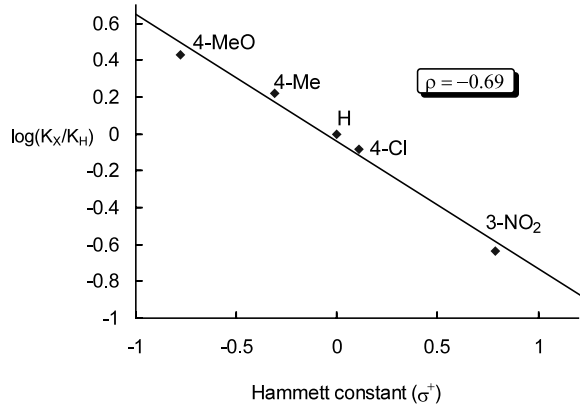


Figure 2. Hammett plot for the cyclopropanation of substituted styrenes with EDA using $Cu(\mathbf{L_6})(OTf)_2$ complex as catalyst.

active species are quite different during reaction. This result also rules out the possibility that $\mathbf{L_3}$ ligand is reduced to **4** during reaction.

Further investigation is necessary to find out the active species in these reactions. However, with the results from absolute configuration, enantioselectivity and the ρ values of the Hammett study, we would like to propose that terpyridine mono-*N*-oxide and terpyridine di-*N*-oxide are bidentate *N*,*O*-coordinating ligands in this catalytic system, while the parent terpyridine, instead of acting as a tridentate *N*,*N*,*N*-coordinating ligand, [27,28] is a bidentate *N*,*N*-coordinating ligand in the active species for the cyclopropanation.

In these proposed models, three coordinated copper intermediates are involved, with ligands providing two of the coordinating atoms and the carbene providing the third atom (Scheme 3). The rectangular plane shown in Scheme 3 contains a copper, a carbene carbon and the two substituents of the carbene. The alkenes approach to the top face, (but not the bottom face), of the plane to provide the correct absolute configuration of the products. This model of approach is in agreement with the one previously cited by Pflatz for other *N*,*N*-bidentate ligands.[29]

These models explain the absolute configurations and the similar enantioselectivities obtained with $\mathbf{L_3}$ and **4** as the different coordinations between $\mathbf{L_3}$ and **4** do not lead to a great change in the steric environment where the carbene moves (backward away from the rectangular plane) during carbene transfer. This is in sharp contrast to the reactions of $\mathbf{L_6}$ as the non-coordinated *N*-oxide may force the entire pyridine group to move away from the metal carbene thus giving a sterically very different environment. Besides, as both *N*-oxide and di-*N*-oxide are *N*,*O*-coordinating in the model, it also explains nicely why $\mathbf{L_3}$ and $\mathbf{L_6}$ gave very similar ρ values (−0.7 versus −0.69) in the Hammett competition study when compared to each other but different ρ values when compared to **4** (−0.76), which is *N*,*N*-coordinating in the model.

3. Conclusion

In summary, new families of chiral terpyridine mono-*N*-oxide and di-*N*-oxide ligands $\mathbf{L_1}$–$\mathbf{L_6}$ were successfully synthesized by simple oxidation reactions. These ligands are good for copper-catalyzed asymmetric cyclopropanation. Enantiomeric excess up to 83% and yield up to 97% were achieved. Work is in progress to study the mechanism of the reactions and extend the application of these ligands in other catalytic asymmetric reactions.

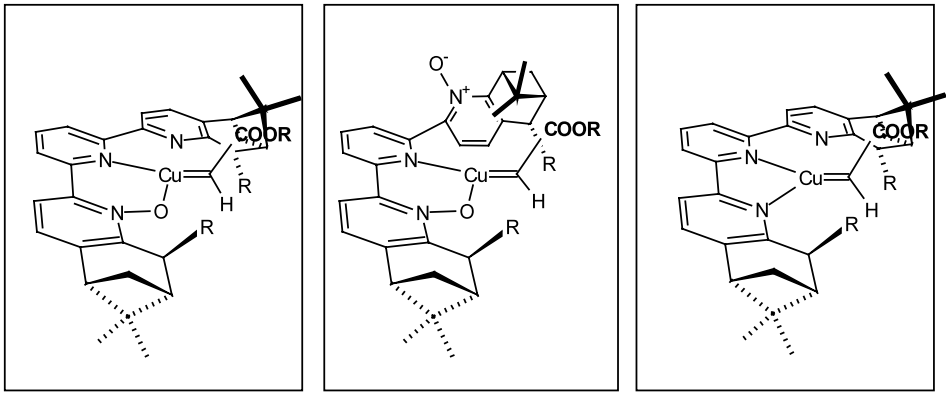
4. Experimental

4.1. General

Chemicals were of reagent-grade quality were obtained commercially. Terpyridines **2**–**4** were prepared according to the literature.[27,28] IR spectra (KBr plates) in the range 500–4000 cm^{-1} were recorded on a Perkin–Elmer model 1600 FTIR spectrometer. ^1H and ^{13}C NMR spectra were recorded on a Varian 300 MHz Mercury instrument. Elemental analyses were performed on a Vario EL elemental analyzer. ESMS were recorded using a PE SCIEX API 365 mass spectrometer. Optical rotations were measured using a JASCO DIP-370 digital polarimeter. Melting points were measured using an electrothermal digital melting point apparatus.

4.2. Chiral terpyridine mono-*N*-oxide $\mathbf{L_1}$

To a solution of chiral terpyridine **2** (0.21 g, 0.5 mmol) in dry CH_2Cl_2 (3 mL), a solution of *m*-chloroperbenzoic acid (0.31 g, 1 mmol) in dry CH_2Cl_2 (3 mL) was added slowly. The resulting solution was then stirred for 2 h. The reaction was quenched with saturated $NaHCO_3$ solution and diluted with dichloromethane (10 mL). The resulting solution was washed with saturated $NaHCO_3$ solution (2×20 mL), and then with water (20 mL). The organic layer was then collected and dried over anhydrous magnesium sulfate. After removal of solvent, the crude product was purified by



Cu-$\mathbf{L_3}$ carbene Cu-$\mathbf{L_6}$ carbene Cu-**4** carbene

Scheme 3. Proposed models in copper-catalyzed cyclopropanation using $\mathbf{L_3}$, $\mathbf{L_6}$ and **4**.

flash chromatography, eluting with diethyl ether and followed by Et_2O:methanol (25:1), to obtain chiral terpyridine mono-*N*-oxide **L_1** (0.066 g, 30% yield). Mp = 194.8–196.2°C; $[\alpha]_D^{25} = -29.6$ (*c* 0.45, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.72 (s, 3H), 0.78 (s, 3H), 1.33 (d, 2H, $J = 5.1$ Hz), 1.46 (s, 3H), 1.49 (s, 3H), 2.33–2.38 (m, 2H), 2.73–2.83 (m, 2H), 3.00 (d, 2H, $J = 2.4$ Hz), 3.04 (d, 2H, $J = 2.4$ Hz), 3.12 (t, 1H, $J = 5.4$ Hz), 4.16 (t, 1H, $J = 5.4$ Hz), 7.20 (d, 1H, $J = 7.8$ Hz), 7.55 (d, 1H, $J = 7.5$ Hz), 7.89 (t, 1H, $J = 7.5$ Hz), 8.11 (d, 1H, $J = 7.8$ Hz), 8.26 (d, 1H, $J = 7.8$ Hz), 8.41 (d, 1H, $J = 7.8$ Hz), 8.87 (d, 1H, $J = 7.8$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 21.3, 21.4, 25.8, 26.1, 30.3, 30.4, 30.9, 31.3, 31.6, 39.1, 39.2, 39.9, 40.2, 40.3, 118.8, 120.9, 124.7, 125.0, 125.4, 130.6, 133.2, 135.9, 136.8, 145.1, 149.8, 152.0, 156.0, 156.3, 165.8; IR (KBr): 2922, 1558, 1429 cm^{-1}. Anal calcd for $C_{29}H_{31}N_3O\cdot(CH_3CH_2)_2O$: C, 77.46; H, 8.08; N, 8.21. Found: C, 77.11; H, 7.85; N, 8.03%. Positive ion MS (API) *m*/*z*: 438 (M^++H).

4.3. Chiral terpyridine mono-*N*-oxide L_2

To a solution of chiral terpyridine **3** (0.225 g, 0.5 mmol) in dry CH_2Cl_2 (3 mL), a solution of *m*-chloroperbenzoic acid (0.236 g, 0.75 mmol) in dry CH_2Cl_2 (3 mL) was added slowly. The resulting solution was then stirred for 8 h. The reaction was quenched with saturated $NaHCO_3$ solution and diluted with dichloromethane (10 mL). The resulting solution was washed with saturated $NaHCO_3$ solution (2×20 mL), and then with water (20 mL). The organic layer was then collected and dried over anhydrous magnesium sulfate. After removal of solvent, the crude product was purified by flash chromatography, eluting with petroleum ether–ethyl acetate (10:1) and followed by dichloromethane–ethyl acetate (4:1), to obtain chiral terpyridine mono-*N*-oxide **L_2** (0.093 g, 40% yield). Mp = 193.5–197.8°C; $[\alpha]_D^{25} = -50.4$ (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.60 (s, 3H), 0.79 (s, 3H), 0.98 (s, 3H), 1.02 (s, 3H), 1.12–1.34 (m, 4H), 1.40 (s, 3H), 1.72 (s, 3H), 1.86–1.97 (m, 2H), 2.11–2.22 (m, 2H), 2.89 (d, 1H, $J = 4.2$ Hz), 2.91 (d, 1H, $J = 4.2$ Hz), 7.19 (d, 1H, $J = 7.8$ Hz), 7.47 (d, 1H, $J = 7.8$ Hz), 7.89 (t, 1H, $J = 7.8$ Hz), 8.07 (d, 1H, $J = 7.2$ Hz), 8.18 (d, 1H, $J = 7.5$ Hz), 8.48 (d, 1H, $J = 7.8$ Hz), 8.80 (d, 1H, $J = 7.8$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 10.3, 12.8, 18.8, 19.3, 20.1, 20.4, 26.1, 26.3, 31.2, 31.8, 51.6, 52.0, 54.2, 55.7, 56.7, 57.2, 118.3, 119.7, 120.7, 124.8, 125.8, 128.5, 136.8, 141.7, 146.0, 146.4, 149.6, 152.3, 154.7, 156.4, 169.9; IR (KBr): 2960, 1557, 434 cm^{-1}. Anal calcd for $C_{31}H_{35}N_3O\cdot CH_3OH$: C, 77.22; H, 7.89; N, 8.44. Found: C, 77.72; H, 7.73; N, 8.35%. Positive ion MS (API) *m*/*z*: 466 (M^++H).

4.4. Chiral terpyridine mono-*N*-oxide L_3

To a solution of chiral terpyridine **4** (0.225 g, 0.5 mmol) in dry CH_2Cl_2 (3 mL), a solution of *m*-chloroperbenzoic acid (0.205 g, 0.65 mmol) in dry CH_2Cl_2 (3 mL) was added slowly. The resulting solution was then stirred for 8 h. The reaction was quenched with saturated $NaHCO_3$ solution and diluted with dichloromethane (10 mL). The resulting solution was washed with saturated $NaHCO_3$ solution (2×20 mL) and then with water (20 mL). The organic layer was then collected and dried over anhydrous magnesium sulfate. After removal of solvent, the crude product was purified by flash chromatography with diethyl ether–petroleum ether (1:1), to obtain chiral terpyridine mono-*N*-oxide **L_3** (0.116 g, 50% yield). Mp = 164.6–168.3°C; $[\alpha]_D^{25} = -17.8$ (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.68 (s, 6H), 1.34 (d, 2H, $J = 9.9$ Hz), 1.43 (s, 6H), 1.48 (d, 3H, $J = 7.2$ Hz), 1.54 (d, 3H, $J = 6.6$ Hz), 2.16–2.22 (m, 2H), 2.53–2.61 (m, 2H), 2.79–2.84 (m, 2H), 3.26–3.29 (m, 1H), 3.44–3.51 (m, 1H), 7.00 (d, 1H, $J = 7.8$ Hz), 7.31 (d, 1H, $J = 8.1$ Hz), 7.91 (t, 1H, $J = 8.1$ Hz), 8.07 (d, 1H, $J = 8.1$ Hz), 8.18 (d, 1H, $J = 7.5$ Hz), 8.49 (d, 1H, $J = 7.8$ Hz), 8.86 (d, 1H, $J = 8.1$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 14.9, 18.3, 20.6, 21.0, 26.0, 26.4, 28.3, 28.6, 35.0, 38.9, 41.5, 41.6, 46.9, 47.1, 47.3, 47.6, 117.8, 120.7, 123.1, 124.8, 125.1, 133.5, 136.9, 142.3, 145.2, 146.1, 149.7, 150.3, 156.0, 160.2; IR (KBr): 2910, 1568, 1437 cm^{-1}. Anal calcd for $C_{31}H_{35}N_3O\cdot(CH_3CH_2)_2O$: C, 77.88; H, 8.40; N, 7.78. Found: C, 77.46; H, 8.03; N, 7.75%. Positive ion MS (API) *m*/*z*: 466 (M^++H).

4.5. General procedure for the preparation of chiral terpyridine di-*N*-oxide ligands

To a stirred solution of *m*-chloroperbenzoic acid (4.0 mmol) in dichloromethane (6 mL), the chiral terpyridine ligand (1.0 mmol) was added. The yellow solution was then stirred under nitrogen atmosphere at room temperature for 8 h. The reaction was quenched with saturated $NaHCO_3$ solution and diluted with dichloromethane (50 mL). The resulting solution was washed with saturated $NaHCO_3$ solution (2×50 mL) and then with water (50 mL). The organic layer was then collected and dried over anhydrous magnesium sulfate. After removal of solvent, the crude chiral terpyridine di-*N*-oxide product was purified by recrystallizing from diethyl ether.

4.5.1. Chiral terpyridine di-*N*-oxide L_4. The general procedure described above was followed, using chiral terpyridine **2** (0.421 g, 1 mmol) and *m*-chloroperbenzoic acid (1.26 g, 4.0 mmol) to afford pure chiral terpyridine di-*N*-oxide **L_4**. (0.317 g, 70% yield). Mp = 227.6–229.4°C; $[\alpha]_D^{25} = -1089.9$ (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.78 (s, 6H), 1.31 (d, 2H, $J = 9.9$ Hz), 1.49 (s, 6H), 2.33–2.37 (m, 2H), 2.75–2.83 (m, 2H), 3.03 (d, 4H, $J = 2.4$ Hz), 4.15 (t, 2H, $J = 5.7$ Hz), 7.17 (d, 2H, $J = 8.4$ Hz), 7.89 (d, 2H, $J = 8.1$ Hz), 7.90 (t, 1H, $J = 8.1$ Hz), 8.77 (d, 2H, $J = 8.1$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 21.4, 25.8, 30.3, 31.6, 39.1, 39.8, 40.3, 124.6, 125.5, 125.6, 133.3, 135.8, 144.8, 150.3, 156.3; IR (KBr): 2908, 1558, 1439 cm^{-1}. Anal calcd for $C_{29}H_{31}N_3O_2\cdot(CH_3CH_2)_2O$: C, 75.11; H, 7.83; N, 7.96. Found: C, 74.48; H, 7.51; N, 7.60%. Positive ion MS (API) *m*/*z*: 454 (M^++H).

4.5.2. Chiral terpyridine di-*N*-oxide L_5. The general procedure described above was followed, using chiral terpyridine **3** (0.449 g, 1 mmol) and *m*-chloroperbenzoic acid (1.26 g, 4.0 mmol) to afford pure chiral terpyridine di-*N*-oxide L_5 (0.308 g, 64% yield). Mp = 254.6–257.4°C; $[\alpha]_D^{25} = -214.2$ (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.78 (s, 6H), 0.98 (s, 6H), 1.14–1.36 (m, 4H), 1.70 (s, 6H), 1.88–1.97 (m, 2H), 2.11–2.21 (m, 2H), 2.90 (d, 2H, $J = 3.3$ Hz), 7.13 (d, 2H, $J = 7.5$ Hz), 7.77 (d, 2H, $J = 7.5$ Hz), 7.85 (t, 1H, $J = 8.1$ Hz), 8.62 (d, 2H, $J = 8.1$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 12.9, 18.9, 20.5, 26.4, 31.4, 52.2, 55.9, 57.5, 119.9, 125.7, 126.0, 135.6, 146.4, 146.6, 150.6, 154.8; IR (KBr): 2950, 1557, 1434 cm^{-1}. Anal calcd for $C_{31}H_{35}N_3O_2 \cdot H_2O$: C, 74.52; H, 7.46; N, 8.41. Found: C, 75.34; H, 7.24; N, 8.77%. Positive ion MS (API) *m*/*z*: 482 (M^++H).

4.5.3. Chiral terpyridine di-*N*-oxide L_6. The general procedure described above was followed, using chiral terpyridine **4** (0.421 g, 1 mmol) and *m*-chloroperbenzoic acid (1.26 g, 4.0 mmol) to afford pure chiral terpyridine di-*N*-oxide L_6 (0.312 g, 65% yield). Mp = 155.3–158.9°C; $[\alpha]_D^{25} = -74.7$ (*c* 0.3, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ 0.69 (s, 6H), 1.44 (s, 6H), 1.47 (d, 2H, $J = 6.6$ Hz), 1.54 (d, 6H, $J = 6.6$ Hz), 2.19–2.24 (m, 2H), 2.55–2.63 (m, 2H), 2.83 (t, 2H, $J = 5.7$ Hz), 3.45 (m, 2H), 6.98 (d, 2H, $J = 7.8$ Hz), 7.84 (d, 2H, $J = 8.1$ Hz), 7.92 (t, 1H, $J = 8.1$ Hz), 8.72 (d, 2H, $J = 7.8$ Hz); ^{13}C NMR (300 MHz, $CDCl_3$): δ 14.9, 20.7, 25.9, 28.3, 35.0, 41.7, 47.1, 47.6, 123.4, 125.1, 125.6, 135.9, 137.4, 145.4, 146.1, 150.4; IR (KBr): 2932, 1564, 1440 cm^{-1}. Anal calcd for $C_{31}H_{35}N_3O_2 \cdot (CH_3OH)$: C, 74.82; H, 7.65; N, 8.18. Found: C, 74.31; H, 7.33; N, 8.33%. Positive ion MS (API) *m*/*z*: 482 (M^++H).

4.6. General procedure for copper-catalyzed cyclopropanation

To a two-necked round-bottomed flask were added $Cu(OTf)_2$ (0.0072 g, 0.02 mmol), CH_2Cl_2 (2 mL) and the chiral terpyridine *N*-oxide ligand **L** (0.022 mmol) under nitrogen. The solution was stirred at room temperature for 2 h. Styrene (0.417 g, 4 mmol) and followed with ethyl diazoacetate (0.2 mmol) were added and the mixture was heated with stirring at 40°C for 0.5 h. After cooling to room temperature, a solution of ethyl diazoacetate (1 mmol) in CH_2Cl_2 (0.5 mL) was added to the reaction mixture over a period of 4 h using a syringe pump. After the addition of ethyl diazoacetate, the mixture was allowed to stir for 16 h at room temperature. The solvent was removed and the crude product obtained was purified by column chromatography (hexane/EtOAc). All the cyclopropanes obtained are known compounds and were characterized by ^1H and ^{13}C NMR, IR, and GC–MS. The enantiomeric excesses of the cyclopropanes were determined by HPLC using a Daicel Chiralcel OJ column. The absolute configurations were determined by comparing with the order of elution of samples with known configuration.[29] Diastereoselectivities (*cis*/*trans* ratio) were measured by GC with Ultra 2-crosslinked 5% PhMesilcone (25 m×0.2 mm×0.33 μm) column.

4.7. General procedure for competition reactions for copper catalysts

To a two-necked round-bottomed flask were added $Cu(OTf)_2$ (0.0036 g, 0.01 mmol), CH_2Cl_2 (1 mL) and terpyridine mono-*N*-oxide L_3 or di-*N*-oxide L_6 (0.011 mmol) under nitrogen. The solution was stirred at room temperature for 2 h. Styrene (1 mmol) and substituted styrene (1 mmol) were added to the stirred solution. Ethyl diazoacetate (0.5 mmol) in CH_2Cl_2 (0.5 mL) was added to the reaction mixture in one portion. The mixture was allowed to stir at room temperature for 16 h. The ratios of resulting cyclopropanes were determined by GC.

4.8. General procedure for preparation of copper(II) terpyridine di-*N*-oxide complexes [Cu(L)Cl$_2$]

Terpyridine *N*-oxide **L** (0.2 mmol) in dichloromethane (2 mL) was added to a solution of $CuCl_2 \cdot 2H_2O$ (0.034 g, 0.2 mmol) in ethanol (5 mL). The solution was heated under reflux overnight to ensure complete complexation. The solution was then cooled and diethyl ether was added until precipitate was formed. The product was isolated by filtration and washed with diethyl ether. The complexes were characterized by IR, UV, CHN and MS analyses.

Cu(L_3)Cl$_2$. The above procedure was followed using L_3 to give Cu(L_3)Cl_2 (0.11 g, 95%). IR (KBr): 2924.6, 1593.2, 1470.3 cm^{-1}. Visible spectrum (CH_2Cl_2), λ_{max} (ε): 262 (33000), 335 (22000), 472 (254), 866 nm (163). Anal. calcd for $C_{31}H_{35}Cl_2CuN_3O \cdot 4H_2O$: C, 55.39; H, 6.45; N, 6.25. Found: C, 56.19; H, 6.24; N, 6.05%. Positive ion MS (API) *m*/*z*: 563 (M^+–Cl).

Cu(L_6)Cl$_2$. The above procedure was followed using L_6 to give Cu(L_6)Cl_2 (0.11 g, 90%). IR (KBr): 2929.7, 1588.1, 1449.8. Visible spectrum (CH_2Cl_2), λ_{max} (ε): 259 (35000), 317 (20000), 384 (3000), 471 (320), 884 nm (210). Anal. calcd for $C_{31}H_{35}Cl_2CuN_3O_2 \cdot 4H_2O$: C, 54.10; H, 6.30; N, 6.11. Found: C, 53.36; H, 6.04; N, 6.01%. Positive ion MS (API) *m*/*z*: 579 (M^+–Cl).

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