

Enantioselective Diels–Alder Reaction Promoted by Achiral Functionalization of a SiO₂-supported Cu–BOX [Bis(oxazoline)] Catalyst

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We have found that surface chemical functionalization of a SiO₂-supported Cu–BOX [bis(oxazoline)] catalyst with achiral 3-methacryloxypropyltrimethoxysilane remarkably increases enantioselectivity in asymmetric Diels–Alder reaction of cyclopentadiene and 3-acryloyl-2-oxazolidinone.

Asymmetric catalysis has been successfully developed mainly in homogeneous systems,¹ while preparation of heterogeneous asymmetric catalysts is still a serious challenge to be tackled.² A new concept to construct effective asymmetric reaction fields on surfaces is indispensable for the development of heterogeneous asymmetric catalysts.³

BOX [bis(oxazoline)] is one of the practical ligands for asymmetric catalysis⁴ and several heterogeneous Cu–BOX systems have been reported.⁵ Nevertheless the asymmetric design of catalytically active sites on surfaces has not been established yet. We have found that the surface functionalization of SiO₂ with achiral 3-methacryloxypropyltrimethoxysilane remarkably amplifies the enantioselective catalysis of Cu–BOX complexes on the SiO₂ surface for asymmetric Diels–Alder reactions.

The SiO₂-supported Cu–BOX catalysts were prepared in a controllable manner (Figure 1). The tail of a BOX ligand (B) was substituted to (C),^{5c} and their Si(OC₂H₅)₃– groups were reacted with surface silanols to immobilize the BOX ligand on SiO₂ (Aerosil 200, Degussa, 200 m² g⁻¹) (D). Unimmobilized residual BOX ligands were removed by washing with CH₂Cl₂. The immobilization of the BOX ligand was confirmed by ²⁹Si solid-state MAS NMR (–49 ppm for –Si(OC₂H₅)₂(OSi), –59 ppm for –Si(OC₂H₅)(OSi)₂, and –68 ppm for –Si(OSi)₃),⁶ and the amount of the supported BOX ligand was estimated to be 0.03 mmol g⁻¹ (0.1 BOX molecule nm⁻²) by δ_{C–H} peak intensity at 1370 cm⁻¹ in FT-IR.⁷ Then an equivalent amount of Cu(ClO₄)₂·6H₂O to that of the supported BOX was coordinated to BOX (E). Surface-functionalized Cu–BOX complexes (F) were prepared using eight silane-coupling reagents (a–h in Figure 2) in dry toluene at 388 K, followed by the coordination of the Cu(ClO₄)₂·6H₂O.

A peak observed around 370 nm in diffuse-reflectance UV–vis for (E) indicates a similar structure of (E) to that of a homogeneous analog Cu(BOX)(ClO₄)₂. The bond distance (R) and total coordination number (CN) of Cu–O (Cu–N) in (E) were 0.199 ± 0.001 nm and 4.4 ± 0.5, respectively by Cu K-edge EXAFS, which were almost the same as 0.198 ± 0.001 nm and 4.5 ± 0.6 for Cu(BOX)(ClO₄)₂. XPS Cu 2p_{3/2} binding energy of (E) was 933.6 eV, which is attributed to Cu²⁺ species.⁸ ESR signal of (E) (*g*_{||} = 2.286, *A*_{||} = 13.4, and *g*_⊥ = 2.071) was observed at higher magnetic fields than that for the Cu(ClO₄)₂ precursor, which demonstrates that the precursor was coordinated to the immobilized BOX ligand because the ESR signals

for Cu²⁺ species coordinated by nitrogen ligands were observed at higher magnetic fields.⁹ XPS (Cu 2p_{3/2} binding energy: 933.7 eV) and Cu K-edge XANES (8995 eV) evidence a similar Cu²⁺ state of (F). The CN and R of Cu–(O/N) were 4.1 ± 0.5 and 0.198 ± 0.001 nm, respectively, and the ESR spectrum was similar to that of (E). Hence, the local coordination spheres of (E) and (F) were similar to each other as illustrated in Figure 1.

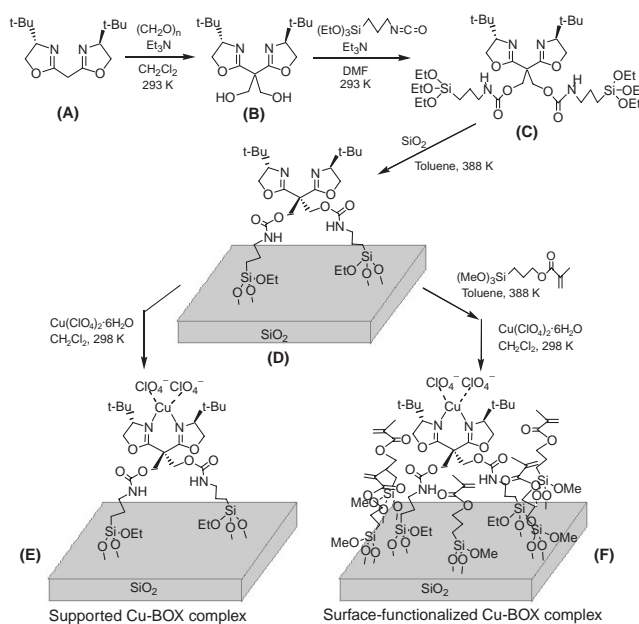


Figure 1. Preparation of SiO₂-supported Cu–BOX complexes (E) and (F).

Catalytic Diels–Alder reaction of cyclopentadiene and 3-acryloyl-2-oxazolidinone (Figure 2) was carried out on Cu(BOX)(ClO₄)₂, (E), and (F). The homogeneous Cu–BOX complex showed a low enantioselectivity of 5 ee% (*S*) in both 25 and 0.35 mmol L⁻¹ of the Cu complex. The catalytic activity of the homogeneous Cu–BOX complex particularly at the low concentration was very low (conversion: 4% after 1 h).

By the immobilization of the Cu–BOX complex on SiO₂, the conversion for the Diels–Alder reaction tremendously increased from 4 to 61%. On the other hand, the enantioselectivity increased a little from 5 to 15 ee%.

Interestingly, the surface functionalization by 3-methacryloxypropyltrimethoxysilane (h) without chirality brought about a large increase in the enantioselectivity as shown in Figure 2. When the SiO₂ surface was covered with (h) at the surface density of 0.3 mmol g⁻¹, ee% of endo increased to 49 ee%. It was found that further surface-functionalization up to a full coverage

of the achiral (h), 0.6 mmol g^{-1} , increased the enantioselectivity to 65% of endo. After 24 h, the conversion reached 100%, while keeping a similar enantioselectivity (63 ee% of endo).

The silane-coupling reagent (h) without attaching on SiO_2 was added to the CH_2Cl_2 solution in which (E) was suspended, but no increase in the enantioselectivity was observed. It is indicated that the chemical attachment of (h) on the surface is indispensable for the promotion of enantioselective catalysis, and the full-coverage functionalization with (h) is most effective for the creation of an enantioselective reaction field. (F) was reusable without significant loss of the catalytic activity (88% conversion at 24 h) and the enantioselectivity (58 ee% of endo).

Other silane-coupling reagents with styryl (a) and vinyl (c) groups cause large decreases in the enantioselectivity. It has been reported that the capping of free surface Si-OH with trimethylsilyl moieties is favorable for asymmetric catalysis on SiO_2 .^{5e,10} However, the results for (F-a) and (F-c) indicate that the capping of silanol groups does not lead to an increase in the enantioselectivity. Long alkyl chains such as octyl (f) and

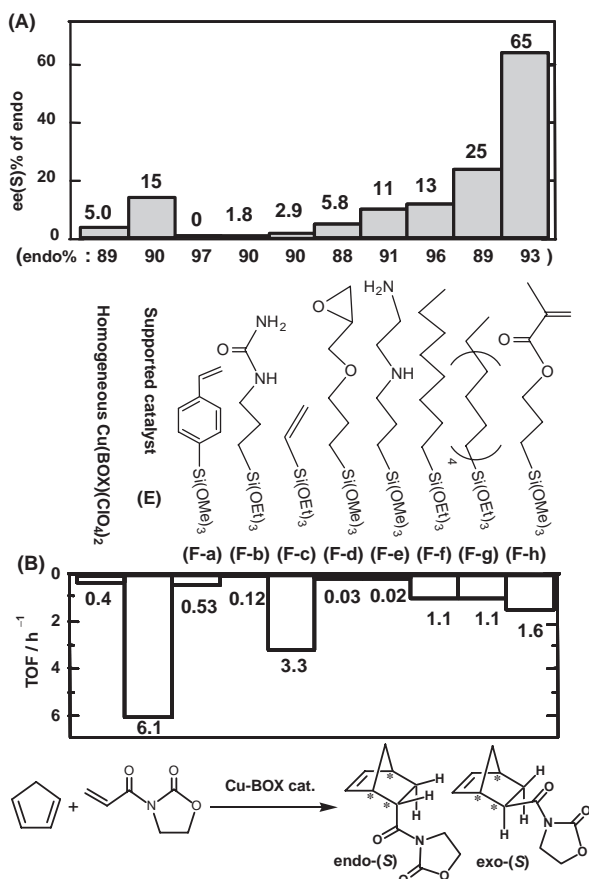


Figure 2. Catalytic performances of homogeneous $\text{Cu}(\text{BOX})-(\text{ClO}_4)_2$, SiO_2 -supported Cu-BOX complex (E), and surface-functionalized SiO_2 -supported Cu-BOX complexes (F-a)–(F-h) for asymmetric Diels–Alder reaction of cyclopentadiene and 3-acryloyl-2-oxazolidinone. TOF (turn over frequency) is defined as consumed dienophile $\text{Cu}^{-1} \text{ h}^{-1}$ of the catalytic reaction. Cu : $3.5 \times 10^{-6} \text{ mol}$, cyclopentadiene: $10.5 \times 10^{-5} \text{ mol}$, 3-acryloyl-2-oxazolidinone: $3.5 \times 10^{-5} \text{ mol}$, CH_2Cl_2 : 10 mL, 263 K, N_2 atmosphere. The catalytic reaction was monitored by GC-MS and HPLC.

octadecyl (g) groups influenced ee% a little. Ee% for the longer octadecyl group (F-g) (25 ee%) was higher than 13 ee% for the shorter octyl group (F-f), while the catalytic activities were similar to each other. Urea (b), epoxy (d), and amino (e) moieties brought about large loss of the catalytic activities (Figure 2) because these reagents act as bidentate ligands for Cu^{2+} to probably decompose the original Cu-BOX complex.

Only the methacryl-functionalized catalyst (F-h) showed the high enantioselectivity for the reaction. As the lengths of methacryl reagent (h) and the BOX ligand on SiO_2 are similar to each other, the oxygen of methacryl group may interact with the NH group of the chiral BOX ligand by hydrogen bonding. The dependency of the enantioselectivity on the coverage of (h) indicates that the achiral methacryl groups surround the supported chiral BOX ligand to form a new assembled structure of the chiral BOX with the achiral methacryl groups, resulting in the large increase in the ee%. Ee% in polar CHCl_3 and ethanol were so small as 0.8 and 5 ee%, respectively, also agreeing with the assumption of the assembled structure on the surface.

Briefly, the enantioselectivity for the asymmetric Diels–Alder reaction on the SiO_2 -supported Cu-BOX complexes were amplified by functionalization of the SiO_2 surface with the achiral silane-coupling reagent (h). The supported Cu-BOX complex was more active than the homogeneous counterpart and reusable for the Diels–Alder reaction of cyclopentadiene and 3-acryloyl-2-oxazolidinone. Positive interaction between the chiral BOX ligand and the methacryl reagent was suggested to create a new enantioselective assembly, which cannot be prepared in solutions.

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