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Chiral Metal-Organic Framework as a Platform for Cooperative Catalysis in Asymmetric Cyanosilylation of Aldehydes

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ABSTRACT: In this work we demonstrate for the first time the cooperative asymmetric catalysis by metal-organic framework (MOF) as exemplified in the context of catalyzing cyanation of aldehydes with a VO(salen)-MOF, which after oxidation affords remarkably increased stereoselectivity (up to >99% ee) compared to the homogeneous VO(salen) counterpart as a result of the pairs of VO(salen) units in close proximity within its open channels. The cooperative asymmetric catalysis has been evidenced by the significantly decreased stereoselectivity and activity when one VO(salen) in such pairs of VO(salen) units is replaced with one Cu(salen), which results in blocking the VO-VO synergistic pathway whilst prompting unimolecular activation of substrates. The heterogeneous nature of VO(salen)-MOF has been verified by the fact that it can be easily recycled and reused without significant loss of catalytic activity and enantioselectivity, and its practical utility as asymmetric cyanation catalysist has been illustrated in the gram scale synthesis of the antiviral natural products (*R*)- and (*S*)-enantiomers of tembamide. Our work therefore advances chiral MOF as an attractive platform for cooperative asymmetric catalysis in a variety of syntheses.

KEYWORDS: *metal-organic framework, porous material, chiral material, asymmetric catalysis, heterogeneoous catalysis.*

INTRODUCTION

Inspired by the intriguing mode of action of bimetallic enzymes and their impressive catalytic performance,[1] the synergistic cooperation of multiple metal centers has been intensively studied for artificial catalyst systems, as they often show higher reactivity and selectivity than the analogous mononuclear species.[2] The proper arrangement of active centers in close proximity is the key to the success for efficient catalysis. By employing metal-metal, metal-organo and organo-organo catalysts, cooperative catalysis has become a powerful tool,[3] especially in asymmetric synthesis, allowing access to new chemical reactivity and high stereocontrol in diverse reactions.[3b,3c] However, it remains difficult to create such a cooperative activation in a solid catalyst because of its inability to control the proper proximity and conformation of active centers.[4]

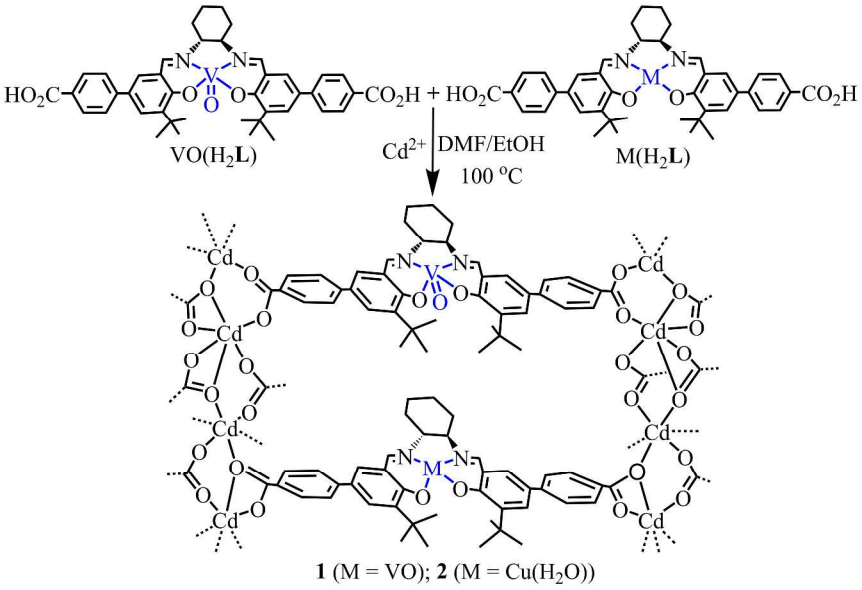
Metal-organic frameworks (MOFs) offer great potential in heterogeneous catalysis due to their large surface areas, composition tunability and well-defined reaction environments.[5,6] Among the asymmetric MOF catalysts reported to date, the most efficient examples all contain privileged chiral ligands such as BINOL- and salen-based derivatives.[5-10] Incorporation of molecular catalysts in the MOFs allows for the possibility of spatial control of the different groups.[11] They can be either separated by far away from each other to activate substrates in a unimolecular fashion or intimately mixed with suitable orientations to achieve the synergistic activation catalysis.[11] Nonetheless, MOFs that take advantage of cooperative effects to improve catalytic activities and/or selectivities have been rarely reported.[9d,11]

It's been known that VO(salen) complexes are asymmetric catalysts for cyanation of aldehydes to produce cyanohydrins that follow either a mono- and bimetallic co-activation mechanism.[12] Albeit the bimetallic pathway gives intrinsically faster catalysts with higher stereoselectivity, it remains a challenge to control the reaction mechanism particularly in homogeneous systems. Nevertheless, such

challenge can be addressed via the construction of two chiral porous MOFs based upon VO(salen) and Cu(salen) complexes as reported herein.[13] The channel surfaces of the constructed two chiral porous MOFs are decorated with pairs of VO(salen) or VO(salen) and Cu(salen) units in close proximity that are capable of asymmetrically catalyzing cyanation of aldehydes *via* a bimetallic or monometallic activation pathway. Our work thus represents the very first example of cooperative asymmetric catalysis by MOF.

RESULTS AND DISCUSSION

Scheme 1. Synthesis of MOFs 1 and 2.



Synthesis and characterization. As shown in Scheme 1, olive-green single crystals of $[Cd_2(VO\mathbf{L})_2]\cdot 5H_2O$ (**1**) and $[Cd_2(VO\mathbf{L})(Cu\mathbf{L})]\cdot 4H_2O$ (**2**) were obtained by heating $Cd(NO_3)_2\cdot 6H_2O$ and $VO(H_2\mathbf{L})$ (a 1:1 molar ratio) or $[VO(H_2\mathbf{L})]/[Cu(H_2\mathbf{L})(H_2O)]$ (1:0.5:0.5 molar ratio) in DMF and EtOH at 100 °C, respectively. The products were stable in air and insoluble in water and common organic solvents and were formulated based on elemental analysis, IR spectroscopy and thermogravimetric analysis (TGA). The 1:1 molar ratio of V to Cu in **2** was confirmed by ICP-OES (Inductively coupled plasma optical emission spectrometry). The phase purity of the bulk samples was verified by the consistence between their observed and simulated powder X-ray diffraction (PXRD) patterns.

1 adopts a 3D chiral porous framework and crystallizes in the chiral orthorhombic space group $P222_1$.[14] The basic building block is infinite Cd-O-C chains linked together by VO**L** ligands (Figure 1a). Each V center adopts a square-pyramidal geometry with the equatorial plane occupied by the N_2O_2 donors of one **L** ligand and the apical position by one double bond oxygen atom. The V=O bond lengths of 1.382(8) and 1.421(11) Å are typical V-oxido species.[15] Of the four independent six-coordinated Cd ions, two (Cd1 and Cd4) are coordinated by two water molecules and four oxygen atoms from two bidentate and two tridentate carboxylate groups, another two (Cd2 and Cd3) are coordinated by six oxygen atoms from two bidentate and four tridentate carboxylate groups. The infinite Cd-O-C rods are thus linked by VO**L** ligands to give a 3D framework with 1D quadrilateral channels of 1.26 nm along an edge and 2.72 nm along the diagonal (Figure 1c). The channel surfaces are uniformly lined with chiral VO**L** units with coordinatively unsaturated V ions that are accessible to guest molecules.

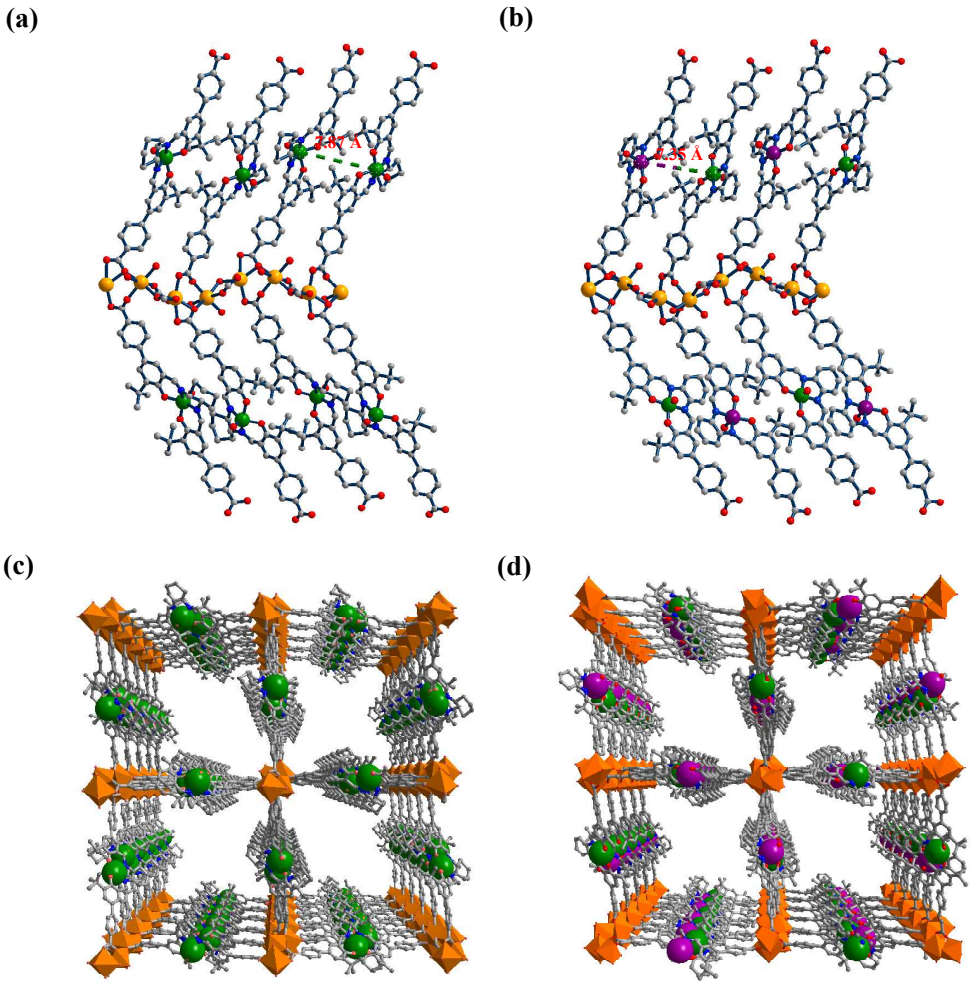


Figure 1. X-ray structure of (*R*)-**1** and (*R*)-**2**. Cd- carboxylate chains linked by VO**L** ligands in **1** (a) and a mixed ligands of VO**L** and Cu**L** in **2** (b). View of 3D porous structures of **1** (c) and **2** (d) along the c-axis (the Cd atoms are shown in polyhedra). Cd yellow, V green, Cu purple, O red, C gray, N blue.

2 is isostructural to **1** and has an almost identical porous 3D structure with open channels of 1.2 × 0.8 nm^2 along the *a*-axis. In contrast to **1**, the infinite Cd-O-C chains in **2** are linked together by an equal mixture of VOL and Cu**L**(H_2O) ligands (Figure 1b and 1d). PLATON calculations show that both **1** and **2** have about 56% of void spaces available for guest inclusion.[16]

Solid-state circular dichroism (CD) spectra of **1** and **2** made from *R* and *S* enantiomers of H_4**L** are mirror images of each other, suggesting their enantiomeric nature. XPS (X-ray Photoelectron Spectroscopy) spectra of **1** and **2** show the appearance of V $2p_{3/2}$ line at ~516.1 eV, indicative of +4 oxidation state for the V ions. TGA (thermal gravimetric analysis) reveals that the guest molecules could be removed in the temperature range from 100 to 220 ^oC and the frameworks are stable up to ~370 ^oC. PXRD indicated that their framework and crystallinity remain intact upon removal of the guest molecules. Their permanent porosities were confirmed by N_2 adsorption isotherms at 77K and liquid-phase adsorptions. Both **1** and **2** exhibited a Type-I sorption behavior, with BET surface areas of 628 and 690 m^2/g, respectively (Figure 2). They could adsorb ~1.4 methyl orange (MO, ~1.47 nm × 0.53 nm × 0.53 nm in size) per formula unit and the inclusion samples had almost the same PXRD pattern as the pristine solids.

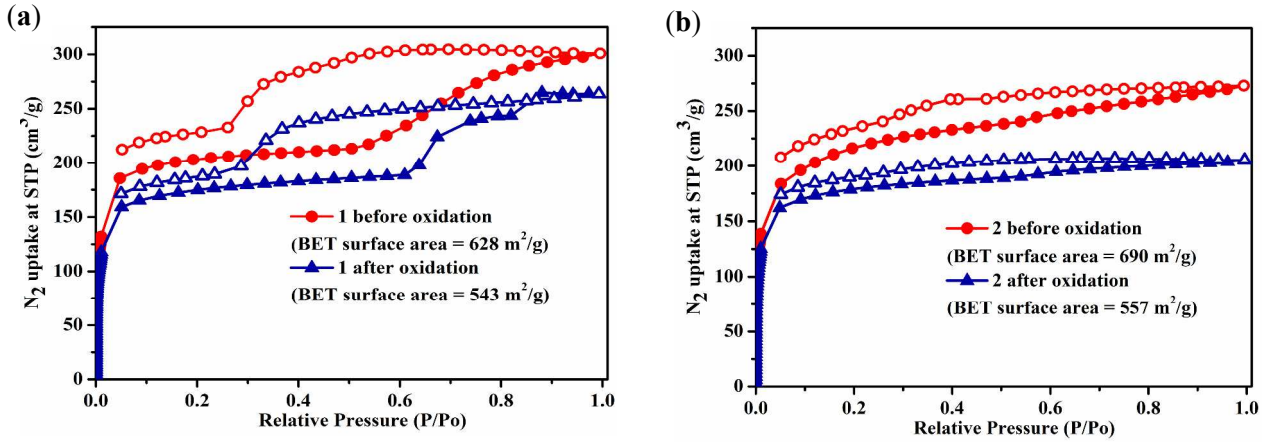


Figure 2. N_2 sorption isotherms in **1** (a) and **2** (b) at 77 K.

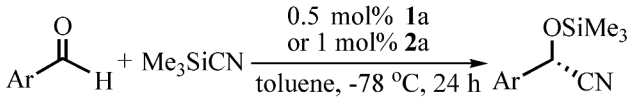
Asymmetric catalysis. We evacuated the catalytic activities of **1** (10 mol% loading) in the context of cyanation reactions between aromatic aldehydes and TMSCN but with low yields were observed. This may be attributed to that weak Lewis acidity of V(IV) does not favor its strong binding to the substrate thus not facilitating the reaction to occur.[17] Treatments of **1** or **2** with $(NH_4)_2Ce(NO_3)_6$ afforded the oxidated V^VO-MOFs **1a** and **2a**, accompanying with a slightly color change from dark green to green. The individual crystals remained transparent but with apparent fracturing, preventing us to get their single-crystal structures. The oxidation of V(IV) to V(V) was confirmed by the V $2p_{3/2}$ line appeared at ~518.0 eV in the XPS spectra. PXRD analysis showed that the oxidized samples **1a** and **2a** remained high crystallinity. They displayed decreased BET surface areas of 543 and 557 m^2/g, respectively, as compared with the parent MOFs and still can adsorb ~1.3 MO per formula unit in solution, indicative of their structural integrity and porosity.

After optimization of reaction conditions, **1a** was found to be an active catalyst for cyanation of aldehydes with TMSCN at -78 ^oC. Typically, 0.5 mol% loading of (*R*)-**1a** with regard to the aldehydes afforded cyanohydrin trimethylsilyl ethers in 96-99% conversions and 82-99% ee in 24h (Table 1). Cyanation of benzaldehyde by (*S*)-**1a** gave the *R* enantiomer over the *S* enantiomer (87% ee), indicating that the chiral nature of the product was controlled by the handedness of the catalyst. The catalytic reactions proceeded in excellent conversions and good to excellent enantioselectivity with benzaldehydes bearing an electron-donating group, but the introduction of an electron-withdrawing -Br group into the phenyl ring of the substrate led to slightly decreased enantioselection (82% ee, entry 5). Heterocyclic compounds 2-furylaldehyde and 3-pyridylaldehyde gave ~99% and 98% conversions with 93% and 82% ee, respectively. For the vinyl-type aromatic aldehyde cinnamaldehyde, 95% ee and 97% conversion were obtained. 1- and 2-naphthaldehydes were readily converted to the products with 96% and >99% ee, respectively.

When a more sterically demanding aldehyde, 3-GOC_6H_4CHO, was subjected to the cyanation condition, less than 5% conversion was observed after 24 h, which was much lower than ~62% conversion obtained with $V^VO(Me_2\mathbf{L})$. This result showed that this bulky substrate may not access the

catalytic sites located within the pore walls due to the size exclusion, which conversely supports that the cyanosilylation is indeed occurring within the pores for other smaller substrates.

Table 1. Cyanation of Aldehydes Catalyzed by the MOFs.[a]



entry	Ar	catalyst[b]	conv (%)[c]	ee (%)[d]
1	C_6H_5	*R*-**1**a/*S*-**1**a	98/98	86/87 (*S*/*R*)
		R-**2**a	49	76 (*S*)
		R-VO(Me_2**L**)[e]	99	78 (*S*)
2	4-MeC_6H_4	*R*-**1**a	97	95 (*S*)
3	3-$MeOC_6H_4$	*R*-**1**a	98	95 (*S*)
		R-**2**a	47	64 (*S*)
4	4-$MeOC_6H_4$	*R*-**1**a	96	96 (*S*)
		R-**2**a	55	74 (*S*)
		R-VO(Me_2**L**)[e]	97	81 (*S*)
5	4-BrC_6H_4	*R*-**1**a	98	82 (*S*)
		R-VO(Me_2**L**)[e]	99	73 (*S*)
6	2-furyl	*R*-**1**a	99	93 (*S*)
		R-VO(Me_2**L**)[e]	99	79 (*S*)
7	3-pyridyl	*R*-**1**a	98	82 (*S*)
8	C_6H_5CH=CH	*R*-**1**a	97	95 (*S*)
9	1-naphthyl	*R*-**1**a	97	96 (*S*)
		R-**2**a	51	69 (*S*)
10	2-naphthyl	*R*-**1**a	96	>99 (*S*)
		R-**2**a	49	77 (*S*)
11	3-GOC_6H_4[f]	*R*-**1**a/VO(Me_2**L**)[e]	5/62	n.d.

[a]For reaction details see Experimental section. [b]Catalyst loading based on aldehyde. [c]Calculated by ^{1}H NMR. [d] ee values were determined by HPLC (letters in brackets specify the preferable isomer). [e]Catalyzed by 1 mol% (R)-VO(Me_2**L**) and reaction time of 12 h. [f]See Figure S1 for the structure of 3-GOC_6H_4CHO.

The supernatant from cyanation of benzaldehyde after filtration did not give any additional cyanohydrin product. Upon completion of the reaction, (*R*)-**1a** could be recovered in quantitative yield and used repetitively several times, as shown in Table 2. The initial TOF of the catalyst was gradually decreased upon recycling, which is typical of supported catalysts, but the recycled MOF catalyst still afforded 91% conversion of benzaldehyde and 84% ee of the product after ten cycles. These results indicate that the MOF catalyst had good efficiency and recyclability in enantioselective cyanation of

aldehydes. PXRD analysis indicated that **1a** remained its crystallinity after ten cycles, although a structural distortion occurred. Moreover, the solid was still able to adsorb ~1.3 MO per formula unit in solution, further suggesting the maintenance of its structural integrity. The XPS measurement showed that V in the recovered MOF retained +5 oxidation state, as evidenced by the V $2p_{3/2}$ line at ~518.0 eV. ICP-OES analysis of the product solution indicated negligible loss of the metal ions (~0.0002% for Cd and ~0.0035% for V from the structure per cycle).

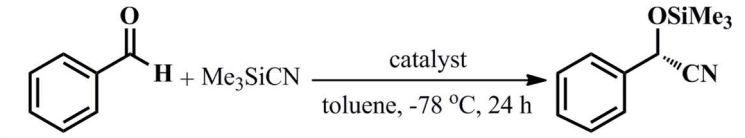
Table 2. Recycling Studies of 1a in cyanation of benzaldehyde[a]

cycle	Conv. (%)[b]			Initial TOF (h^{-1})[d]
	6 h	12 h	24 h	
1	44	90	98 (85)[c]	23.1
2	46	88	97 (87)[c]	24.5
3	46	88	98 (84)[c]	21.7
4	43	82	94 (82)[c]	19.4
5	42	82	94 (85)[c]	19.4
6	44	81	92 (87)[c]	19.2
7	42	83	93 (85)[c]	19.0
8	42	80	91 (85)[c]	19.0
9	41	78	92 (85)[c]	18.6
10	38	78	91 (84)[c]	18.1

[a]For reaction details see Experimental section. [b]Calculated by ^{1}H NMR. [d]ee values after 24 h that were determined by HPLC.

Using 1.0 mol% $V^VO(Me_2\mathbf{L})$ (the same loading of V^VO(salen) as the heterogeneous reaction), cyanation of benzaldehyde and 4-methoxybenzaldehyde, 4-bromobenzaldehyde and 2-furyl-aldehyde after 12 h afforded 99% conversion with 78% ee of the product and 97% conversion with 81% ee, 99% conversion with 73% ee and 99% conversion with 79% ee, respectively. The framework-confined catalyst thus gave about 8-15% higher ee values than its homogeneous counterpart, although it needed longer reaction time for the diffusion of reactants into the pores.

Table 3. Cyanation of Benzaldehyde Catalyzed by (*R*)-1a and (*R*)-$V^{V}O(Me_2L)$ at Different Catalyst/Substrate Ratios.[a]



	R-$V^{V}O(Me_2L)$[c,d]		*R*-**1a**[c,d]		*R*-**2a**[c,d]	
C/S[b]	conv (%)	ee (%)	conv (%)	ee (%)	conv (%)	ee (%)
1:100	99[e]	78[e]	98	86	50	75
1:1000	74	70	78	82	33	68
1:5000	27	51	42	78	13	63
1:10000	<5	n.d.	31	68	<5	n.d

[a]For reaction details see Experimental section. [b]The molar ratio of VO(salen) to benzaldehyde. [c]Conversions were calculated by ^{1}H NMR. [d]ee values were determined by HPLC (letters in brackets specify the preferable isomer).[e]Obtained in 12h.

The difference between the heterogeneous and homogeneous catalysts in catalytic performances became even more significant as the C/S ratio (the molar ratio of VO(salen) to substrate) decreased. As shown in Table 3, at a C/S of 1:1000, **1a** is still capable of catalyzing cyanation of benzaldehyde affording 78 % conversion with 82% ee of the product in 24 h, and $V^{V}O(Me_2L)$ gave 74% conversion with 70% ee. When the C/S ratio was decreased from 1:1000 to 1:5000, **1a** is able to afford 42 % conversion with 78% ee whereas $V^{V}O(Me_2L)$ only gives 27% conversion with 51% ee. Even at a C/S ratio as low as 1:10000, **1a** can catalyze the reaction giving 31% conversion with 68% ee, whilst $V^{V}O(Me_2L)$ only gave <5% conversion. These results highlight that the VO(salen) catalyst confined in the MOFs exhibits much higher activity than the homogeneous counterpart, which indicates that the $V^{V}O$-MOF catalyzed reactions could go through a different pathway from that of homogeneous reactions.

A careful examination of the crystal structure of **1** revealed the channel surfaces are uniformly lined with twisted VO(salen) units with open V sites pointing to the open channels. Importantly, the adjacent V-V distances with a face-to-face orientation for both active sites in the channel surfaces are 7.87 Å. Intermolecular cyanide transfer is only possible if two adjacent VO(salen) units adopt a face-to-face orientation related to their open sites, thus allowing the activated aldehyde and cyanide to be located close to each other. Therefore, the appropriate proximity and spatial orientation of adjacent VO(salen) units with a distance of 7.87Å is anticipated to facilitate that the cyanide activated by one VO(salen) species could attack the aldehyde activated by another VO(salen). As a result, the main cycle of the cyanation catalysis may thus be switched from the two parallel catalytic cycles to the bimetallic cycle, thereby leading to significant increase in the reaction rate and stereoseletivity. Whereas in homogenous systems, the possibility for VO(salen) species to meet each other decreases when at much lower C/S ratios, thus unfavorable for the bimetallic activation process thereby resulting in dramatic drop in catalytic activitys. In contrast, even at lower C/S, the MOF catalyst is still capable of providing the bimetallic cooperative activation, thus to afford much better substrate conversions and enantioselectivity.

In order to prove for the presence of the synergistic dual activation catalysis, we examined the catalytic activity of **2a** that contains the close proximity of the Cu(salen) and VO(salen) facing each other, precluding the possibility of a cooperative VO-VO mechanism of nucleophile and electrophile activation. As shown in Table 1, 1.0 mol% *R*-**2a** (the same loading of VO(salen) as *R*-**1a**) catalyzed cyanation of benzaldehyde, 3-methoxybenzaldehyde, 4-methoxybenzaldehyde, 1-naphthaldehyde and 2-naphthaldehyde to afford 49% conversion with 76% ee of the product and 47% conversion with 64% ee, 55% conversion with 74% ee, 51% conversion with 69% ee and 49% conversion with 77% ee, respectively. Obviously, both conversions and ee values are significantly lower (about 41-51% and 10-31%, respectively) than those observed for **1a**. Several tests also demonstrated the heterogeneous nature of **2a** in cyanation reactions.

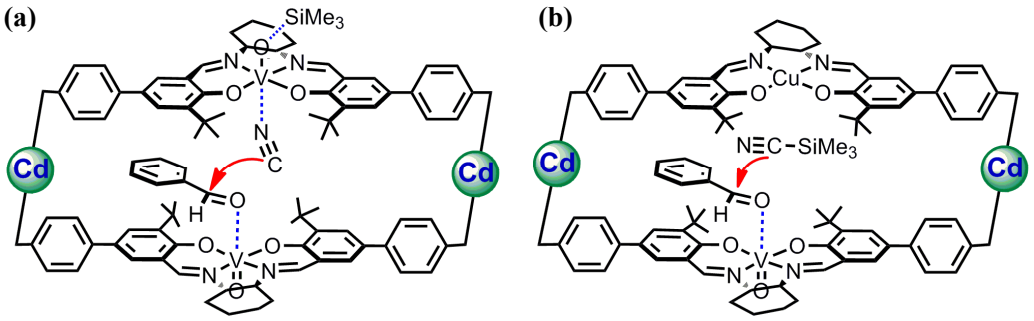


Figure 3. Proposed bimolecular (a) and unimolecular (b) activation pathways for cyanation of aldehyde by **1a** and **2a**, respectively.

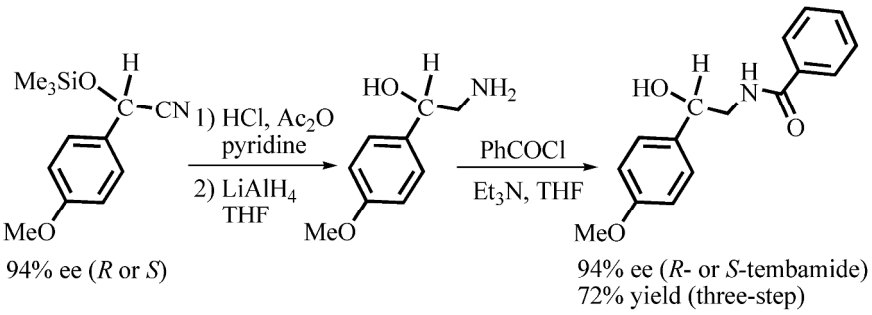
When Cu(Me_2**L**)(H_2O) was used as the catalyst, only a trace of products was detected in cyanation of benzaldehyde, 4-methoxybenzaldehyde or 2-naphthaldehyde.[12b,18] It suggests that the VO(salen) moieties, instead of Cu(salen) and Cd centers in **1a** and **2a**, are the active sites for the cyanation. In contrast to **1a** with fixed pairs of VO**L** to generate cooperative effects, substituting one Cu**L** for one VO**L** in each pair of VO(salen) may block the VO-VO synergistic pathway and prompt the unimolecular activation of substrates (Figure 3), leading to decreased stereoselectivity and activity. Synergistic catalysis by the VO-Cu pair in **2a** might also be involved in the reaction, but should not be the dominated pathway, because such cooperativity usually improves the performance of a catalyst. Indeed, cyanation of benzaldehyde with **2a** gave much lower reactivity than $V^{V}O(Me_2$**L**), at different C/S ratios. Meanwhile, both the reactivity and stereoselectivity are significantly lower than those obtained with **1a**. In particular, at a C/S ratio of 1:10000, **2a** almost can not catalyze the reaction, but **1a** is able to afford 31% conversion with 68% ee of the product over 24 h, further suggesting that cyanation reactions catalyzed by **2a** mainly follow a unimolecular activation way. A more in-depth investigation of the mechanistic aspect of this catalytic system is still in progress.

The silylcyanation of aldehydes and ketones catalyzed by asymmetric homogeneous catalysts to produce enantiopure cyanohydrins, which are versatile synthetic intermediates for pharmaceuticals, has received much attention.[19] The present enantioselectivities for cyanation of aldehydes are comparable with those of reported high-performing homogeneous VO(salen) catalysts and higher than those of other

heterogeneous VO(salen) catalysts immobilized on diverse supports such as mesoporous silica, carbon nanotubes, and activated carbon.[20] Note that cyanation of aldehydes catalyzed by MOFs,[21] including two asymmetric examples with moderate to high enantioselectivtiy has also been documented.[8d,10f] The work is expected to inspire new types of enantioselective heterogeneous cooperative catalysts based on crystalline frameworks.

The utility of the present cyanation procedure for practical synthesis was demonstrated in the gram scale synthesis of (*R*)- and (*S*)-enantiomers of tembamide, which have different biological activities, displaying good hypoglycemic activity and the anti-HIV activity, respectively. With 0.5% mol loading of **1a** as the catalyst, the 4-methoxybenzaldehyde was converted to cyanohydrin trimethylsilyl ether and then cyanohydrin acetate in 90% yield with 94% ee (Scheme 2). The reduction of cyanohydrin acetate with $LiAlH_4$ afforded the intermediate amino alcohol, which was acylated with benzoyl chloride gave (*R*)- or (*S*)- tembamide in 80% two-step yield with 94% ee.

Scheme 2. Synthesis of (*R*) and (*S*)-tembamides.



CONCLUSIONS

In summary, we reported two chiral porous MOFs of VO(salen) and Cu(salen) complexes and, after oxidation, the VO-MOF displayed enhanced stereoselectivity and comparable activity in cyanation of aldehydes when compared to its homogeneous counterpart via an efficient VO-VO cooperative

activation pathway. Such cooperativity was evidenced by the control experiments on the VO/Cu-MOF, which gave much more decreased activity and steroselectivity through a monometallic activation pathway. Our work therefore advances chiral MOF as a new platform for cooperative asymmetric catalysis in a variety of syntheses, and also highlights the unique role of MOF catalysts in the study of reaction pathways/mechanisms and in organic synthesis by exploiting novel and distinct reaction pathways.

EXPERIMENTAL SECTION

Materials and general procedures. All reagents and solvents used in these studies are commercially available and used without further purification. Elemental analyses were performed with an EA1110 CHNS-0 CE elemental analyzer. The IR (KBr pellet) spectra were recorded (400-4000 cm-1 region) on a Nicolet Magna 750 FT-IR spectrometer. The CD spectra were recorded on a J-800 spectropolarimeter (Jasco, Japan). All UV/Vis absorption spectra were recorded on a Lambda 20 UV/Vis Spectrometer (Perkin Elmer, Inc., USA). Thermogravimetric analyses (TGA) were carried out in an air atmosphere with a heating rate of 10 ^{o}C/min on a STA449C integration thermal analyzer. Powder X-ray diffraction (PXRD) data were collected on a DMAX2500 diffractometer using Cu-Kα radiation. The calculated PXRD patterns were produced using the SHELXTL-XPOW program and single crystal reflection data. 1H and 13C NMR experiments were carried out on a MERCURYplus 400 spectrometer operating at resonance frequencies of 100.63 MHz. Electrospray ionization mass spectra (ES-MS) were recorded on a Finnigan LCQ mass spectrometer using DMSO as mobile phase. Analytical high performance liquid chromatography (HPLC) was performed on a YL-9100 HPLC with UV detection. Analytical CHIRALCEL OD-H and AS-H columns (4.6 mm × 25 cm) from Daicel were used.

Synthesis of MOFs 1 and 2. A mixture of $Cd(NO_3)_2 \cdot 6H_2O$ (3.5 mg, 0.01 mmol) and (*1R*, *2R*)-[VO(H_2**L**)] (7.4 mg, 0.01 mmol) or (*1R*, *2R*)-[VO(H_2**L**)] (3.7 mg, 0.005 mmol)/(*1R*, *2R*)-[Cu(H_2**L**)(H_2O)] (3.8 mg, 0.005 mmol), DMF (1.0 mL) and EtOH (0.05 mL) in a capped vial was

heated at 100 °C for 12 hours. Olive green block-like crystals were filtered, washed with EtOH, and dried at room temperature. Yield: (*R*)-**1**, ~6.0 mg (~60.0 %); (*R*)-**2**, ~5.8 mg (~58.0 %). The products can be best formulated as $[Cd_2(VOL)_2]\cdot 5H_2O$ (**1**) and $[Cd_2(VOL)(CuL)]\cdot 4H_2O$ (**2**) on the basis of microanalysis, single-crystal diffraction and TGA. Elemental analysis of **1**: Calcd for $C_{84}H_{94}Cd_2N_4O_{19}V_2$: C, 56.35; H, 5.29; N, 3.13;; N, 3.91. Found: C, 55.97; H, 5.24; N, 3.11. IR (KBr pellet, ν/cm-1): 3428 (m), 2942 (m), 2865 (m), 1663 (s), 1600 (s), 1537 (s), 1394 (s), 1347 (m), 1314 (m),1269 (m), 1256 (m),1198 (w), 1180 (w), 1172 (m), 1101 (w), 1032 (w), 1015 (w), 984 (m), 929 (w), 896 (w), 859 (w), 816 (w),787 (m), 772 (m), 728 (w), 710 (w), 665 (w), 618 (w), 562 (w), 517 (w), 490 (w), 451 (w). Elemental analysis of **2**: Calcd for $C_{84}H_{94}Cd_2CuN_4O_{18}V$: C, 56.46; H, 5.30; N, 3.14;. Found: C, 55.91; H, 5.27; N, 3.11. ICP-OES showed a 1:1 molar ratio of V to Cu. IR (KBr pellet, ν/cm-1): 3430(s),2935(s), 2860(w), 1660(m), 1602(s), 1532(s), 1416(s), 1347(w), 1316(w), 1256(w), 1167(m), 1100(w), 1032(w), 1014(w), 983(m), 895(w), 858(m), 815(w), 787(m), 771(m), 727(w), 710(w), 663(w), 517(m), 489(w).

Single-Crystal X-ray Diffraction. Single-crystal XRD data for compounds **1** and **2** was collected on a Bruker SMART Apex II CCD-based X-ray diffractometer with Cu-Kα radiation (λ = 1.54178 Å) at 173 K. We have collected about several datasets for **1** using Cu-Kα radiation. Among the several datasets for **1**, the best dataset was used for structure solution and refinement. The empirical absorption correction was applied by using the SADABS program (G. M. Sheldrick, SADABS, program for empirical absorption correction of area detector data; University of Göttingen, Göttingen, Germany, 1996). The structure was solved using direct method, and refined by full-matrix least-squares on F_2 (G. M. Sheldrick, SHELXTL97, program for crystal structure refinement, University of Göttingen, Germany, 1997). In the compound, the all non-H atoms were subjected to anisotropic refinement by full-matri program. Contributions to scattering due to these highly disordered solvent molecules were removed using the SQUEEZE routine of PLATON. The structures were then refined again using the data generated. Crystal data and details of the data collection are given in Table S1, while the selected bond distances and angles are presented in Tables S2 and S3.

ASSOCIATED CONTENT

Supporting Information.

Details on experimental procedures, X-ray crystallographic data, supporting figures, reaction procedures and spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(14) CCDC 1055182 (**1**) and 1055183 (**2**) contain the supplementary crystallographic data. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data _request/cif.

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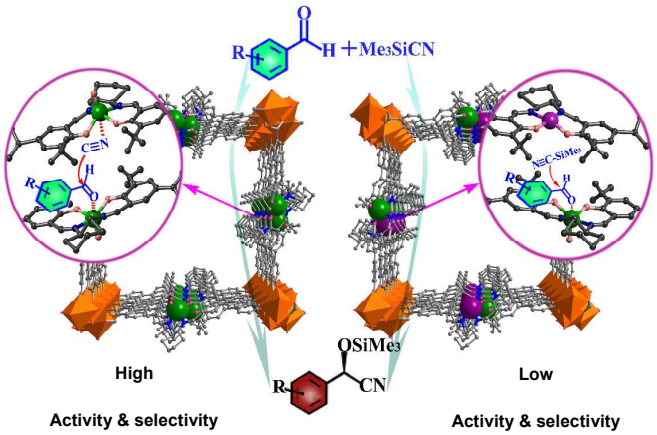
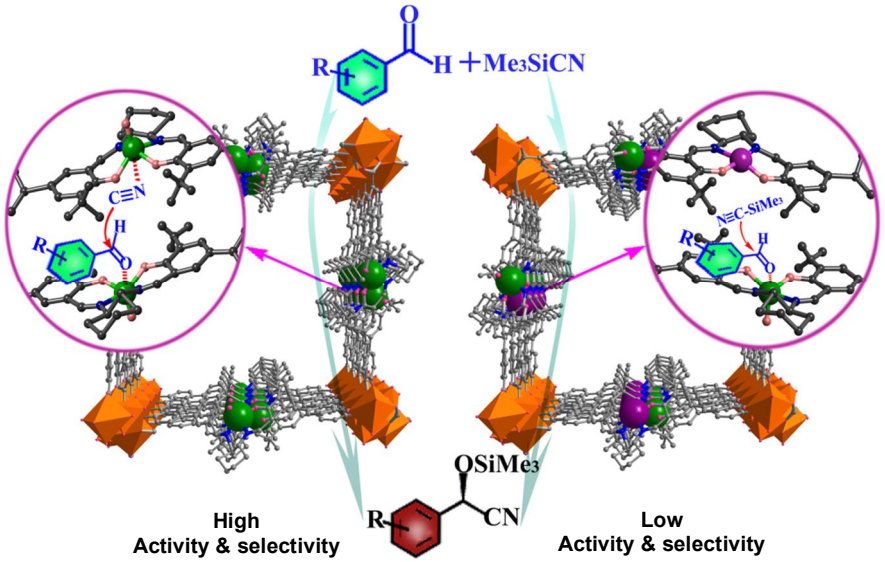
Graphic Content



Two chiral porous isostructural metal-organic frameworks (MOFs) are constructed by utilizing dicarboxyl-functionalized ligands of VO(salen) or a mixed VO/Cu(salen). After oxidation, the $V^{V}O$-MOF is a highly efficient and recyclable heterogeneous catalyst for cyanation of aldehydes with up to >99% ee and >99% conversion, whereas the $V^{V}O$/Cu-MOF is less reactive and selective. Compared with the homogeneous $V^{V}O$(salen) catalyst, the $V^{V}O$- and $V^{V}O$/Cu-MOFs displayer markedly increased and decreased catalytic performance, respectively, owing to that the frameworks fix pairs of VO(salen) units or VO/Cu(salen) into close proximity that facilitate activation of substrates *via a* bimolecular or unimolecular pathway. The practical utility of this cyanation was demonstrated in the gram scale synthesis of the antiviral natural products (*R*)- and (*S*)-tembamide.


Me3SiCN
High
Activity & selectivity
Low
Activity & selectivity
OSiMe3
CN