Electronic Supplementary Information for

AI-Powered Oriented Synthesis of Naphthalenediimide-based MOFs for Photochromic Encryption and Ammonia Sensing

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Table of Contents

Section 1. Experimental and Computational Details

Materials and Methods

All starting materials used in the experiments were without further purification (Macklin Biochemical Co., Ltd, Shanghai, China), N, N'-bis(carboxymethyl)-1,4,5,8-naphthalenediimide (H_2CMNDI) was synthesized by the reported method. The large language model (LLM) adopted in this research is DeepSeek, a Chinese technology enterprise specializing in the development of large-scale artificial intelligence models. Its main products include DeepSeek-V3, DeepSeek-V2, and the most powerful DeepSeek-R1. This model can be accessed for free through its official website, mobile application, or API interface. Although the model can be accessed through programming interfaces or web interfaces, both are suitable for the system architecture design of this research, but considering the research objectives and operational convenience, we ultimately chose the web-based chat interaction interface, as it does not require researchers to have a programming background to operate. All tasks involved in this research can be processed by DeepSeek-R1 as the core language model in the default mode. It should be noted that the chat model used in this research is based on the 2024 version and is supported by DeepSeek-R1.

Calculation methods

All the calculations were performed with Gaussian 09 package[1]. The B3LYP hybrid functional was employed. The 6-31g(d) basis set was used for the C, H, O, and N atoms. Using the Multiwfn wave function analysis program[2, 3]. The structures of CMNDI, analytes were optimized and their highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) energy levels were calculated according to the density functional theory. The image is presented through the VMD visualization software[4].

Instruments and measurements

Infrared (IR) spectra were obtained using Nicolet iS50 FTIR spectrometer (Thermo Fisher Scientific, Shanghai, China) with infrared module. The Perkin-Elmer 240C automatic analyzer (Perkin-Elmer, Waltham, USA) was used for the elemental analyses.

Powder X-ray diffraction (PXRD) measurements were performed on a Bruker Advance-D8 X-ray powder diffractometer (Bruker, Karlsruhe, Germany) with Cu Kα radiation with a step size of 0.02° (2θ) and an acquisition time of 2s per step in the range of 5° <2θ< 50°. Simulated PXRD patterns were obtained by single crystal data and diffraction crystal module of the Mercury program via http://www.ccdc.cam.ac.uk/mercury/[5]. Thermogravimetric (TG) analysis of sample was carried out on a Perkin Elmer Diamond TG/DTA (Perkin-Elmer, Waltham, USA) at a heating rate of 10 °C/min in N_2 with the range of 20~800 °C. Cary 300 Ultraviolet-visible Spectrophotometer (Agilent, California, USA) was employed to record the UV-vis spectra 200~800 nm, for solid sample). The EPR spectra were measured on Bruker A300 Electron Paramagnetic Resonance spectrometer (Bruker, Karlsruhe, Germany). The emission spectra were obtained by Fluoromax-4-TCSPC spectrofluorometer (HORIBA Scientific, Piscataway, USA) with Spectra LED Pulsed LED sources at room temperature (200~800 nm).

X-ray crystallographic determination

Single crystal diffraction data of Zn-CMNDI were collected on a XtaLAB Pro II AFC12 (RINC): Kappa dual offset/far diffractometer graphite monochromatized Cu Kα radiation (λ = 1.54184 Å) at room temperature, with empirical absorption correction using spherical harmonics. Single-crystal X-ray diffraction data for Cd-CMNDI were collected at room temperature on a Bruker AXS SMART APEX II CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). Data were processed with SADABS for semi-empirical absorption correction. Using the Olex2 platform, the space group was determined and all non-hydrogen atoms were refined anisotropically by direct methods (XL) and least-squares refinement (XS) in the final cycles[6-8]. Some reflections may be blocked by the beamstop, which caused systematic errors, those reflections are removed from the refinement via OMIT command. The structures were checked by PLATON program[9]. The R1 value is mainly attributed to the poor crystal quality, the data were the best result up to now. Crystallographic data have been deposited at the Cambridge Crystallographic Data Centre (CCDC no. 2488428-2488429).

Section 2. Optimization and Comparative Analysis of Zn/Cd-CMNDI Synthesis Strategies

Table S1. Screening conditions for Zn-CMNDI synthesis.

Iters	Plan	Exp.	$ZnCl_2$ (mg)	H_2CMNDI (mg)	DMA (mL)	H_2O (mL)	EtOH (mL)	8M HNO_3 (μL)	Notes
0	Plan 1	Zn-1	1.4	4	1.5	0.5		150	T:90 ℃ t:72 h
1	Plan 1	Zn-2	1.54	3.6	1.8	0.6		150	T:90 ℃ t:96 h
	Plan 2	Zn-3	1.54	3.6	1.5	0.5		150	T:65 ℃ t:120 h
2	Plan 1	Zn-4	1.4	4	1.5	0.5		75	T:90 ℃ t:72 h
	Plan 2	Zn-5	1.4	4	1.5	0.5		225	T:90 ℃ t:72 h
	Plan 3	Zn-6	1.54	3.2	1.5	0.5		200	T:90 ℃ t:72 h
3	Plan 1	Zn-7	3	4	1.2	0.5		180	T:90 ℃ t:72 h

	Plan 2	Zn-8	3	4	1.8	0.6		180	T:90 ℃ t:72 h
4	Plan 1	Zn-9	3	4	1.5	0.5		150	T:90 ℃ t:72 h
5	Plan 1	Zn-10	3	4	1.5	0.5	0.2	150	T:90 ℃ t:72 h
	Plan 1	Zn-11	3	4	1.5	0.5	0.4	150	T:90 ℃ t:72 h

Table S2. Screening conditions for Cd-CMNDI synthesis.

Iters	Plan	Exp.	$Cd(NO_3)_2\cdot 4H_2O$ (mg)	H_2CMNDI (mg)	DMA (mL)	H_2O (mL)	8M HNO_3 (μL)	Notes
0	Plan 1	Cd-1	4.17	4	1.5	0.5	150	T:90℃ t:72 h
1	Plan 1	Cd-2	4.17	3.6	1.8	0.6	150	T:90℃ t:96 h
2	Plan 1	Cd-3	3.17	4	1.5	0.5	75	T:90℃ t:72 h
3	Plan 1	Cd-4	3.17	4	1.5	0.5	225	T:90℃ t:72 h
	Plan 1	Cd-5	3.17	4	1.5	0.5	200	T:90℃ t:72 h
	Plan 1	Cd-6	3.17	4	1.5	0.5	150	T:90℃ t:72 h

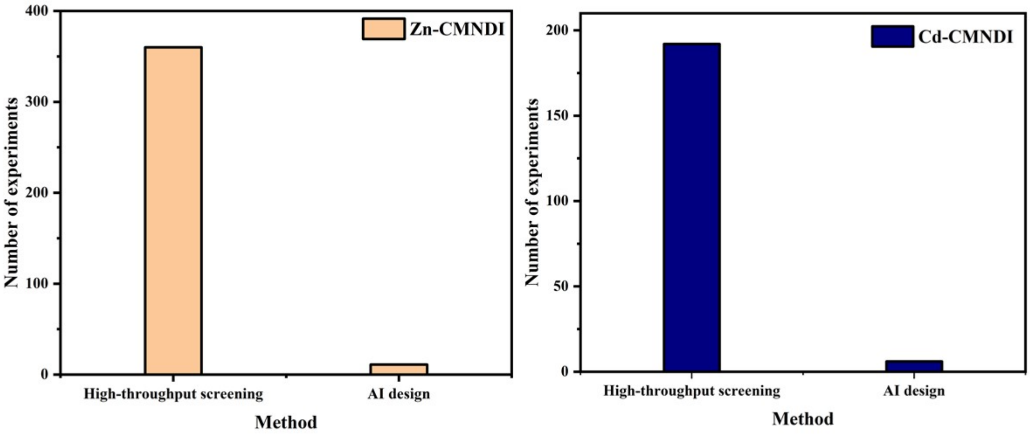
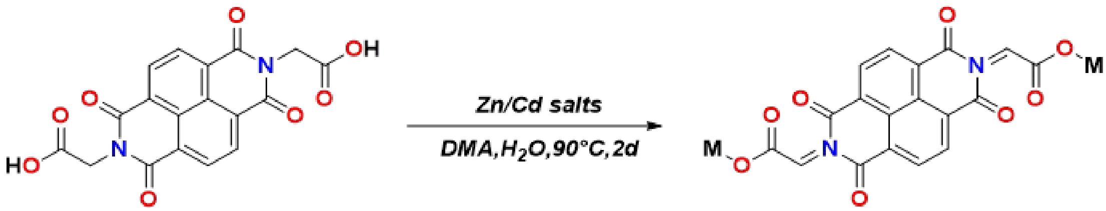


Figure S1. Comparison of experiments required between high-throughput screening and AI design methods.

Section 3. Synthesis and Structure of Zn/Cd-CMNDI



Scheme S1. Schematic diagram of M-CMNDI (M = Zn and Cd) synthesis process.

Table S3. Crystallographic information of Zn-CMNDI and Cd-CMNDI*.

	Zn-CMNDI	Cd-CMNDI
Formula	$C_{40}H_{32}N_6O_{16}Zn$	$C_{40}H_{32}CdN_6O_{16}$
M (g·mol^{-1})	918.08	965.11
Crystal system	*monoclinic*	*monoclinic*
Space group	*C2/c*	*C2/c*
a (Å)	16.4449(16)	15.6766(9)
b (Å)	9.2865(7)	9.2956(5)
c (Å)	25.735(2)	26.7478(15)
α (°)	90	90
β (°)	101.373(9)	100.870(2)
γ (°)	90	90
V (Å^3)	3852.9(6)	3827.8(4)
Z	1	1
D_c (g·cm^{-3})	1.583	1.675
F(000)	1888.0	1960.0
M(Mo Kα) (mm^{-1})	1.641	0.658
θ (°)	3.504 to 68.593	2.56 to 25.035

Reflections collected	7841	16282
Independent reflections(I>2σ(I))	3404(2622)	3359(2953)
Parameters	287	287
Δ(ρ)(e $Å^{-3}$)	1.92&-1.2	0.47&-0.34
Goodness of fit on F^2	1.503	1.062
R^a	$0.1235(0.1424)^b$	$0.0352(0.0827)^b$
wR_2^a	$0.3558(0.3752)^b$	$0.0435(0.0869)^b$

*[a]$R=\sum|F_O-F_C|/\sum|F_O$, $wR_2=\{\sum[w(F_O^2-F_C^2)^2]/\sum[w(F_O^2)^2]\}^{1/2}$; [$F_O>4\sigma(F_O)$]. [b]Based on all data.

Table S4. Selected bond lengths (Å) for Zn-CMNDI and Cd-CMNDI*

Zn-CMNDI and Cd-CMNDI			
Zn-O1	1.947(5)	Zn-O1[#1]	1.947(5)
Zn-O3[#1]	1.944(6)	Zn-O3	1.944(6)
Cd-O1[#1]	2.232(2)	Cd-O1	2.232(2)
Cd-O7[#2]	2.360(2)	Cd-O7[#3]	2.360(2)
Cd-O8[#3]	2.330(2)	Cd-O8[#2]	2.330(2)

*Symmetry codes: Zn-CMNDI: #1: 1-X, Y, 1/2-Z; Cd-CMNDI: #1: 1-X, Y, 1/2-Z; #2: X, 1-Y, -1/2+Z; #3: 1-X, 1-Y, 1-Z.

Table S5. Selected bond angles (°) for Zn-CMNDI and Cd-CMNDI*

Atom1	Atom2	Atom3	Angle/°
O1[#1]	Zn	O1	180.0
O3[#1]	Zn	O1[#1]	84.17(10)
O3	Zn	O1	95.83(10)
O3	Zn	O1[#1]	95.83(10)
O3[#1]	Zn	O1	84.17(10)
O3	Zn	O3[#1]	92.63(11)
O1[#1]	Cd	O1	96.37(13)
O1	Cd	O7[#2]	90.93(8)
O1[#1]	Cd	O7[#2]	105.16(8)
O1	Cd	O7[#3]	105.16(8)
O1[#1]	Cd	O7[#3]	90.90(8)
O1[#1]	Cd	O8[#2]	82.79(9)
O1	Cd	O8[#3]	82.79(9)
O1	Cd	O8[#2]	144.54 (8)
O1[#1]	Cd	O8[#3]	144.54(8)

*Symmetry codes: Zn-CMNDI: #1: 1-X, Y, 1/2-Z; Cd-CMNDI: #1: 1-X, Y, 1/2-Z; #2: X, 1-Y, -1/2+Z; #3: 1-X, 1-Y, 1-Z.

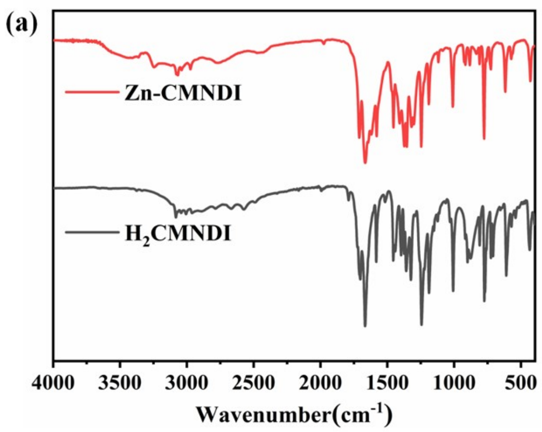


Figure S2. Infrared spectra of (a) H_2CMNDI and Zn-CMNDI; (b) H_2CMNDI and Cd-CMNDI.

Section 4. Photochromism of Zn/Cd-CMNDI

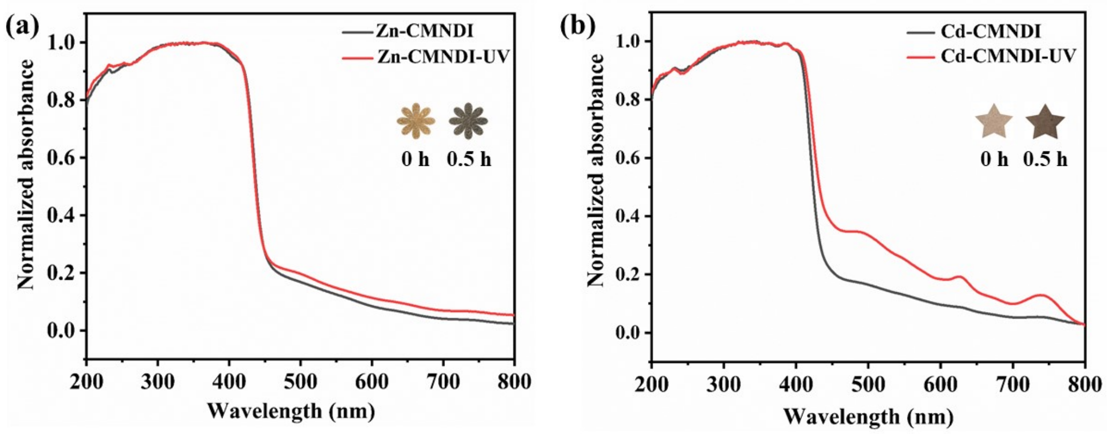


Figure S3. Color change diagram of Zn/Cd-CMNDI under ultraviolet light irradiation and corresponding UV-vis spectra. (a) Zn-CMNDI and (b)Cd-CMNDI.

Table S6. Average R. G. B. values of time-dependent photochromic photos

CNs	Zn-CMNDI	Cd-CMNDI
0	(219, 198, 146)	(226, 212, 172)
0.25 h	(165, 143, 99)	(143, 125, 109)
0.5 h	(115, 108, 86)	(113, 98, 83)
1 h	(85, 79, 63)	(94, 90, 73)

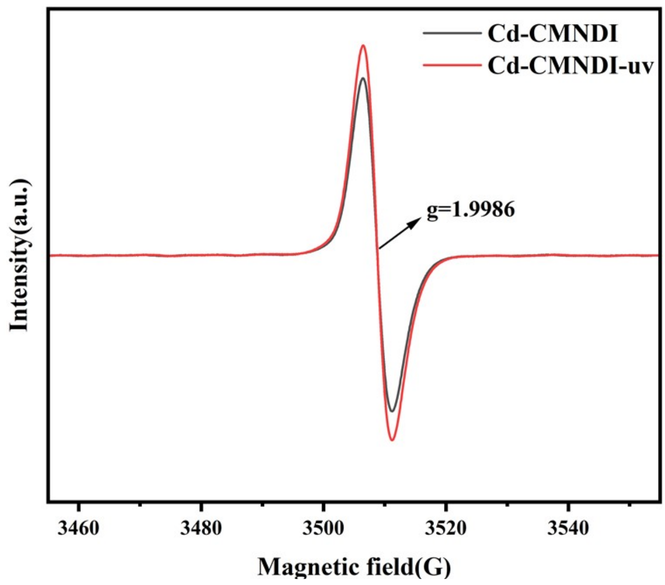


Figure S4. EPR spectra of as-synthesized Cd-CMNDI and Cd-CMNDI after ultraviolet irradiation.

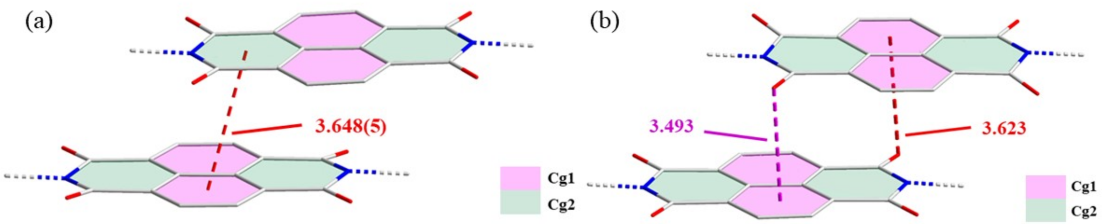


Figure S5. Schematic diagram of the interactions in Zn-CMNDI (for clarity, only the NDI core in the structure is retained). (a) n-π interactions; (b) π-π interactions.

Table S7. π-π interactions parameters in Zn-CMNDI*

π-π interactions						
Cg(I)[a]	Cg(J)	Cg-Cg(Å)[b]	α(°)[c]	β(°)[d]	γ(°)[e]	Symmetry code(J)
Cg1	Cg2	3.648	2.8(4)	20.9	18.5	1-X, 2-Y, 1-Z

Cg1: N1→C3→C5→C8→C6→C4→; Cg2: C10→C11→C12→C13→C13_f→C14_f→; Cg2: C10→C11→C12→C13→C13_f→C14_f→;

Table S8. n-π interactions parameters in Zn-CMNDI*

n-π interactions				
Y-X	Cg(J)[c]	X..Cg (Å)[d]	Y-X..Cg (°)[e]	Symmetry code(J)
C1-O5	Cg1	3.493(9)	80.2(5)	1-X, 2-Y, 1-Z
C2-O8	Cg2	3.623(10)	77.0(6)	1/2+X, 1/2+Y, Z

Cg1:C5→C7→C9-b→C6-b→C8-b→C8→; Cg2:C10→C11→C12→C13→C13-f→C14-f→;

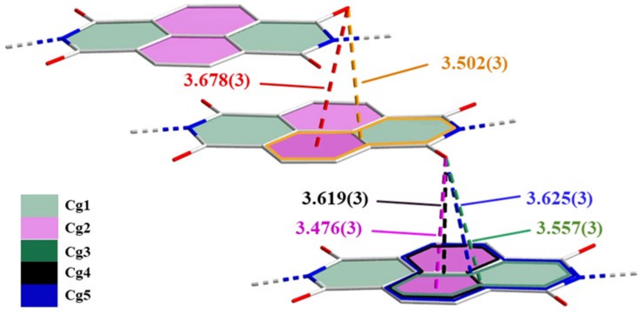


Figure S6. Schematic diagram of the n-π interactions in Cd-CMNDI (for clarity, only the NDI core in the structure is retained).

Figure S7. Photographs illustrating the inkless-print and rewritability of Cd-CMNDI.

Table S9. n-π interactions parameters in Cd-CMNDI*

n-π interactions				
Y-X	Cg(J)[c]	X..Cg (Å)[d]	Y-X..Cg (°)[e]	Symmetry code(J)
C1-O3	Cg1	3.678(3)	71.5(2)	1-X, 1-Y, 1-Z
C1-O6	Cg1	3.476(3)	88.27(19)	1/2-X, 1/2-Y, 1-Z
C2-O3	Cg2	3.502(3)	88.6(2)	1-X,1-Y,1-Z
C3-O6	Cg3	3.557(3)	89.33(19)	1/2-X,1/2-Y,1-Z
C4-O6	Cg4	3.619(3)	71.86(18)	1/2-X,1/2-Y,1-Z
C5-O6	Cg5	3.625(3)	78.19(18)	1/2-X,1/2-Y,1-Z

Cg1: C4→C7→C10→C11→C12→C8→; Cg2: N2→C15→C11→C10→C7→C4→C8→C12→C14→C16→; Cg3: N1→C3→C4→C8→C12→C14→C13→C9→C6→C5→; Cg4: C4→C7→C10→C11→C12→C14→C13→C9→C6→C8→; Cg5: N1→C3→C4→C7→C10→C11→C12→C14→C13→C9→C6→C5→C10→C11→C12→C13→C13-f→C14-f→;

Fluorescence sensing of Zn-CMNDI··

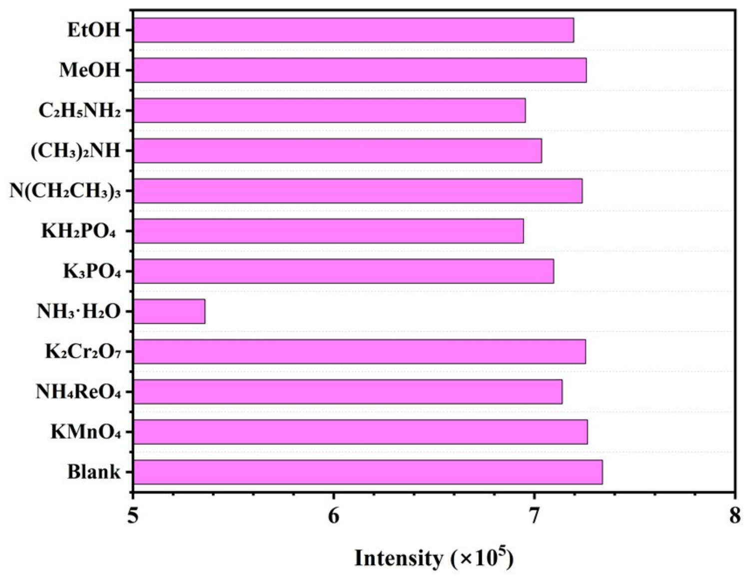


Figure S8. Response of Zn-CMNDI to variety of potential interferents.

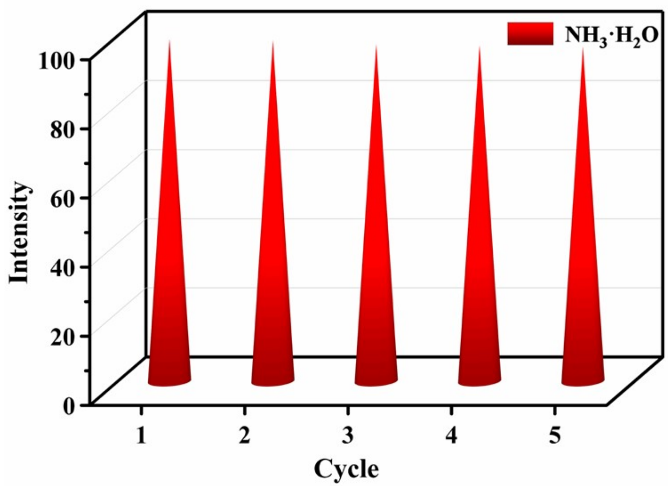


Figure S9. Fluorescence intensities of Zn-CMNDI towards ammonia in five cycles experiments.

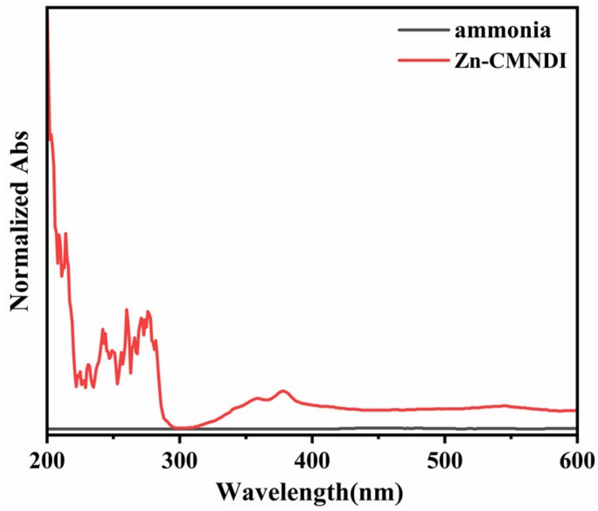


Figure S10. The ultraviolet absorption spectra of Zn-CMNDI suspension and ammonia water solution.

Table S10. Frontier molecular orbital energy levels

	HOMO/eV	LUMO/eV	HOMO-LUMO gap/eV
CMNDI	-7.1	-3.51	3.59
Ammonia	-6.815	2.122	8.937

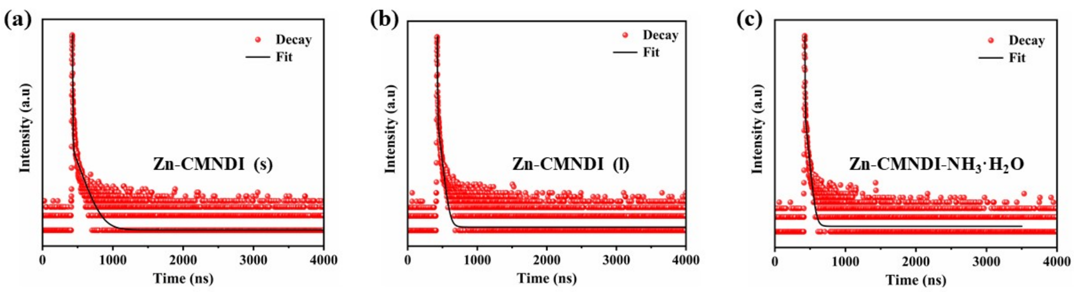


Figure S11. Lifetime decay curves of Zn-CMNDI (s), Zn-CMNDI (l), and Zn-CMNDI-$NH_3 \cdot H_2O$ at room temperature.

Table S11. The fitting parameters of lifetime of Zn-CMNDI (s), Zn-CMNDI (l) and Zn-CMNDI-$NH_3 \cdot H_2O$

	CHISQ	Lifetime (ns)	Average Lifetime (ns)
Zn-CMNDI (s)	1.51	τ_1=23.37 τ_2=0.64	0.75
Zn-CMNDI (l)	1.27	τ_1=0.58 τ_2=7.69	0.73
Zn-CMNDI-$NH_3 \cdot H_2O$	1.10	τ_1=0.43	0.58

τ_2=6.55

Section 6. Chemseek designs prompt and output workflow, as well as comparative efficiency analysis.

Flowchart of DeepSeek's Input and Output.

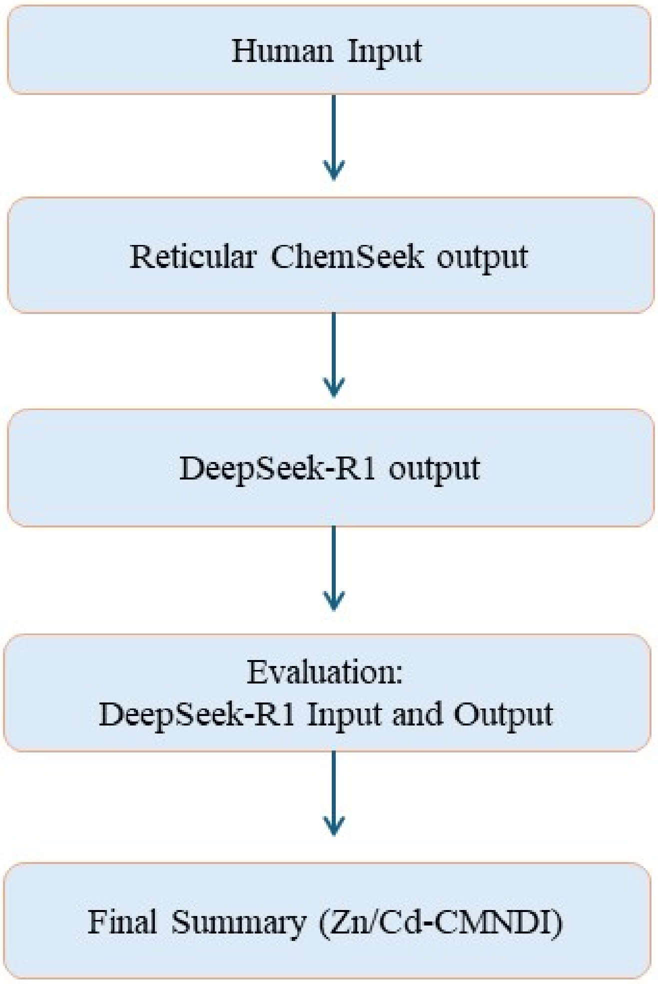


Illustration of the prompt used to develop Reticular ChemSeek.

Reticular ChemSeek Tips

You are an AI assistant specializing in network chemistry, responsible for assisting human apprentices in a research project-developing new zinc metal and cadmium metal organic framework materials using ligand H2CMNDI. Firstly, you need to have a comprehensive understanding of the standard operating procedures for network chemistry, which requires both referencing the text provided below and combining your existing professional knowledge reserves. Subsequently, you need to propose five stages for the project and clarify the goals or completion criteria for each stage. This process can be likened to writing Python code: the entire project is broken down into several generic function modules, and subsequent function testing relies on the completion of the preceding modules. Similarly, we need to guide this apprentice who knows very little about network chemistry to gradually complete the task and ultimately master the standard operating procedures in the field.

In addition, there are several additional explanations regarding this study:

1) The target ligand is not yet readily available, but relevant structures have been reported in literature.

2) Our goal is to discover and synthesize a novel structure of zinc metal and cadmium metal organic framework (Zn/Cd-MOF) by screening synthesis conditions.

3) We focus more on structural analysis to gain a deeper understanding of its formation mechanism, rather than simply pursuing practical application value.

4) We are equipped with various analytical instruments such as X-ray powder diffraction (PXRD), thermogravimetric analysis (TGA), ultraviolet visible spectroscopy (UV-Vis), and infrared spectroscopy (IR) for comprehensive testing. In addition, we have standard organic synthetic fume hoods and can purchase most commercially available materials according to demand.

Users can interact further with the Reticular ChemSeek to refine the stage content until they are satisfied with the blueprint.

Reticular ChemSeek output

Stage 1: Synthesis of H2CMNDI linkers

Objective: This phase aims to synthesize H_2CMNDI linkers. This process will use organic synthesis methods, and we have equipped standard fume hoods. Completion target: Verify the successful synthesis of H_2CMNDI linker through spectroscopic techniques such as infrared spectroscopy, nuclear magnetic resonance, and mass spectrometry. Purity needs to be evaluated and impurities minimized as much as possible.

Stage 2: Synthesis of the MOF

Objective: This phase focuses on utilizing the prepared H_2CMNDI linker to synthesize MOFs with zinc and cadmium ions. Parameters such as molar ratio, reaction temperature, reaction additives, solvent, and reaction time need to be optimized. Completion target: Verify the MOF structure through powder X-ray diffraction (PXRD) and possible single crystal X-ray diffraction (SXRD) to ensure that its atomic structure conforms to the expected pattern.

Stage 3: Analysis and Testing

Objective: Analyze the structure of synthesized MOFs and verify their architectural stability. Specifically, it includes parameter testing such as phase purity, chemical composition, crystallinity, pore size distribution, and overall structural stability. Completion target: By combining powder X-ray diffraction (PXRD), single crystal X-ray diffraction (SXRD), microscopy techniques, and in-situ spectroscopy for comprehensive structural analysis, it can be determined that this stage has been successfully completed.

Stage 4: Reproduction and Validation

Objective: To ensure the reproducibility of experimental results, MOF materials need to be synthesized multiple times by different researchers in the laboratory.

Completion criteria: When the MOF material can be stably and repeatedly synthesized with consistent results, it is considered to have completed this stage, indicating that the experimental process is reproducible and the results are reliable.

Prompt for Reticular ChemSeek. The input prompt for DeepSeek-R1 includes the following elements: (a) responsibility definition; (b) The final project phase determined by the Reticular ChemSeek system after manual optimization; (c) Detailed output requirements and specific definitions of each output component; (d) Input data; (f) Output template. For each H_2CMNDI ligand, the placeholder "ligand name" in the input prompt should be replaced with the actual ligand name. Except for the "manual feedback" section that needs to be filled out according to the template provided by Reticular ChemSeek, the rest of the input text usually comes from the output results of the previous iteration. At the beginning, I imported some literature reports on MOFs synthesized using H_2CMNDI as a ligand and other metal salts, and requested that you help me design several schemes for synthesizing Zn/Cd-CMNDI. The system will directly generate a complete abstract, which includes successful cases and reports on the synthesis methods of Zn/Cd-CMNDI. This precedent provides a guiding template for improving the evaluation capability and decision-making process of Reticular ChemSeek. Subsequent projects will continue the same pattern: for example, after the first project (Cd-CMNDI) is successfully launched, it will directly use the summary of the first project as input, and so on. The complete abstract content of both TM-CMNDI compounds can be found in the "Human Artificial Intelligence Interaction" section.

Illustration of the prompt used to develop the Reticular ChemSeek.

Prompt for Reticular ChemSeek

You are an AI reticular chemist assisting a human apprentice in a research project to develop a novel Zn/Cd-MOF using {*linker name*} as a ligand. The project is structured into five stages:

1) Synthesis of ligands.

2) Confirm the molecular structure of the synthesized product through single-crystal X-ray diffraction analysis (SCXRD).

3) High throughput screening of MOFs and optimization of synthesis results through PXRD.

4) Detailed structural analysis and characterization of MOFs.

5) Repeatability verification and final confirmation.

In each interaction, you'll be provided with the current project summary, the most recent task suggestion, and the feedback from the human apprentice. With these inputs, you should generate the following:

Output Summary: Construct an updated summary that primarily draw from the previous summary, adding only one or two sentences regarding the latest task and its outcomes based on human feedback, and another one sentence discussing the status of the current stage. The summary should tell the story of the project so far, summarizing both successes and failures from all completed stages and tasks.

This requires a concise analysis of one or two sentences. Based on this logic, explain how you have formulated three task options for the current stage steps. Output task options: Provide two to three next step tasks for students to choose from, and guide them in a detailed step-by-step manner for the next steps. The first sentence should summarize the key steps, followed by specific operational instructions. If the feedback from the student indicates that they have completed the current stage, they can choose one of the tasks to encourage them to say 'I am ready to move on to the next stage. Please be sure to only recommend tasks related to the current stage and avoid mentioning content related to subsequent stages.

Prompt for Reticular ChemSeek. The input prompt for DeepSeek-R1 includes the following content: (a) role definition; (b) The final project phase proposed by Reticular ChemSeek after manual optimization; (c) Request to generate long-term memory prompts based on accumulated memories at each stage; (d) Request to generate a step-by-step operation guide for the selected task; (e) The input data should include the number of iterations and a summary report of the previous stage. Not all memories need to be included in this input. If the content of a certain stage is highly similar, only the latest iteration result of that stage can be used. But the specific choice can be flexibly adjusted according to the needs. The input data also includes the latest iteration results, status assessment report, and three tasks recommended by Reticular ChemSeek. These pieces of information enable the Reticular ChemSeek to provide detailed operational guidance based on the selected task.

Illustration of the prompt used to develop the Reticular ChemSeek.

You are an AI reticular chemist assisting a human apprentice in a research project to develop a novel Zn/Cd-MOF using {*linker name*} as a ligand. The project is structured into five stages:

1) Synthesis of ligands.

2) Confirm the molecular structure of the synthesized product through single-crystal X-ray diffraction analysis (SCXRD).

3) High throughput screening of MOFs and optimization of synthesis results through PXRD.

4) Detailed structural analysis and characterization of MOFs.

5) Repeatability verification and final confirmation

You have already collaborated with the human apprentice to complete a few stages, and at the end of each stage, you have written down a summary. Below, I will provide you with these summaries, and your first job is to consolidate them into a comprehensive summary. This final summary should be as explicit as possible, detailing every success and failure at all stages. There is no word limit for the final summary. It will be used to instruct and inform another AI reticular chemist, who will guide another human apprentice to carry out a similar research project. Second, you job is to show me step by step how do choice {*number*} and give me a template on how to report to you the results.

Illustration of an exemplary output generated by the DeepSeek-R1 in response to a given prompt.

Reticular ChemSeek output

Abstract:

This comprehensive report elaborates on the research progress of developing a novel Zn/Cd-MOF using N,N'-di(carboxymethyl)-1,4,5,8-naphthalimide (H_2CMNDI) as a linker. The research is divided into five stages: ligand synthesis, single-crystal X-ray diffraction analysis (SCXRD), high-throughput screening and PXRD of MOFs, MOF structure analysis and characterization, and repeatability verification and final determination.

In Stage 1, the apprentice begins synthesizing the ligand H2CMNDI. A comprehensive review of the literature can help determine the synthetic route, which initially involved the use of 1,4,5,8-naphthalenetracarboxylic acid dianhydride and glycine.

After the successful synthesis of ligands, the second stage began to introduce MOFs that had been reported in literature to be synthesized using H_2CMNDI as a ligand and other metal salts. Based on the research results in the references, we have determined the optimal reaction conditions for Zn/Cd-MOF using H2CMNDI or similar ligands.

Given the current stage of the research, the next steps revolve around further optimizing reaction conditions, exploring the impact of mixed modulators.

The step-by-step process of task selection 2:

1. Prepare reaction reagents to ensure sufficient dosage of N, N '-dimethylacetamide (DMA) and other regulators (ethanol, water, nitricacid).

2. Maintain the previously determined optimal conditions (H_2CMNDI to zinc/cadmium ratio of 1:2, temperature of 90 ℃, reaction time of 72 hours) constant.

3. Design a series of reaction schemes such that the regulator is a 3:1 mixture of DMA and H_2O.

4. Start the synthesis experiment.

5. After synthesis, separate MOF products from each reaction and perform PXRD analysis.

6. Use PXRD to analyze each sample and carefully record changes in peak intensity, broadening phenomena, or other characteristic parameters that may reflect changes.

7. Record and interpret the experimental results.

Result report template:

Reaction Conditions:

- H_2CMNDI: Zn/Cd Ratio: 3:4
- Temperature: [Temperature used]
- Reaction Time: [Reaction time used]

Mixed Modulator Approach:

- Modulator Ratios Used:
  - The ratio of DMA: H_2O: HNO_3=1.5:0.5:0.0150
  - The ratio of DMA: H_2O: HNO_3=1.8:0.6:0.0150
  - The ratio of DMA: H_2O: HNO_3=1.5:0.5:0.0075
  - The ratio of DMA: H_2O: HNO_3=1.5:0.5:0.0225

• The ratio of DMA: H_2O: HNO_3=1.2:0.5:0.0180

• The ratio of DMA: H_2O: HNO_3=1.8:0.6:0.0180

• The ratio of DMA: H_2O: EtOH: HNO_3=1.5:0.5:0.4:0.015

Interpretation of Results:

• [Provide a preliminary analysis of the results, considering the impact on MOF's crystallinity and structure]

Schematic diagram of DeepSeeker-R1 prompt output.

DeepSeek-R1 output

of course! The following is a question structure that you can use to guide DeepSeeker R1 as an AI network chemist: You are an AI network chemist specializing in metal organic frameworks (MOFs), tasked with assisting human apprentices in research projects using H_2CMNDI as a ligand to develop novel Zn/Cd-MOF. The entire project will be divided into five stages:

1) Synthesis of ligands.

2) High throughput screening of MOFs and the molecular structure of the synthesized product through single-crystal X-ray diffraction analysis (SCXRD).

3)Optimization of synthesis results through PXRD.

4) Detailed structural analysis and characterization of MOFs.

5) Repeatability verification and final confirmation

You will convey your findings, evaluations, and recommendations through the following structured outputs:

Input template:

Current Summary: {summary}

Last iteration: {iteration}

Latest task: {last task}

Manual feedback: {human feedback}

Output template:

Output Summary:<updated summary>

Current stage and iteration:<X-X>

Status assessment:<reasoning>

Task Selection 1:<next Task Choice 1>

Task selection 2:<alternative next Task choice>

Task selection 3:<alternative next Task choice>

Output content description: The output summary needs to be updated with experimental data in laboratory report format. Old information should be integrated and new details

added to the current summary and the latest tasks and results should be supplemented, with an overall limit of 20 sentences.

Current stage and iteration: It is necessary to clearly label the combination of numbers representing the current stage and iteration (such as 1-3, 2-6).

Status assessment: Analyze the current status based on the current summary and the latest task results, and provide a detailed explanation of the subsequent task arrangements.

Task selection: Provide instructions for the next steps that humans should try, including up to three possible task options that may continue the current stage, each of which should be explained in no more than 10 concise sentences.

Shows a schematic diagram of testing the original prompt on DeepSeek-R1.

Evaluation: DeepSeek-R1 Input and Output

You are an AI grid chemist specializing in the research of metal organic frameworks (MOFs), responsible for assisting human apprentices in conducting research and development projects. The project aims to develop novel Zn/Cd-MOF materials using H_2CMNDI as a ligand, and you will participate in the five stages of the project:

Current progress: Preparation of ligands using solvent method

Latest iteration: 1-5 Latest task: Synthesis of H_2CMNDI ligand User feedback: Ready to enter the next stage.

Final summary diagram of the development of the network ChemSeek.

Final Summary (Cd-CMNDI)

We have developed a new Cd-CMNDI research project using naphthalimide (H_2CMNDI) as a ligand. After five key stages of in-depth exploration, we have achieved significant results.

In the first stage, we started synthesizing the ligand H_2CMNDI. For this purpose, we systematically reviewed relevant literature and used 1,4,5,8-naphthalene tetracarboxylic acid dianhydride and glycine as reaction materials. After small-scale synthesis experiments, a yellow solid was finally obtained, which was confirmed to be the H_2CMNDI product by nuclear magnetic resonance spectroscopy analysis. The 1H and 13C nuclear magnetic resonance spectra were consistent with the expected H_2CMNDI structure, thus successfully verifying the synthesis of the organic linker.

In the second stage, our research focus shifted to high-throughput screening of MOFs, aiming to optimize the synthesis efficiency. Based on the successful synthesis of H_2CMNDI ligand, we conducted a series of experiments and ultimately determined that the optimal MOF formation effect was achieved when the ratio of H_2CMNDI to cadmium was 1:2. In addition, water has been proven to be an effective regulator, and the mixed use of DMA and H_2O can significantly improve crystal quality. When the ratio of DMA to H_2O is 3:1, adding HNO_3 (8 M,150 μL) can maintain the same crystallinity. By examining the reaction time, we found that the effects of 48 hours and 72 hours on MOF formation were negligible and the yield is highest at 90°C.

In the third stage, the PXRD peaks are consistent. MOFs synthesized at 90°C exhibit similar crystallinity and purity, with the highest yield.

In the fourth stage, we conducted a detailed structural analysis and characterization of MOF, confirming that its thermal stability can reach 300°C and it maintains chemical stability in most solvents.

Finally, in the fifth stage, we aim to verify the reproducibility of the entire process from MOF synthesis to post-processing and characterization. All tests, including thermogravimetric analysis and chemical stability testing, were consistent with previous results, confirming the accuracy and reproducibility of our synthetic approach. Finally, a new type of Cd-CMNDI was successfully developed, and its thermal and chemical stability were verified.

Final summary diagram of the development of the network ChemSeek.

Final Summary (Zn-CMNDI)

We have developed a new Zn-CMNDI research project using naphthalimide (H_2CMNDI) as a ligand. After five key stages of in-depth exploration, we have achieved significant results.

In the first stage, we started synthesizing the ligand H_2CMNDI. For this purpose, we systematically reviewed relevant literature and used 1,4,5,8-naphthalene tetracarboxylic acid dianhydride and glycine as reaction materials. After small-scale synthesis experiments, a yellow solid was finally obtained, which was confirmed to be the H_2CMNDI product by nuclear magnetic resonance spectroscopy analysis. The 1H and 13C nuclear magnetic resonance spectra were consistent with the expected H_2CMNDI structure, thus successfully verifying the synthesis of the organic linker.

In the second stage, our research focus shifted to high-throughput screening of MOFs, aiming to optimize the synthesis efficiency. Based on the successful synthesis of H_2CMNDI ligand, we conducted a series of experiments and ultimately determined that the optimal MOF formation effect was achieved when the ratio of H_2CMNDI to zinc was 1:2. In addition, ethanol has been proven to be an effective regulator, and the mixed use of DMA and H_2O can significantly improve crystal quality. Add 1.5mL DMA, 0.5mL H_2O, 0.4mL EtOH, and then add HNO_3 (8 M,150 μL) to maintain consistent crystallinity. By examining the reaction time, we found that 48 hours and 72 hours had little effect on MOF formation, while the yield was highest at 90°C.

In the third stage, the PXRD peaks are consistent. MOFs synthesized at 90°C exhibit similar crystallinity and purity, with the highest yield.

In the fourth stage, we conducted a detailed structural analysis and characterization of MOF, confirming that its thermal stability can reach 300°C and it maintains chemical stability in most solvents.

Prompt for Reticular ChemSeek and Output.

Prompt for Reticular ChemSeek (initial)：

1. $MgSO_4$ (3 mg, 0.025 mmol) and H_2CMNDI (4 mg, 0.0105 mmol) were dissolved in a mixed solution of 0.5 mL H_2O and 1.5 mL DMA, and HNO_3(150 µL 8 M) solution was added dropwise. The solution was stirred at room temperature until it became clear and transparent. The solution was transferred to a Pyrex heat-resistant glass bottle and heated in a 90 °C oven for 2 days. After cooling at room temperature, brown block crystals were obtained;

2. Dissolve $CaCl_2$ (4 mg, 0.0360 mmol) in 0.5 mL H_2O, then dissolve H_2CMNDI (3 mg, 0.0079 mmol) in 1.5 mL DMA, following the same method as Mg-CMNDI, to obtain yellow block shaped crystals;

3. $Sr(NO_3)_2$ (3 mg, 0.0142 mmol) and H_2CMNDI (4 mg, 0.0105 mmol) were dissolved in a mixed solution of 0.5 mL H_2O and 1.5 mL DMA. The subsequent method was the same as Mg-CMNDI to obtain brown block shaped crystals;

4. $Co(NO_3)_2 \cdot 6H_2O$ (3 mg, 0.0103 mmol) and H_2CMNDI (4 mg, 0.0105 mmol) were dissolved in a mixed solution of 0.5 mL H_2O and 1.5 mL DMA. Then add HNO_3 (150 µL 8 M) solution to the mixture. Stir the solution mixture at room temperature until it becomes clear and transparent, then transfer it to a Pyrex heat-resistant glass bottle. After heating at 90 °C for 2 days, cool it to room temperature to produce red block crystals.

Now, I plan to synthesize Zn-CMNDI and Cd-CMNDI. Given that zinc nitrate is a controlled explosive precursor with strict management and usage restrictions, I will choose zinc and cadmium salts other than zinc nitrate respectively, with the ligand being H_2CMNDI. Please help me design several schemes to cultivate better single crystals.

Reticular ChemSeek Output (initial)：

Plan 1: Direct Analog to Co/Ni/Cu Method (Baseline)

Target: Initial attempt mimicking successful transition metal syntheses.

Rationale: Proven reliability; acidity and solvothermal conditions suit Zn/Cd.

For Zn-CMNDI:

$ZnCl_2$ (anhydrous, MW=136.3): 1.40 mg (0.0103 mmol); H_2CMNDI: 4.00 mg 0.0105 mmol); Solvent: H_2O (0.5 mL) +DMA (1.5 mL); Add: HNO_3 (8 M, 150 μL) Stir at RT until clear → Transfer to Pyrex vial → Heat at 90°C for 3 days → Cool slowly to RT. M:L=1:1.02 (slight ligand excess)

For Cd-CMNDI:

$Cd(NO_3)_2 \cdot 4H_2O$ (MW=308.48): 3.17 mg (0.0103 mmol); H_2CMNDI: 4.00 mg (0.0105 mmol); Solvent: H_2O (0.5 mL) + DMA (1.5 mL); Add: HNO_3 (8 M, 150 μL) Stir at RT until clear → Transfer to Pyrex vial → Heat at 90°C for **3 days** → Cool slowly to RT. M:L=1:1.02 (slight ligand excess)

Plan 2: Liquid-phase diffusion method

Target: Zn-CMNDI and Cd-CMNDI

Metal salt solution (inner tube): Weigh an appropriate amount of metal salt ($Zn(OAC)_2$ or $CdCl_2$, approximately 0.01 mmol) and dissolve it in 0.5 mL of pure a H_2O: DMA = 1:1 mixed solvent.

Ligand solution (outer tube): Weigh H_2CMNDI (approximately 0.010 mmol) and dissolve it in 2.0 mL of pure DMA. It is advisable to add 1-2 microliters of dilute nitric acid (e.g., 1 M) or dilute acetic acid (e.g., 1 M) to assist dissolution, but this is not mandatory.

Prompt for Reticular ChemSeek (The first iteration)：

Plan 1：

Zn-CMNDI：The smaller crystal residue was obtained, with poor transparency of the crystal and some black dot-like non-transparent substances appearing.

Cd-CMNDI：A small amount of crystal residue was obtained in the clear and transparent liquid.

Plan 2:

Zn-CMNDI：White flocculent matter appeared in the solution, along with a small amount of sediment.

Based on the above experimental phenomena, please provide a solution and the adjusted formula. Under the premise of synthesizing transparent block-shaped crystals, try to ensure the yield as much as possible.

Reticular ChemSeek Output (The first iteration)：

Plan 1: Increased Metal Ratio & Lower Concentration

Target: Prevent ligand-dominated precipitation; slower growth.

Rationale: Increasing the metal-to-ligand ratio (M: L > 1) ensures that the ligands are completely coordinated and consumed by metal ions, thereby inhibiting their separate precipitation due to supersaturation. Meanwhile, reducing the total concentration of reactants can effectively decrease the supersaturation of the system, lower the nucleation rate, and encourage the limited growth units to be preferentially used for the slow and orderly growth of a few nuclei, ultimately resulting in larger-sized and defect-free crystals.

For Zn-CMNDI:

$ZnCl_2$: 1.54 mg (0.0113 mmol); H_2CMNDI: 3.60 mg (0.0095 mmol); Solvent: H_2O (0.6 mL) +DMA (1.8 mL) (Total vol.=2.4 mL-0.0047 M in Zn); Add: HNO_3 (8 M, 150 μL)

Stir until clear → Pyrex vial → 90°C for **4 days** → Slow cooling. *M: L=1.19:1*

For Cd-CMNDI:

$Cd(NO_3)_2{\cdot}4H_2O$: 4.17 mg (0.0135 mmol); H_2CMNDI: 3.60 mg (0.0095 mmol); Solvent: H_2O (0.6 mL) + DMA (1.8 mL) (~0.0050 M in Cd); Add: HNO_3 (8 M, 150 μL)

Stir until clear → Pyrex vial → 90°C for4 days → Slow cooling. *M: L*=1.42:1

Plan 2: Solvent Diffusion/Gradient Method

Bottom Layer: Dissolve metal salt in 0.5 mL H_2O; Add HNO_3 (8 M, 150 μL); Transfer to Pyrex vial or thin tube.

Middle Layer: Carefully add 0.5 mL dry DMA (avoid mixing).

Top Layer: Dissolve H_2CMNDI in 1.0 mL DMA; Layer gently on top of middle layer.

Crystallization: Cap vial loosely (allow slight evaporation); Place at 60-70°C for 5-7 days (lower temp slows diffusion); Monitor crystal growth at interface/middle layer.

Ratios (Adjust based on Scheme 2):

Zn: $ZnCl_2$ (1.54 mg, 0.0113 mmol) +H_2CMNDI (3.60 mg, 0.0095 mmol)

Prompt for Reticular ChemSeek (The second iteration)：

Plan 1：

Zn-CMNDI： The obtained liquid is almost clear and transparent.

Cd-CMNDI： A large amount of white flocculent sediment appeared at the bottom of the bottle.

Plan 2：

Zn-CMNDI： A large number of relatively transparent and fine particles appeared. Based on the above experimental phenomena, please provide a solution and the adjusted formula. Under the premise of synthesizing transparent block-shaped crystals, try to ensure the yield as much as possible.

Reticular ChemSeek Output (The second iteration)：

For Zn-CMNDI:

Plan 1: Reduce acidity and explore the mild growth window.

Target: Obtain single crystals that are larger in size, have fewer defects and are more complete.

Rationale: High acidity (150 μL) forces the ligand to protonate rapidly, leading to disordered aggregation and the formation of a large number of defective nuclei. Reducing the acidity allows the ligand (H_2CMNDI) to deprotonate at a more controllable rate and extent, thereby reducing the nucleation density.

Experimental plan:

Basic recipe (per serving):

$ZnCl_2$: 1.4 mg (0.0103 mmol)

H_2CMNDI: 4.00 mg (0.0105 mmol)

H_2O: 0.5 mL

DMA: 1.5 mL

HNO_3 (8 M): 75 μL

Stir until clear → Pyrex vial → 90 °C for 3 days → Slow cooling

Plan 2: Increase the acidity and test the crystallization boundary conditions.

Target: Under the same volume system, the amount of nitric acid was significantly increased to 225 μL to create an extremely acidic environment.

Rationale: Extremely high acidity will cause the carboxyl groups of the ligand to be almost completely protonated, seriously hindering their coordination ability with zinc ions.

Experimental plan:

Basic recipe (per serving):

$ZnCl_2$: 1.4 mg (0.0103 mmol)

H_2CMNDI: 4.00 mg (0.0105 mmol)

H_2O: 0.5 mL

DMA: 1.5 mL

HNO_3 (8 M): 225 μL

Stir until clear → Pyrex vial → 90°C for 3 days → Slow cooling

Plan 3: Adjust the stoichiometry and acidity to optimize the driving force of the reaction.

Target: Comprehensively adjust multiple parameters: 1) Use metal in excess (M:L = 1.54:3.2 ≈ 1.44:1); 2) Moderately high acid (200 μL); 3) High concentration (total volume 2.0 mL).

Rationale: It is essential to ensure that the ligand is a "limiting reactant" that can be completely consumed in theory. This helps increase the crystallization yield and may alter the kinetics of crystal growth, favoring the growth of certain crystal faces. The use of 200 μL of nitric acid represents a balance point between "possibly too acidic" and "sufficiently dissolved". The aim is to control the nucleation rate by acidity while ensuring the ligand is fully dissolved.

Experimental plan:

Basic recipe (per serving):

$ZnCl_2$: 1.54 mg (0.0113 mmol)

H_2CMNDI: 3.2 mg (0.0084 mmol)

H_2O: 0.5 mL

DMA: 1.5 mL

HNO_3 (8 M): 200 µL

Stir until clear → Pyrex vial → 90°C for 3 days → Slow cooling

For Cd-CMNDI:

Plan 1: Halving the amount of nitric acid while maintaining the metal excess strategy aims to promote the ordered self-assembly of the Cd-CMNDI coordination polymer, thereby obtaining high-quality single crystals.

Target：By eliminating the "lock" of high acidity on the coordination reaction and taking advantage of the driving force of metal excess, high-quality, three-dimensionally grown Cd-CMNDI single crystals were induced to form.

Rationale: Reducing the amount of nitric acid from 150 µL to 75 µL is the most crucial and direct improvement. The high acidity environment keeps the carboxyl groups of the ligand (H_2CMNDI) protonated, preventing them from effectively coordinating with Cd^{2+}. Lowering the acidity creates a moderate deprotonation condition for the ligand, allowing it to coordinate with the metal center in the form of carboxylate, which is the primary prerequisite for forming an ordered crystalline network structure. Excess metal ions can act as "connectors" or "structure-directing agents", filling in the ligand network structure, potentially connecting different layers or altering the charge balance and steric hindrance during the crystallization process, thereby suppressing the dominant growth of two-dimensional sheets and encouraging the crystal to develop in the thickness direction (the third dimension) as well, which is conducive to forming thicker block-like crystals.

Basic recipe (per serving):

$Cd(NO_3)_2·4H_2O$: 3.17 mg (0.0134 mmol)

H_2CMNDI: 4.00 mg (0.0105 mmol)

H_2O: 0.5 mL

DMA: 1.5 mL

HNO_3 (8 M): 75 μL

Stir until clear → Pyrex vial → 90°C for 3 days.

Prompt for Reticular ChemSeek (The third iteration: Zn-CMNDI):

Plan 1： The obtained crystals exhibit suboptimal dimensions and possess surfaces with insufficient smoothness.

Plan 2： Needle-shaped crystals.

Plan 3： Thinner flaky crystals were observed, accompanied by a small amount of insoluble precipitate.

Reticular ChemSeek Output (The third iteration: Zn-CMNDI)：

Target: Enhance the overall crystallinity and morphological uniformity of the crystals.

Rationale: Nitric acid serves a dual function in the reaction system: it functions not only as a proton source but also as a provider of coordinating anions in the reaction system. Variations in its concentration directly influence the equilibrium between these two competing processes.

Plan 1: $ZnCl_2$: 3 mg (0.0220 mmol); H_2CMNDI: 4.00 mg (0.0105 mmol); Solvent: H_2O (0.5 mL) +DMA (1.2 mL); Add: HNO_3 (8 M, 180 μL)

Stir until clear → Pyrex vial → 90°C for **3 days** → Slow cooling.

Plan 2: $ZnCl_2$: 3 mg (0.0220 mmol); H_2CMNDI: 4.00 mg (0.0105 mmol); Solvent: H_2O (0.6 mL)

+DMA (1.8 mL); Add: HNO_3 (8 M, 180 μL)

Stir until clear → Pyrex vial → 90°C for **3 days** → Slow cooling.

Prompt for Reticular ChemSeek (The fourth iteration: Zn-CMNDI):

Plan 1: A small quantity of pale yellow crystals, and flocculent aggregates.

Plan 2: Fine particulate matter is observed in the solution, resulting in turbidity.

Based on the above experimental phenomena, please provide a solution and the adjusted formula. Under the premise of synthesizing transparent block-shaped crystals, try to ensure the yield as much as possible.

Reticular ChemSeek Output (The fourth iteration: Zn-CMNDI)：

Target: Modulate solubility to achieve a balanced interplay between nucleation and crystal growth.

Rationale: The reduction of the nitric acid concentration shifted the system from inhibiting to promoting crystallization, representing a critical balance between ligand coordination and metal hydrolysis.

Plan 1: $ZnCl_2$: 3 mg (0.0220 mmol); H_2CMNDI: 4.00 mg (0.0105 mmol); Solvent: H_2O (0.5 mL) +DMA (1.5 mL); Add: HNO_3 (8 M, 150 μL)

Stir until clear → Pyrex vial → 90°C for 3 days → Slow cooling.

Prompt for Reticular ChemSeek (The last iteration: Cd-CMNDI)

$Cd(NO_3)_2 \cdot 4H_2O$ was 3.17 mg, H_2CMNDI was 4 mg, the volume of DMA was 1.5 mL, water was 0.5 mL, and nitric acid was 75 μL, and the reaction conditions were set at 90°C for 72 hours, the formation of irregular thin sheets was observed. Based on experimental phenomena, please provide a solution to make the crystal grow thicker and offer suitable formulas.

Reticular ChemSeek Output (The last iteration: Cd-CMNDI)：

Plan 1: Control the acidity to optimize crystal morphology.

Target: Adjusting the acidity control the nucleation and growth kinetics.

Rationale: Acidity directly affects the deprotonation rate and extent of ligands, thereby controlling the nucleation and growth kinetics.

Adjusting acidity is the most crucial approach to promoting the crystal growth from 2D thin sheets to 3D thick blocks.

Prepare 3 vials for each metal:

Vial 1: HNO_3 (8 M, 75 μL)

Vial 2: HNO_3 (8 M, 150 μL)

Vial 3: HNO_3 (8 M, 225 μL)

Heat at 90°C for 3 days and compare crystal size/clarity.

Plan 2: Implement a layered diffusion strategy to achieve controlled self-assembly (Alternative solutions).

Target: Leverage a stable liquid-liquid interface to create a gentle concentration gradient for reagents, facilitating slow nucleation and ordered growth conducive to high-quality single crystals.

Rationale: This method separates metal ions and ligands physically, allowing gradual diffusion and meeting at the interface. It significantly reduces nucleation density and prevents rapid, disordered aggregation, avoiding thin sheets or powders. Slow interfacial mass transport favors thermodynamically stable structures and enables uniform growth in all dimensions, producing thicker, well-defined crystals suitable for structural analysis.

Lower layer (aqueous phase): Dissolve 3.5 mg of $Cd(NO_3)_2 \cdot 4H_2O$ in 1.0 mL of H_2O.

Middle layer (buffer layer): Carefully add 0.5 mL of DMA/H_2O (v/v = 1:1) mixed solvent.

Upper layer (ligand layer): Dissolve H_2CMNDI (4.0 mg) in 1.0 mL DMA and add HNO_3 (8 M, 10 μL). // The acid and the ligand are both in the organic phase.

Reaction procedure:

1. Carefully add the three layers of liquid in sequence to a slender glass tube or small bottle, avoiding mixing.

2. Seal it with a sealing film and pierce several small holes in it to allow for extremely slow solvent evaporation.

3. Place it in a dark place at room temperature and free from vibration.

4. Let it stand for 1 to 2 weeks, and regularly observe the crystal growth at the interface (especially at the middle and lower layer interfaces).

Prompt for Reticular ChemSeek (The last iteration: Zn-CMNDI)

3.00 mg (0.0220 mmol) of anhydrous $ZnCl_2$ (molecular weight 136.3 g/mol) and 4.00 mg (0.0105 mmol) of H_2CMNDI were weighed and dissolved in a mixed solvent of H_2O (0.5 mL) and DMA (1.5 mL). Then, 150 μL of 8 M HNO_3 was added, and the solution was stirred at room temperature until it became clear. The solution was then transferred to a Pyrex reaction flask and heated at 90°C for 72 hours. Afterward, it was slowly cooled to room temperature. The experiment observed the formation of thick plate-like crystals with crystal defects. Based on the crystal phenomena obtained from this formula, the formula was further optimized to control the crystal growth process, aiming to obtain crystals with high integrity, few defects and suitable for single crystal XRD testing.

Reticular ChemSeek Output (The last iteration: Zn-CMNDI)：

Plan 1: Ethanol cosolvent optimization method

Target: By introducing ethanol as a poor solvent, the supersaturation of the system and the nucleation process are regulated to suppress crystal defects and promote the growth of complete and high-quality single crystals.

Rationale: The addition of ethanol will reduce the solubility of the coordination polymer in the mixed solvent, thereby increasing the supersaturation of the system and regulating the nucleation kinetics. By controlling the proportion of ethanol, uniform nucleation and three-dimensional balanced growth can be promoted, avoiding the formation of two-dimensional thin sheets or defective crystals, and ultimately obtaining thicker and more transparent single crystals.

Experimental plan:

Basic recipe (per serving):

$ZnCl_2$: 3 mg (0.0220 mmol)

H_2CMNDI: 4.00 mg (0.0105 mmol)

H_2O: 0.5 mL

DMA: 1.5 mL

HNO_3 (8 M): 150 μL

Ethanol gradient setting:

Prepare three identical reaction tubes and add ethanol to each tube in the following proportions:

Tube A (Low Ethanol): Anhydrous ethanol 0.2 mL (ethanol content 10% v/v)

Tube B (High Ethanol): Anhydrous ethanol 0.4 mL (ethanol content 20% v/v)

Procedure:

1.Dissolve & Acidify:

Dissolve $ZnCl_2$ in 0.5 mL H_2O → add HNO_3 (150 μL) → stir until clear.

In a separate vial, dissolve H_2CMNDI in 1.5 mL DMA.

2.Combine & Add Ethanol:

Mix metal and ligand solutions → stir 5 min.

Add ethanol (0.2 and 0.4 mL) dropwise while stirring → solution should remain clear.

(If cloudiness appears: add 1–2 drops HNO_3 until clear).

3.Crystallization:

Transfer to 5mL Pyrex vial → seal tightly.

Heat at 90°C for 3 days.

Then cool at a rate of 5°C per hour to 60°C and maintain at this temperature for 12 hours.

Finally, allow to cool naturally to room temperature.

Plan 2: Seed crystal method and slow evaporation (**Alternative solutions**).

Target: Utilizing the obtained "thick plate" as a seed, the growth of a new generation of high-quality crystals is guided in a near-equilibrium environment.

Rationale: Defective crystals usually originate from spontaneous nucleation. Using preformed crystals (seeds) as perfect templates can significantly reduce the energy required for nucleation and suppress the formation of new defects. Slow evaporation can gently increase supersaturation, promoting extremely slow and ordered epitaxial growth of the seeds.

Optimize the formula:

Mother liquor preparation:

$ZnCl_2$, 2.50 mg (0.0183 mmol)

H_2CMNDI, 3.20 mg (0.0084 mmol) // Reduce concentration to prevent spontaneous nucleation

Solvent: DMA (1.0 mL) + H_2O (0.5 mL)

30 μL of 8 M HNO_3

Experimental Procedure:

1. Prepare the above-mentioned mother liquor and ensure it is completely clear.
2. Filter the mother liquor through a 0.22 μm filter head to remove dust and other nucleation sources.
3. Transfer the mother liquor to a small glass bottle with a lid (such as a scintillation vial).
4. From your previous products, select the smallest and most intact thick plate crystal under a microscope with a fine needle as the seed crystal.
5. Carefully place the seed crystal into the mother liquor.
6. Loosely cover the bottle cap (for example, by pricking a few small holes in the sealing film), allowing the solvent to evaporate very slowly.

7. Place the entire device on a vibration-free and temperature-stable laboratory bench, and let it stand at room temperature for 1 to 2 weeks. Observe regularly whether the seed crystal has grown.

Compared with the AI design method, the high-throughput screening method may require a greater number of experiments

With its in-depth knowledge in the related fields, ChemSeek guides research from "trial and error" to "mechanism-based rational design", significantly reducing the number of experimental iterations compared to simple empirical and high-throughput screening methods. Here, we take Zn-CMNDI as an example to compare it with simple empirical and high-throughput screening methods, visually demonstrating the significance of ChemSeek for the rapid design and synthesis of MOFs.

ChemSeek Iters: 0

$ZnCl_2$ 1.4mg

H_2CMNDI 4mg

DMA 1.5mL

H_2O 0.5mL

8M HNO_3 150 μL

90°C for 72 hours

Final formula

$ZnCl_2$ 3mg

H_2CMNDI 4mg

DMA 1.5mL

H_2O 0.5mL

8M HNO_3 150μL

EtOH 0.4mL

90°C for 72 hours

This formula was derived by ChemSeek through a comprehensive analysis of literature data. Based on this formula as the initial condition, a strategy combining traditional empirical trial-and-error methods with high-throughput screening techniques was adopted, along with practical experience in single crystal cultivation, to estimate the number of experimental iterations required to obtain the final optimized formula.

H_2CMNDI: The final formula contains 4 mg of H_2CMNDI.

$ZnCl_2$: The final formula contains 3 mg of $ZnCl_2$. The dosage of $ZnCl_2$ was gradually increased from 1.4 mg to 3.0 mg in increments of 0.2 mg, requiring a total of 9 experimental steps.

H_2O: The final formula contains 0.5 ml of H_2O.

8M HNO_3**:** The final formula contains 150 μL of 8M HNO_3**.**

EtOH: The final optimized formula contains 0.4 mL of ethanol. Based on experimental experience, the amount of ethanol added was gradually increased from 0 mL to 1.0 mL in increments of 0.2 mL, requiring a total of 6 experimental steps.

Temperature: The final formula temperature is 90°C.

Starting from the initial recommendation of ChemSeek at the 0th iteration, combined with experimental experience and high-throughput screening methods, it is estimated that 5×9=45 experiments are needed to obtain the final formula. This estimation is based on the premise that key parameters such as nitric acid, water, and temperature remain unchanged during the optimization process. If all these factors are considered to be variable and the most optimistic estimate is made, with each variable changing only twice, then there will be 2×2×2=8 combinations of conditions for the four factors.

Therefore, the total number of experiments will increase to 45×8=360. It should be noted that this is only a theoretical estimate; in the actual MOF synthesis process, due to the influence of various complex factors, the exact number of experiments is difficult to precisely define. In the practice of MOF single crystal cultivation, conducting 300 to 600 experiments using high-pressure resistant vials or autoclaves is within the normal range of operations. In contrast, ChemSeek significantly reduces the experimental requirements through rational design based on reaction mechanisms, successfully compressing the required cultivation steps to 11, greatly enhancing the efficiency of MOF crystal synthesis and fully demonstrating its significance in the rapid design and efficient synthesis of MOF materials.

Similarly, when the Cd-CMNDI system was evaluated using the same approach based on pure experimental experience and high-throughput screening strategies, it was estimated that 192 experiments would be required. However, ChemSeek reduced the number of experiments to just 6. To more intuitively demonstrate the significant advantage of ChemSeek in reducing the number of crystal growth attempts, the differences in the number of experiments between the formula optimized by ChemSeek and the traditional empirical method combined with high-throughput screening were compared and analyzed using a bar chart, as shown in Fig. S1.

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