# Moisture-triggered Controlled Release of a Natural Food Preservative by a Microporous Metal-Organic Framework

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# **Supporting Information**



**Fig. S1.** Top: Chemical structure of AITC and some AITC containing plants; Bottom: 3D space filling of the AITC molecule and its dimension.

#### S1. Synthesis and Structure Characterization

#### S1a. Ligand synthesis and MOF synthesis

*Synthesis of 4,4'-azobispyridine (apy):* The apy was synthesized based on published method.<sup>1</sup> All chemicals purchased are of reagent grade and were used without purification. A solution of 4-aminopyridine (Alfa Aesar, 12 g, 98%, 0.128 mol) in DI water (240 mL) was added dropwise into a two-neck round bottom flask containing

1.6 L of sodium hypochlorite (VWR, 10-14wt %, NaOCl, being chilled in ice-water bath and magnetically stirred) over a period of 1 hr. The mixture was stirred at 0 °C for another 30 min before the orange-colored precipitate was filtered and the filtrate extracted with chloroform (200 mL  $\times$  3). The extracted solution was dried over anhydrous sodium sulfate for 20 min and evaporated to let them dry with a rotary evaporator. Filtered precipitate and dried filtrate are combined and then re-dissolved in DI water. They are boiled and placed it in ice-water bath to re-crystallization of crude product. The pure product was obtained as an orange-colored, crystalline solid (needle shaped crystals, 7.32 g, 64% yield based on 4-aminopyridine). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): 7.75 (d, 4H, J = 6.2 Hz), 8.88 (d, 6H, J = 6.2 Hz).

Synthesis of **1**: Compound **1** was prepared solvothermally by mixing Zn(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (98%, Acros , 0.1485g, 0.5mmol), 4,4'-apy (0.0460g, 0.25mmol) and biphenyldicarboxylic acid (bpdc, Aldrich, 99%+, 0.1210g, 0.5mmol) in 10 mL of DMF (Fischer, 99%+ Reagent Grade ) in a 20 mL glass vial. The mixture was homogenized in ultrasonic bath for 2 min to agitate particles in the solution. The vial was heated in an oven at 100 °C for 20 hours and then cooled down naturally to room temperature. The reddish crystals were filtered and washed with DMF and dried in air (yield: 94.2%). Crystal data from single crystal X-ray diffraction study for Compound *1*:  $C_{63.40}H_{56.57}N_{7.08}O_{15.08}Zn_3$ ,  $M_r = 1355.06$ , Monoclinic, space group  $P2_1/c$ , a = 19.6891(18) Å, b = 13.7933(13) Å, c = 26.276(2) Å,  $\beta = 96.242(2)^\circ$ , V = 7093.8(11) Å<sup>3</sup>, Z = 4, GOF = 1.023, R1[I > 2 $\sigma$ (I)] = 0.0763, wR2[I > 2 $\sigma$ (I)] = 0.1719, CCDC number: 1429414.

#### S1b. Crystal structure determination:

Single crystal X-ray diffraction analysis of Compound 1 was performed on a Bruker APEX-II CCD system with monochromized Mo K $\alpha$  radiation ( $\lambda = 0.71073$  Å). Crystal structure was solved by the SHELX97 program with the final full-matrix least-square refinement on F2. Summary of single crystal data is listed in Table S1.

Compound	[Zn <sub>3</sub> (bpdc) <sub>3</sub> (apy)]·3.08DMF
Formula	$C_{63.40}H_{56.57}N_{7.08}O_{15.08}Zn_3$
М	1355.06
Crystal system	Monoclinic
Space group	$P2_1/c$
a, Å	19.6891(18)
b, Å	13.7933(13)
c, Å	26.276(2)
α, °	90.00
β, °	96.242(2)
γ, °	90.00
V, Å <sup>3</sup>	7093.8 (11)
Ζ	4
Temperature, K	100(2)
λ(Mo Kα), Å	0.71073
D, g/cm <sup>3</sup>	1.269
Reflections collected	59805
$R1^{a} [I > 2\sigma(I)]$	0.0763
$wR2^{b}\left[I > 2\sigma(I)\right]$	0.1719
Goodness-of-fit	1.023
CCDC number	1429414

 Table S1. Single crystal data for Compound 1.

 $aR1 = \sum |Fo-Fc| / \sum |Fo|$ 

 $^{b}wR2 = \sum [w(Fo2 - Fc2)2] / w(Fo2)2]1/2$ 

# S1c. Powder X-ray diffraction (PXRD) analysis:

Powder X-ray diffraction patterns were recorded on a Rigaku Ultima-IV X-ray diffractometer using Cu K $\alpha$  radiation ( $\lambda = 1.5406$  Å). Graphite monochromator was used and the generator power settings were at 40 kV and 40 mA. Data were collected between a 20 of 3-50° with a step size of 0.02° at a scanning speed of 2.0 deg/min.



**Fig. S2.** PXRD patterns of Compound 1: Simulated (black), as made (red) and after gas sorption study (blue).

### S1d. Thermogravimetric analysis (TGA):

Thermogravimetric analysis (TGA) was carried out on a TA Instrument Q5000R thermal gravimetric analyzer. Around 5 mg of sample was loaded onto a platinum sample pan and heated from room temperature to 600 °C at a rate of 5 °C/min under nitrogen purge.



Fig. S3. TGA curve of Compound 1.

#### **S2.** Gas Sorption Measurements

Gas sorption experiments at low pressure (up to 1 bar) were performed using a volumetric gas sorption analyzer (Autosorb-1 MP, Quantachrome Instruments). Cryogenic temperatures are reached by using liquid nitrogen (77 K) or liquid argon (87 K) as coolants. Ultra high purity (99.999%) argon, hydrogen were used. Around 150 mg outgassed sample was used for the measurements. The initial outgassing process for as made sample was carried out at 433 K overnight (under vacuum). The weight of sample was recorded before and after outgassing to confirm the removal of guest molecules. The outgassing procedure was repeated on the same sample between experiments for 2~4 hour.



**Fig. S4.** Ar adsorption (closed symbols) and desorption (open symbols) isotherms at 87 K on **1**' (left) and Horvath-Kawazoe pore size distribution of **1**' calculated from Ar adsorption isotherm at 87 K (right).

#### **S3.** AITC Loading Experiments

Allyl Isothiocyanate (AITC, 98% Matrix Scientific, Colombia, SC, USA) was loaded onto 1' via vapor adsorption on an adsorption analyzer modified from TGA Q50 (TA instruments). Ultra high purity (99.999%) nitrogen was used as carrier gas to flow through an AITC bubbler (18 °C) to produce saturated AITC vapor in nitrogen. AITC partial pressure was varied by changing the blending ratios of AITC-saturated nitrogen and pure nitrogen gas streams. In order to confirm that Compound 2 does not adsorb AITC, a similar loading experiment was performed on 2 under the same experimental conditions. The results are plotted in Fig. S4.



Fig. S5. AITC loading on Compound 1' (red) and 2 (black).

#### **S4. AITC Controlled Release Experiments**

The release of encapsulated AITC from **1**' was studied through gas chromatographic (GC) headspace analysis.

#### S4a. AITC Calibration:

Seven concentrations of AITC (98%, Matrix Scientific, Colombia, SC, USA), namely 2, 4, 10, 20, 40, 64, 100 ppm ( $\mu$ L AITC/250 mL glass jar) were used for preparing AITC headspace calibration curve. The glass jars were sealed properly and kept at room temperature (25 ± 1 °C) for 48 hrs. 0.5 ml of gaseous sample was drawn from each glass jar's headspace with a gas tight 0.5 ml syringe (Baton, Rouge, LA, USA) and injected into the 5890A Hewlett Packed Gas chromatograph operated using the following conditions:

-DB-1 Column (30 m by 0.32 mm diameter; 1 µm film thickness)

-Inlet temperature 220 °C

-Flame ionization detector 250 °C

-Helium as carrier gas

-Column temperature starting at 50 °C for 3 minutes and then increased to 180°C at a rate of 10 °C/min.

The area under the curve for each concentration was obtained from chromatograph software and was plotted against AITC concentration to prepare calibration curve.



Fig. S6. The AITC peak position observed in GC experiments (at 10.97 min).

#### S4b. Controlled release measurements:

AITC was loaded onto 1' through vapor adsorption method mentioned above. In a typical controlled release experiment, ~45 mg AITC loaded 1' (~11 mg AITC) was used. Prepared samples were weighted and placed in the airtight 250 mL glass jars. Three independent studies were conducted as follows:

1). 45 mg of AITC@1' was added to a 250 mL glass jar and sealed properly. The glass jar was maintained at room temperature ( $25 \pm 1$  °C) and room humidity (30 < RH% < 35) to mimic regular room relative humidity condition for storage applications.

2). 45 mg of AITC@1' was added to a 250 mL glass jar and sealed properly. The glass jar was maintained at room temperature ( $25 \pm 1 \text{ °C}$ ). 6 µL water was injected into the sealed jar with a GC syringe through the airtight valve (Mininnert valves, Supelco, Bellefonte, PA, USA) to build up 100% RH, stimulating the instant high relative humidity of fresh produce.

3). ~10 mg ( $\cong$ 10 µL) of pure AITC, while 6 µL water was injected into the sample jar at the onset of the experiment to monitor the effect of instant high relative humidity on the concentration of pure AITC in the vapor phase. The glass jar was maintained at room temperature (25 ± 1 °C)

At the onset of each experiment, 0.5 mL of gaseous headspace from each glass jar was taken by using an airtight clean syringe. The headspace samples (0.5 mL) were taken on a timely manner to measure AITC concentration changes in the gaseous phase.

AITC evaporation		AITC@1' (30%-35% RH)			AITC@1' (100% RH)			
Time (hr)	Peak ar	ea	Time (hr)	Peak area		Time (hr)	Peak area	
	1 <sup>st</sup> test	2 <sup>nd</sup> test		1 <sup>st</sup> test	2 <sup>nd</sup> test		1 <sup>st</sup> test	2 <sup>nd</sup> test
1	16116	16089	1.5	2449.7	2740.0	1	5665.4	2761.0
2	16255	16654	5	3541.03	3555.5	23	16024	15340
3	17565	17294	25	5647	5115	33	16023	16313
22	17338		34	7120	5701	48	16300	16381
48	17392		45	5235	5549			

Table S2. GC trace data for the release of AITC.

#### **S5. Modelling and Calculations**

The molecular structure of AITC was optimized using the Gaussian  $09^2$  suite of programs prior to the simulation. The calculation was performed using the B3LPY<sup>3</sup> hybrid functional and 6-31+G(d)<sup>4</sup> split-valence basis set. A frequency calculation was performed after the geometry optimization to confirm that a true minimum was reached. Then, optimized structure of AITC loaded MOF (AITC@1') was obtained by simulated adsorption employing the Material Studio Sorption package.<sup>5</sup> In this

modeling system, the GCMC method and Burchard Universal Force Field are employed. A supercell of ~  $40 \times 30 \times 50$  Å of the framework structure which contains  $2 \times 2 \times 2$  unit cells was created. The simulation was performed at room temperature for  $10^7$  equilibrium steps to make sure full equilibrium was reached in the final AITC loaded structure. The equilibrium uptake was ~ 8 AITC molecules per unit cell of **1**', thus four AITC molecules per channel segment (each unit cell contains two identical channel segment). For each of the four AITC molecules, the strongest interactions with the MOF framework were identified. Simulated geometry of each AITC molecule with its nearest secondary building unit is shown in Fig. S7, in which atomic distances smaller than the sum of van der Walls radii are indicated by dashed lines. Helium simulated adsorption (at 1 K and 1 bar,  $10^7$  equilibrium steps) was performed on the same supercell to obtain the channel shape and dimensions. The results (Fig. S7a) show the 1D channel is segmented, cylinder shaped. The length of each segment is the same as the unit cell length along a direction (~ 20 Å) and the width is around 7 Å.





(b)



Fig. S7. (a) Simulation of He (at 1 K and 1 bar) showing the 1D, segmented channel in 1' (left). The dimension of each segment is 7 Å  $\times$  20 Å. Each unit cell contains two identical segments (right). (b) Optimized structure of AITC@1' showing the locations of four AITC molecules within a single segment. (c) Each of the four AITC molecules with its nearest secondary building unit (SBU). Pink dashed lines represent the closest distances.

As shown in Fig. S7, each channel segment contains 4 AITC molecules. The strongest AITC-MOF interactions were identified (See Fig. S7, bottom), and an orbital overlap population analysis was performed using extended Hückel method.<sup>6</sup> Because of the large size of the absorption complex with more than 200 atoms in the asymmetric unit, the interaction between AITC and the MOF is estimated by the semi-empirical extended Hückel (EH) method. The four interaction configurations corresponding to Fig. S7c were calculated using the EH package *CACAO*.<sup>7</sup> The EH parameters used are the default values in the package.

The sum of the absolute fragment molecular orbital overlap (SAFMOO), namely the total molecular overlap between AITC and the MOF is in the order of ~1.0 for each of the four molecules within the channel segment (Fig. S7 and Table S3), indicating an extremely strong attraction between the two entities. These values (0.83-1.92) are significantly higher than other analyte-MOF interactions previously investigated by us, for example NB-Zn<sub>2</sub>(oba)<sub>2</sub>(bpy)<sup>8</sup> (NB = nitrobenzene, oba = 4,4'-oxybis(benzolate), bpy = 4,4'-bipyridine), for which the orbital overlap is in the order of ~0.3, too small to trap the NB molecules as the gas pressure is reduced from 1 atm. The calculated absolute reduced overlap population (AROP) between AITC and the MOF is in the order of 0.03, suggesting that while overlap is strong, the type of interaction is still characterized as physisorption that can facilitate the release of the absorbent upon stimulus.

Complex	SAFMOO	AROP
AITC@1' Molecule 1	1.32	0.034
AITC@1' Molecule 2	1.92	0.036
AITC@1' Molecule 3	1.34	0.028
AITC@1' Molecule 4	0.83	0.011

**Table S3.** Sum of the absolute fragment molecular orbital overlap (SAFMOO) and the absolute reduced overlap population (AROP) between AITC molecules and the MOF.

Table S3 lists the calculated sum of the absolute fragment molecular orbital overlap (SAFMOO) and the absolute reduced overlap population (AROP) between the four AITC molecules within each channel segment and the MOF. SAFMOO is used because some molecular orbital overlap is positive and some negative depending on the orientation and coordinate system chosen. If only the overlaps are summed, many will cancel each other. Thus a better measure of the orbital interaction strength is the sum of the absolute overlap. For the same reason, AROP is used.

The SAFMOO is in the order of 1.0 for all four AITC molecules, compared to that of 0.3 of other MOF systems where guest molecules are not trapped inside pores when guest pressure is reduced.<sup>8</sup> This is an indication of very strong interaction between AITC and compound **1**'.

#### **S6. Humidity Stability Test**

To further look into the correlation between the time dependent release curve and the time dependent changes of the phase composition of the carrier material, we performed PXRD analysis on **1** with humidity treatments at different levels (Fig. S8). Saturated aqueous solution of potassium acetate (CH<sub>3</sub>COOK), magnesium nitrate (Mg(NO<sub>3</sub>)<sub>2</sub>), sodium chloride (NaCl), and lead nitrate (Pb(NO<sub>3</sub>)<sub>2</sub>) were placed in four identical airtight desiccators and let it equilibrate for a few hours to afford humid

environment of 23% RH, 52% RH, 75% RH, and 97% RH, respectively. Four idential as made samples of Compound 1 (around 20 mg) were placed in the abovementioned four desiccators and taken out for pxrd measurments after 10 hours, 3, and 5 days. As shown in Fig. S8, Compound 1 was stable under low humidity condition (23% RH) and no structural transformation was observed within 5 days. Again, this confirms that the storage stability of AITC@1' system under low humidity is not a concern. At higher humidity conditions (52% - 75% RH), the structural transformation from 1 to 2 took place gradually, which was not complete within the experimental period (5 days). When the humidity was further increased to 97% RH, structural transformation was observed in a couple of hours and completed within 3 days, which reasonably explains the time dependent release profile of AITC under similar humidity. These time dependent changes of phase composition under different humidity conditions will enable the release of AITC to take place in a fully controlled manner.



(a)



(b)



(c)





**Fig. S8.** PXRD patterns of Compound **1** after different humidity treatments: (a) 23% RH, (b) 52% RH, (c) 75% RH, (d) 97% RH. In each figure, from bottom to top: black, red, blue, purple, magenta, oliva patterns represent simulated **1**, as made **1**, as made **1** after treatment for 10 hrs, 3 days, 5 days, and simulated **2**, respectively.

#### **S7. UV-Vis Spectroscopic Study**

UV-Vis spectroscopic experiments were carried out to determine the fate of the apy ligand after the controlled release of AITC. The results are shown in Fig. S9. A comparison of UV absorption spectra reveals that apy molecules were mostly released from **1**' upon dispersion in water.



**Fig. S9**. UV-Vis absorption spectra of the filtrate of RPM6-Zn dispersed in 10 mL water (0.01 mmol, containing 1.0 mmol/L of apy): at the on-set of the experiment (black); after 1 day (blue). The reference spetrum of apy aqueous solution (1.0 mmol/L) is shown in red.

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