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Chromium(III) Terephthalate Metal Organic Framework (MIL-101): HF-Free Synthesis, Structure, Polyoxometalate Composites, and Catalytic Properties

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Supporting Information

ABSTRACT: Hybrid materials of the metal–organic framework (MOF), chromium(III) terephthalate (MIL-101), and phosphotungstic acid (PTA) were synthesized in aqueous media in the absence of hydrofluoric acid. XRD analysis of the MIL101/PTA composites indicates the presence of ordered PTA assemblies residing in both the large cages and small pores of MIL-101, which suggests the formation of previously undocumented structures. The MIL101/PTA structure enables a PTA payload 1.5–2 times higher than previously achieved. The catalytic performance of the MIL101/PTA composites was assessed in the Baeyer condensation of benzaldehyde and 2-naphthol, in the three-component condensation of benzaldehyde, 2-naphthol, and acetamide, and in the epoxidation of caryophyllene by hydrogen peroxide. The catalytic efficiency was demonstrated by the high (over 80–90%) conversion of the reactants under microwave-assisted heating. In four consecutive reaction cycles, the catalyst recovery was in excess of 75%, whereas the product yields were maintained above 92%.



exceptional stability, and reactivity of the novel composites indicate potential in utilization of these catalytic matrices in a multitude of catalytic reactions and engineering processes.

KEYWORDS: metal-organic framework, chromium(III) terephthalate, phosphotungstic acid, Baeyer condensation, epoxidation

■ INTRODUCTION

Metal organic frameworks (MOFs) are crystalline porous materials whose structures are defined by metal ions or metallic clusters that are connected to bi- or multipodal organic linkers.¹⁻⁶ Their large surface areas, low framework densities, and high pore volumes relative to other porous matrices have motivated a great deal of interest in these materials, which have significant potential for use in a variety of applications ranging from storage of gases to heterogeneous catalysis.⁷⁻²⁰ In particular, externally accessible nanosized cavities and channels allow for the incorporation of substrates inside the crystal to facilitate the heterogeneous catalytic action of these MOFs.^{6,21} Despite the vast number of MOF structures discovered (more than 10 000),²² relatively few reports detail applications of MOFs functionalized by incorporation of metal ions,²³ organic molecules incorporated via host-guest interactions (doping),²⁴ or nanoparticles.²⁵⁻²⁸ The focus of our research has been on applications of well-known MOF matrices that are rendered functional by doping with inorganic guest molecules with a known functionality tailored for catalytic functions. We studied chromium(III) terephthalate (MIL-101) because of its high thermal, chemical, and solvent stability, and large (~3.5 nm) cavities that enable mass transport via pentagonal and hexagonal windows (~1.5 nm).²⁹ In addition, the presence of chromium clusters not bound to the linkers provides coordinatively unsaturated sites (CUS) with mild Lewis acid properties. The acidic CUS sites allow for the postsynthesis modification of MIL-101 with amines that transform MIL-101 into a basic catalyst functional in a Knoevenagel condensation.³⁰ Due to its open-pore structure with large cavities, MIL-101 can be functionalized by Pd or Au nanoparticles and polyoxometalate (POM) anions, making the resulting composite materials effective in hydrogenation reactions and as oxidation catalysts.^{6,31} Among other POM materials that can be utilized to functionalize MIL-101 frameworks, we are interested in phosphotungstic acid (PTA), the strongest heteropolyacid known, with a good thermal stability in the solid state.^{32,33} Following work by Férey et al.,²⁹ there have been several reports on MIL-101 and PTA composites (MIL101/PTA) and their use in oxidation of alkenes using molecular oxygen and aqueous hydrogen peroxide as oxidants,³¹ H₂O₂-based alkene epoxidation,³⁴ Knoevenagel condensation of benzaldehyde and ethyl cyanoacetate, liquid and gas-phase acid-catalyzed esterification (acetic acid with n-butanol, methanol dehydration),²² and carbohydrate dehydration.³⁵

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In the present work, we prepared MIL-101 and MIL101/ PTA composites in water without toxic and highly corrosive hydrofluoric acid (HF). This approach makes the synthesis by solvothermal methods far less challenging. Further, the MIL101/PTA composites were synthesized by either simple thermal treatment of aqueous mixtures of chromium(III) nitrate, terephthalic acid and PTA or by impregnating already synthesized MIL-101 with PTA in aqueous media. It appeared that novel structures of the MIL101/PTA composites ensued, with Keggin ions of PTA being aligned within the MIL-101 pores and cavities. We exploited the acidic properties of the MIL-101 and MIL101/PTA to catalyze Baeyer condensation reactions, wherein arylaldehydes react with phenols or N,Ndimethylaniline (see the Supporting Information, S-1). Heterogeneous acid catalysis of these industrially important reactions³⁶ enhances product purity and greatly simplifies catalyst recovery and recycling, compared to the widely utilized homogeneous catalysis by strong acids such as hydrochloric or sulfuric acids and the like.^{37–39} In the present work, we chose Baeyer reactions that are conducted solvent-free and thus attenuated the effect of the catalyst. Representative syntheses of bioactive drug intermediates, dibenzo $[a_{ij}]$ xanthenes and 1amidoalkyl-2-naphthols,^{39–44} by condensation of 2-naphthol and benzaldehyde were conducted. We showed that MIL101/ PTA catalyst could be reused several times without extensive activity loss. The mild operating conditions and microwave assisted heating did not cause any significant deterioration in the catalyst composition and structure, yet high yields were attained within minutes.

Similarly, the MIL101/PTA composites appeared to catalyze epoxidation of caryophyllene by aqueous hydrogen peroxide. Caryophyllene oxide, an oxygenated terpenoid resulting from this reaction, is well-known as a preservative in food, drugs and cosmetics, and as an antimicrobial and antifungal agent.⁴⁵ Caryophyllene epoxidation is analogous to reactions such as epoxidation of olefins, with epoxides being important intermediates that can be stereo- and regioselectively converted to a variety of oxygen-containing compounds.^{31,46–50} Because of the efficient heat supply by the microwaving, we were able to attain over 90% of the caryophyllene conversion within minutes under mild conditions compared to hours required with conventional heat sources,³¹ and our MIL101/PTA composites were shown to be recyclable.

EXPERIMENTAL SECTION

Materials. Chromium(III) nitrate nonahydrate (99%), terephthalic acid (\geq 99%), 2-naphthol (99%), benzaldehyde (purified by redistillation, \geq 99.5%), β -caryophyllene (\geq 98.5%, sum of enantiomers, GC), and acetamide (\geq 99.0%) were all obtained from Sigma-Aldrich Chemical Co. and were used as received. Hydrated 12-tungstophosphoric acid (H₃PW₁₂O₄₀, PTA) (Sigma-Alrich, >99%) was dried at 70 °C for 8 h to obtain H₃PW₁₂O₄₀·6H₂O.^{32,33} All other chemicals and solvents used were obtained from commercial sources and were of the highest purity available.

MOF MIL-101 Particle Synthesis. Particles of MOF MIL-101 were synthesized hydrothermally, utilizing either a microwave (MW) or an autoclave oven heat supply. In the autoclave method, $Cr(NO_3)_3.9H_2O$ (2.0 g, 5 mmol), terephthalic acid (0.83 g, 5 mmol), and deionized water (20 mL) were blended and briefly sonicated resulting in a dark blue-colored suspension with a pH of 2.58. The suspension was placed in a Teflon-lined autoclave bomb and kept in an oven at 218 °C for 18 h without stirring. After the synthesis and equilibration at room temperature, pH 0.5 was recorded in the suspension.

In the MW synthesis, $Cr(NO_3)_3.9H_2O$ (1 mmol, 400 mg), terephthalic acid (166 mg, 1 mmol), and deionized water (4500 mg, 250 mmol) were blended and briefly sonicated, resulting in a suspension with initial pH 2.60. In a separate series of experiments, the pH was adjusted using 1 M aqueous NaOH. A sample (1 mL) was withdrawn from the suspension, placed in a glass tube and microwaved using a CEM Discover MW oven (CEM Corp., Matthews, NC) at 220 °C for 15 min using 300 mW power under constant stirring.

After either synthesis, the MOF solids were separated from water using a centrifuge (5,000xg, 10 min) and washed with water, methanol and acetone. The suspension in acetone was centrifuged and separated, the solids were placed in N,N-dimethylformamide (20 mL) and the suspension was sonicated for 10 min and then kept at 70 °C overnight.^{51,52} The resulting solids were separated by centrifugation, repeatedly washed with methanol and acetone, dried at 75 °C overnight, and then under vacuum (1×10^{-5} Torr) at ambient temperature for 2 days. Total yield of dry MIL-101 particles based on chromium was 54–63 wt %. Typical elemental analysis, wt %: C, 48.1; Cr, 10.3.

Synthesis of MIL-101 and Phosphotungstic Acid (PTA) Hybrid Materials (MIL101/PTA). The hybrid materials were synthesized by either autoclaving chromium nitrate, terephthalic acid and phosphotungstic acid mixtures in water or by impregnating already prepared MIL-101 by aqueous solution of phosphotungstic acid in water. In a typical "joint autoclaving" synthesis (resulting MOF designated MIL101/PTA_{ja}), $Cr(NO_3)_3$ ·9H₂O (2.0 g, 5 mmol), terephthalic acid (0.83 g, 5 mmol), phosphotungstic acid (2 g, 0.7 mmol), and deionized water (20 mL) were blended and briefly sonicated resulting in a dark blue-colored suspension with a pH of 2.58. The suspension was placed in a Teflon-lined autoclave bomb and kept in an oven at 218 °C for 18 h without stirring. The resulting MIL101/PTA_{ja} solids were separated by centrifugation and washed with water, methanol, and acetone, and then dried under a vacuum until constant weight. Elemental analysis (wt %): C, 33.1; Cr,7.58; W, 21.8.

In the "impregnation" method, 1 g of dry MIL-101 synthesized in autoclave as described above was suspended in aqueous solution of phosphotungstic acid (1.0 g in 20 mL). The suspension was sonicated and shaken at 300 rpm at ambient temperature for 2 days. The solids were separated by centrifugation, repeatedly washed by methanol and water and dried under vacuum. The resulting MOF was designated MIL101/PTA_{imp}. Elemental analysis (wt%): C, 33.5; Cr, 9.23; W, 19.9. Based on the elemental analysis results and molecular weight of hydrated PTA (H₃PW₁₂O₄₀·6H₂O, W content, 73.8%; MW, 2988 Da), we estimated the PTA content of the MIL101/PTA_{ia} and MIL101/PTA_{imp} materials to be approximately 90 μ mol/g of dry powder, or 27 wt %. The content of hydrated PTA, or *P*, was calculated according to the formula, *P* (μ mol/g) = 1 × 10⁶(W content in the hybrid material, %)/(2988 × 73.8%). The content of tungsten in various batches prepared as described above varied within ±4%.

Catalytic Reactions. Synthesis of Dibenzoxan-thene.^{39,40,42,51-55} A finely powdered aliquot of 2-naphthol (144 mg, 1.0 mmol) was mixed with 53 mg (0.5 mmol) of benzaldehyde and a measured amount of catalyst powder. The mixture, in a sealed stirred glass vial, was microwaved at a given temperature ranging from 60 to 90 °C for 2–10 min using 300 mW power under constant stirring. A rapid dissolution of 2naphthol in benzaldehyde was observed at $T \ge 60$ °C. At a given time, the contents of the vial were placed on dry ice, dissolved in 2 mL of deuterated THF or methanol, and centrifuged at 15 000 g for 30 s, following which the supernatant solutions were kept on dry ice until ¹H NMR spectra were recorded. The separated catalyst was rinsed with methanol three times, dried under vacuum and weighed. No side reactions such as hemiacetal or hemiketal formation with CD₃OD were detected under these conditions. For the reaction yield measurement, the product separated from the solid catalyst in THF was dried under vacuum, dissolved in ethanol at 75 °C and the solution was chilled on ice to 0 °C. The ensuing crystals of the dibenzoxanthene product were dried

under vacuum and weighed to afford the reaction yield, which was calculated as a ratio of the actual to calculated product yield, based on the stoichiometry of the reaction. The overall reaction is given below (Scheme 1) and more detailed reaction mechanism is presented in S-2.





Product Characterization after Recrystallization. ¹H NMR (400 MHz, THF-d₈) $\delta_{\rm H}$: 5.0 (1H, –CH), 7.08 (2H, naphthalene), 7.21–7.31 (5H, benzene), 7.47 (4H, naphthalene), 7.75 (2H, naphthalene), 7.81 (2H, naphthalene), 8.17 (2H, naphthalene). ¹³C NMR (100 MHz, CDCl₃) $\delta_{\rm C}$: 45.3, 115.5, 118.8, 123.2, 126.7, 127.2, 128.4, 129.7, 133.5, 138.6, 153.6. Melting temperature, 181 °C. Anal. Calcd. for C₂₇H₁₈O: C, 90.47; H, 5.06. Found: C, 90.35; H, 5.07.

To confirm the heterogeneous nature of the catalytic reaction of 2naphthol and benzaldehyde condensation with MIL101/PTA materials, we performed hot-filtration experiments as follows. A finely powdered aliquot of 2-naphthol (1.44 g) was mixed with 0.53 g of benzaldehyde and the dispersion was brought to 70 °C in an oven, at which temperature a transparent homogeneous solution was observed. The solid catalyst (either MIL101/PTA_{imp} or MIL101/PTA_{ja}, 100 mg) was placed in the hot 2-naphthol/benzaldehyde solution, the suspension was sonicated briefly and shaken for 1 min at 70 °C, and then the catalyst particles were removed rapidly from the hot solution by filtration steps using syringe-fitted membrane filters (Acrodisc Syringe Filters with PTFE membrane, pore diameter, 0.2 μ m, Pall Corporation). A 100 μ L aliquot of the filtered solution was dissolved in deuterated THF for analysis. The remaining filtrate was then subjected to two consecutive microwaving steps at 70 °C for 10 min using 300 mW power under constant stirring. The resulting fluid was placed on dry ice and dissolved in deuterated THF, centrifuged at 15,000 g for 30 s and kept on dry ice until ¹H NMR spectra were recorded. No crystal formation in the cold solutions of the filtrate that had been separated from the catalyst was observed. ¹H NMR revealed that after filtering the catalysts from the hot 2-naphthol/benzaldehyde solution, the yield of dibenzoxanthene was $20 \pm 5\%$ (*n* = 3). Following the catalyst filtration, the microwaving steps of the filtered solution did not produce any additional dibenzoxanthene formation. Synthesis of 1-Amidoalkyl-2-naphthol.^{56,57} A mixture of 2-

Synthesis of 1-Amidoalkyl-2-naphthol.^{56,57} A mixture of 2naphthol (172 mg, 1.2 mmol), benzaldehyde (127 mg, 1.2 mmol) and acetamide (257 mg, 1.7 mmol), along with a measured amount of a finely powdered MIL-101, MIL101/PTA or PTA was microwaved in a sealed stirred glass vial at 130 °C for 5 min and equilibrated at ambient temperature. The products were dissolved in 3 mL ethanol at 75 °C and the catalyst was removed by centrifugation for 30 s and 15 000 g. The liquid supernatant was diluted by hot ethanol (10 mL, 75 °C) and then cooled to 4 °C, at which point the precipitated crystalline products were removed by centrifugation at 15 000 g. The solid product (N-((2-hydroxynaphthalen-1-yl)(phenyl)methyl)acetamide) was dried under a vacuum and weighed, affording the calculation of yield. The reaction is presented in Scheme 2.

To confirm the heterogeneous nature of the catalytic reaction of 2naphthol, benzaldehyde, and acetamide condensation with MIL101/ PTA materials, we performed hot-filtration experiments as follows. A finely powdered aliquot of 2-naphthol (1.44 g) was mixed with 0.53 g of benzaldehyde and acetamide (2.57 g). The dispersion was brought to 130 °C in an oven, at which temperature a transparent homogeneous solution was observed. The solid catalyst (100 mg) was placed in the hot solution, the suspension was briefly (5 s) sonicated, and the catalyst particles were rapidly removed from the hot Scheme 2. Condensation of Benzaldehyde, 2-Naphthol, and Acetamide 56,57



solution by filtration using syringe-fitted membrane filters (Acrodisc Syringe Filters with PTFE membrane, pore diameter, 0.2 μ m, Pall Corporation). The filtrate was then subjected to microwaving at 130 °C for 5 min under constant stirring. The resulting fluid was dissolved in hot ethanol (30 mL) at 75 °C. The solution liquid supernatant was diluted by hot ethanol (10 mL, 75 °C) and then cooled to 0 °C on ice. No precipitated crystalline products were observed. Hence, the hot filtration tests showed that the MIL101/PTA catalysts were of heterogeneous nature.

Product Characterization after Recrystallization. ¹H NMR (400 MHz, DMSO-d₆): 1.86 (3H, -CH₃), 6.25 (1H, *α* –NC=O), 6.91 (1H, naphthalene), 7.21–7.39 (6H, benzene), 7.74 (1H, 1-naphthalene), 8.01 (1H, naphthalene), 8.05 (1H, -NH), 9.35 (1H, naphthalene). ¹³C NMR (100 MHz, DMSO-d₆): 24.3 (–CH₃), 50.6 (–CH), 125.4, 126.7, 129.4, (–CH, benzene), 135.6, 139.8, 143.8 (–C-C, benzene), 169.6 (amide). Melting temperature,186 °C. Anal. Calcd. for C₁₉H₁₇NO₂: C, 78.33; H, 5.88; N, 4.81; Found: C, 78.8; H, 5.84; N, 4.91.

Synthesis of Caryophyllene Oxide from Caryophyllene.³¹ A weighed amount of finely powdered MIL-101, MIL101/PTA or PTA catalyst was added to a solution of β -caryophyllene (110 mg, 0.5 mmol) in 10 mL acetonitrile with brief vortexing and the suspension was mixed with 0.2 mL of 30 wt % aqueous H₂O₂ (1.76 mmol). The suspension was then microwaved in a sealed stirred glass vial at 55 °C for 5 min using 300 mW power. The catalyst was removed by centrifugation (30 s, 15 000 g), the supernatant was diluted by 5 mL of methanol and the solution was chilled at 0 °C for 48 h. Formation of a yellowish crystalline precipitate was observed, which was separated out, washed by chilled methanol, and dried under a vacuum at room temperature. The product, which appeared to be β -caryophyllene oxide, was weighed and characterized. The reaction is given in Scheme 3. For recycling, the removed catalyst was washed with chilled methanol three times, dried, and weighed.

Scheme 3. Schematic of the Caryophyllene Oxidation to Caryophyllene Oxide with Hydrogen Peroxide³¹



To confirm the heterogeneous nature of the catalytic epoxidation of caryophyllene with MIL101/PTA materials, we conducted the following experiments. A weighed amount of MIL101/PTA_{ja} or MIL101/PTA_{imp} powder was added to a solution of β -caryophyllene (110 mg, 0.5 mmol) in 10 mL acetonitrile with brief vortexing and the suspension was mixed with 0.2 mL of 30 wt % aqueous H₂O₂. The suspension was then brought to 55 °C in the oven and the catalyst was removed rapidly by filtering using syringe-fitted membrane filters. The filtrate was microwaved in a sealed stirred glass vial at 55 °C for 5 min using 300 mW power. The resulting fluid was diluted by 5 mL methanol and the solution was chilled at 0 °C for 72 h. Formation of precipitates, if any, was insignificant (<3% relative to theoretical yield) and could not be determined with precision.

Table 1. Properties of MIL-101 Particles Synthesized in Deionized Water at pH 2.6

synthesis method	yield ^a (wt %)	C/Cr content (wt %/wt%)	weight-average hydrodynamic diameter $(nm)^b$	BET surface area $(m^2/g)^c$	Langmuir surface area $(m^2/g)^c$	average pore diameter (nm) ^{c,d}
microwave	55	48.1/10.3	312 ± 20	4004	5510	3.5
autoclave	64	45.7/11.1	396 ± 4	3460	4710	3.6

^{*a*}Yield is calculated using chromium content in purified particles vs initial chromium content set in the synthesis. ^{*b*}Measured in particle suspension in methanol. ^{*c*}Determined from nitrogen adsorption isotherms. ^{*d*}Computed using instrument built-in software based on the Barrett, Joyner, & Halenda method. ⁵⁹



Figure 1. TEM and SEM images of MIL-101 particles synthesized using (a) autoclave and (b) microwave heating methods. The autoclaved samples show a more distinctive morphology compared to the MW samples.

Product Characterization after Crystallization. ¹H NMR (400 MHz, CD₃OD): 0.71 (3H, -CH₃), 0.73 (3H, -CH₃), 0.90 (3H, -CH₃), 1.18 (2H, -CH₂), 1.24 (2H, -CH₂ of cyclobutane ring), 1.31 (1H, -CH of cyclobutane ring), 1.58 (2H, -CH₂), 1.67 (2H, -CH₂), 1.96 (1H, -CH α to =CH₂), 2.01 (2H, -CH₂), 2.16 (1H, -CH α to oxirane ring), 4.92 (=CH₂). ¹³C NMR (100 MHz, CD₃OD): 17.7, 22.1, 27.4, 29.2, 33.9, 39.3, 40.2, 48.5, 52.6, 59.2, 63.2, 112.3 (=CH₂), 151.9. Melting temperature, 63 °C. Anal. Calcd for C₁₅H₂₄O: C, 81.8; H, 11.0. Found: C, 81.3; H, 11.0.

Methods. TEM was performed on a JEOL 200-CX transmission electron microscope. Samples were prepared by placing drops of the MOF dispersion in methanol on lacey carbon-coated 200 Mesh copper grids (Structure Probe, Inc.) and imaged at an accelerating voltage of 200 kV. A JEOL JSM 6700F Scanning Electron Microscope was used for the morphological analysis. Images were collected under 5 kV acceleration voltage and magnifications between 5000× and 65000×. Samples were sputter-coated with a 6 nm layer of gold/palladium alloy using a Desk II cold sputter/etch unit (Denton Vacuum LLC).

MOF surface area and pore parameters were measured using a Micromeritics' ASAP 2020 Accelerated Surface Area and Porosimetry Analyzer (Micromeritics Corp., Norcross, GA). Thermogravimetric Analysis (TGA) was conducted using a Q5000IR thermogravimetric analyzer (TA Instruments, Inc.). Samples were subjected to heating scans (20 °C/min) in nitrogen atmosphere and in a temperature ramp mode. ¹H, ³¹P and ¹³C NMR spectra were collected at 25 \pm 0.5 °C using a Bruker Avance-400 spectrometer operating at 400.01, 161.9, and 100 MHz, respectively. Particle size distribution in MOF suspensions in methanol was measured using a ZetaPALS instrument (Brookhaven Instruments Corp.). The melting points were

determined with a Mel-Temp II apparatus (Laboratory Devices USA) and are uncorrected. Elemental analysis was conducted in a commercial laboratory using an ICP apparatus.

X-ray powder diffraction (XRD) patterns were acquired for 12-24 h with a Panalytical X'Pert Pro multipurpose diffractometer equipped with an X"celerator high-speed detector coupled with a Ni β -filter and using the Cu K α radiation. Samples were packed in a 0.5 mm deep well on a Si zero-background plate. Programmable divergence slits were used to illuminate a constant length of the samples (8 mm), so that the constant volume assumption was preserved given that the penetration depth was calculated to be larger than the sample depth at all incident angles measured. The in situ high-temperature X-ray diffraction experiments were conducted using the TTK 450 non-ambient chamber mounted on the Panalytical X'Pert Pro multipurpose diffractometer. The temperature increment was set at 25 °C. Each scan was set to be 25 min long. The published²⁹ XRD pattern for MIL-101 was used as the reference pattern. Peak assignment and structure refinement were accomplished with X'Pert Highscore Plus v3 software.

The Rietveld technique was adopted for structure refinement of MIL-101 and MIL101/PTA composites. The crystallographic information file for the MIL-101 reference pattern used for structure refinement was obtained from the Cambridge Structure Database (ref code OCUNAC). The laboratory XRD data were not sufficient to refine the atomic coordinates of the MIL-101 and MIL101/PTA composites. Therefore, for the MIL101/PTA composites crystal structure models were constructed using the CrystalMaker 2.3.6 software. For the model with five ordered PTA in a MIL-101 large cage, the five PTA were assumed to form a tetrahedron with the relative orientation and spacing among the five PTA molecules the

same as in the PTA crystal structure. The coordinated water molecules in the PTA crystal were omitted in our models. The orientation of the tetrahedron in the PTA crystal coordinates was set to be the same as it would appear in the MIL-101 crystal coordinates. The fractional coordinates of the PTA tetrahedron were then exported from the CrystalMaker and converted into the fractional coordinates in the MIL-101 crystal structure, by setting the center phosphorus of the 3/8). Inserting the PTA in one large cage suffices, since all other large cages in the unit cell are related by symmetry operations. The converted fractional coordinates of the PTA tetrahedron were input into the MIL-101 crystallographic information file in X'Pert Highscore Plus and the model was refined against the experimental XRD pattern obtained with MIL-101/PTA composites. For modeling disordered PTA molecules in the large cage of MIL-101, all 60 tungsten atoms that constitute the heavy atoms of the five PTA molecules were placed at the center of the large cage (3/8, 3/8, 3/8) and their thermal displacement parameters were set as 10 to approximate the disordered state as diffuse electron clouds. For modeling disordered PTA molecules in the small cage of MIL-101, thirty-six tungsten atoms from three PTA molecules were placed at the center of the small cage at (3/8, 3/8, 3/4) with their thermal parameters also set as 10. All models were refined with the XRD pattern obtained with MIL101/ PTA composites using the Rietveld refinement technique in X'pert Highscore Plus. Only a limited set of parameters were refined, including lattice parameters, peak width and shape parameters, background, and specimen displacement. Atomic parameters were not refined.

RESULTS AND DISCUSSION

MOF Synthesis and Structure. The majority of reports on MIL-101, beginning with those of Férey et al.,²⁹ described utilization of HF in the hydrothermal synthesis of MIL-101. The MIL-101 synthesis applied in the present work differs from the "conventional" preparation in that we avoided the use of hydrofluoric acid (HF) and its attendant incorporation within the crystalline structure in the synthesis procedure, because of its harmful nature and because preliminary experiments did not show any advantages in terms of chemical stability of MIL-101 by having HF incorporated into the crystal structure. Analogously, recent reports where MIL-101 was synthesized with or without HF^{51,52} showed very similar properties, despite subtle but considerable differences in the crystal structure.⁵⁷ In our experiments, the majority of the MOF crystals were synthesized in deionized water without addition of Na⁺ or other cations that could be incorporated into the crystal structure. The properties of the MIL-101 particles synthesized in deionized water at pH 2.6 without pH adjustment are collected in Table 1.

MIL-101 particles synthesized in the process of autoclave heating for 18 h appeared to be very monodisperse in size (Table 1) and all possessed well-defined octahedral shape (Figure 1). MIL-101 particles produced by the microwave (MW) method of synthesis were substantially smaller than those resulting from autoclaving because the MW method provided a more efficient supply of energy that resulted in rapid nucleation of the chromium terephthalate followed by growth of the nuclei during the short heating cycle (see the Supporting Information, S-3). The faster synthesis of the chromium terephthalate crystal under MW is due to the rapid dissolution of the terephthalic acid precursor,³⁰ which is believed to be aided by the MW irradiation, leading to reduction of the induction period for the crystal nucleation.⁶⁰ Particles resulting from the MW method were devoid of any specific shape (Figure 1).

The hydrodynamic diameter of MIL-101 nanoparticles was reduced substantially with increasing pH (see the Supporting Information, S-3). This was shown by the addition of NaOH to adjust the initial pH of the Cr(III) nitrate and terephthalic acid suspension. A higher pH leads to partial ionization of the terephthalic acid $(pK_a 3.52^{61})$, which in turn leads to a higher electrostatic attraction between Cr³⁺ cations and terephthalic acid anions that can form complexes that become nuclei.52,62 The nuclei grow into crystals assembled by corner-sharing supertetrahedra, which consist of Cr₃O trimers and 1,4benzenedicarboxylic acid molecules.^{29,63} The increase in the instantaneous nuclei concentration, early depletion of the chromium ions, and overall nucleation rate afforded the smaller crystals observed at higher pH. The surface area of the MIL-101 nanoparticles made by the MW method also declined with increasing pH (see the Supporting Information, S-3). Therefore, only particles made in deionized water at pH 2.6 were subjected to further studies.

The MOF structure was studied using XRD. Figure.2 shows a spectrum computed for comparison using published crystal



Figure 2. XRD patterns of MIL-101 synthesized in water at pH 2.6 using microwave (red line) or autoclave (blue line) compared with computed spectrum (black line).

parameters by importing the crystallography information file obtained from the Cambridge Structure Database into X'pert Highscore Plus software.²⁹ The diffraction peak positions and relative diffraction intensities of the synthesized, green powder match those of the computed pattern and thus confirm the formation of MIL-101.^{29,58,64} MIL-101 samples prepared by the MW method exhibited significantly broader peaks (albeit identical peak positions) compared to those of the MIL-101 synthesized by the autoclave method, in accord with their smaller crystal particle sizes (Table 1).

Hybrids of MIL-101 and Phosphotungstic Acid (**MIL101/PTA**). The large, 3.6-nm cages of MIL-101 (Table 1) are believed to accommodate the introduction of species such as PTA within the porous structure of the MOF, along with the possibility of the enhanced catalytic reactions favored by confinement effects in the cages.^{29,60,65} It was previously reported that the Keggin anion is of relatively large size (ca. 1.3 nm diameter and 2.25 nm³ volume) and hence, only the large cages of MIL-101 can host it. Férey et al.²⁹ showed that each cage can accept five Keggin ions, i.e., ca. 0.05 Keggin anions per chromium. Five Keggin ions take up 10.1 nm³ volume, which is approximately 50% of the 20.6 nm³ volume of a large cage.⁶⁰ In the present work, we tested whether the MIL101/PTA hybrids resulting from the HF-free synthesis in water are different from those reported previously.²⁹

TEM and SEM images of hybrid materials synthesized by the joint autoclaving of mixtures of the MIL-101 precursors and phosphotungstic acid (MIL101/PTA_{ia}) in water without pH

adjustment are shown in Figure 3. Particles resulting from joint autoclaving of PTA and MIL-101 components were up to 10



Figure 3. (a) SEM and (b) TEM images of the MIL/PTA_{ja} hybrid material obtained by the joint autoclaving of mixtures of MIL-101 components and PTA in deionized water, without pH adjustment.

 μ m in size, with a complex structure comprising rectangular pyramidal crystals on the surface and a spherical interior covered with rectangular crystalline assemblies (Figure 3 and the Supporting Information, S-4–S-6). This structure is distinctly different from that of autoclaved MIL-101 shown in Figure 1. Cr, W, and P were evenly distributed throughout the MIL101/PTA_{ja} particle interior (see EDX results in Figure S-6 in the Supporting Information), indicating inclusion of the PTA molecules into the MOF pores.

Composites synthesized by impregnating MIL-101 crystals with PTA solutions, shown in Figure 4, maintained the overall octahedral shape of the autoclaved MIL-101 particles (shown in Figure 1). The polydispersity of the MIL101/PTA_{imp} particles was higher, and the shape slightly less well defined, than the original autoclaved MIL-101 particles because of the prolonged exposure of the MIL-101 to water in the process of impregnation (see Experimental Section). EDX analysis of the TEM images of MIL101/PTA particles (found, Cr, 10.4 wt %; W, 40.3 wt %) showed large PTA content. Elemental analysis of the MIL101/PTA_{imp} material indicated heterogeneity of the samples, with the tungsten content varying 5-7% from batch to batch.

The quantity of gas absorbed during BET nitrogen absorption isothermal analysis indicated that the pore volumes of the MIL101/PTA materials were 4–5.5 times smaller than those of the original MIL-101 because of the loading of the MIL-101 pores with PTA in the composites (see the Supporting Information, S-7, and Table 2). The smaller average pore size (2.3 nm) in the MIL101/PTA compared to that in Article



Figure 4. (a) TEM and (b) SEM images of the MIL/PTA_{imp} hybrid material obtained by impregnating MIL-101 particles by an aqueous solution of PTA.

Table 2. Properties of MIL101/PTA Hybrid Materials Synthesized by Jointly Autoclaving the MIL-101 Components and PTA in Deionized Water (MIL101/PTA_{ja}) or by Impregnation of MIL-101 by PTA in Water

sample	BET surface area $(m^2/g)^a$	average pore diameter (nm) ^a	Keggin ion content (wt %) ^b
MIL/ PTA _{ja}	860	2.3	30.5
MIL/ PTA _{imm}	1020	2.4	30.9

^{*a*}Determined from nitrogen adsorption isotherms. ^{*b*}Obtained from elemental analysis and calculations based on Keggin structure (H₃PW₁₂O₄₀, W content, 76.6%). The content of the Keggin ion in MIL101/PTA_{imp} is an average of 4 independent measurements. The content of Keggin ions (wt %), or P_{K_2} was calculated according to the formula, P_{K_i} (wt %) = 100(W content in the hybrid material, %)/(76.6%).

the unmodified MIL-101 (3.5 nm) also provides evidence that the pores were partially occupied by the Keggin ions of PTA.

Thermal stability and decomposition patterns of MIL-101 and its composites with PTA were assessed by TGA (see the Supporting Information, S-8). The MIL-101 particles exhibited four steps of weight loss in the 25–200 °C (~6 wt %), 210–350 °C (51 wt %), 360–600 °C (21 wt %), and 900–1000 °C (~10 wt %) temperature ranges. These corresponded to (1) the loss of water molecules, (2) the loss of hydroxylic groups, (3) the degradation of the dicarboxylate linkers,²⁹ and (4) the fusion and decomposition of chromium(III) oxide clusters,⁶⁶ respectively. The MIL101/PTA hybrids showed similar patterns, albeit the loss in weight was only about 50 wt % at 1000 °C. The weight loss of ca. 30 wt % in the 400–600 °C range due to the terephthalic acid linkers and the MOF

structure collapse was rather well-defined. These observations correspond very well with the in situ high-temperature X-ray diffraction (HTXRD) patterns taken in the 25–1000 °C range (Figure 5). In the temperature range of 25–200 °C, the peaks



Figure 5. HTXRD pattern of MIL101/PTA_{imp} hybrid material taken in the 25–1000 $^\circ C$ range.

at ~4, 7.3–8, and ~8.7° 2θ diminished as the temperature approached 200 °C, which may result from the loss of water molecules. The disappearance of diffraction peaks in the HTXRD showed a collapse of the crystalline structure at between 350 and 375 °C because of the degradation of dicarboxylate linkers.

The crystal structures of the MIL101/PTA composites were probed via XRD, with resulting spectra as shown in Figure 6. Significant changes in the diffraction patterns were observed after incorporation of PTA in MIL-101 by either impregnation



Figure 6. Comparison of XRD patterns before and after incorporation of PTA in MIL-101. (a-c) experimental XRD patterns of (a) MIL-101synthesized by autoclaving; (b) MIL101/PTA composite made by impregnation; (c) MIL-101/PTA composite synthesized by joint autoclaving. (d-f) simulated XRD patterns of (d) MIL-101 with 5 disordered PTA in each large cage, (e) MIL-101 with 5 ordered PTA in each large cage, and (f) MIL-101 with PTA in both large and small cages. The regions where diffraction peaks exhibit significant changes after incorporation of PTA are highlighted with light yellow background.

(Figure 6b) or joint autoclaving (Figure 6c), compared with that of pure MIL-101 (Figure 6a). In particular, several "new" peaks emerged between 6° and 8° 2 θ . None of the newly appearing peaks overlap with those of pure PTA (not shown), which exhibits no peaks below $10^{\circ} 2\theta$. It is worth noting that the new peaks are in fact not new in the sense that the Bragg peak positions are consistent with the unit cell of MIL-101. In unmodified MIL-101, those peaks have a null intensity. This suggests that the MIL-101 framework itself is not affected significantly by PTA guest molecules. The incorporation of PTA adds electron density to the crystal structure of MIL-101, which creates the observed diffracted intensity at these peak positions. Interestingly, other researchers reported much smaller or even no changes in this region $(6-8^{\circ} 2\theta)$ of the diffraction pattern of MIL101/PTA composites.^{22,29,35} This distinction leads us to hypothesize that the structure herein may have arisen from the absence of hydrofluoric acid in the MIL-101 crystal structure, afforded by our new synthesis method, which could allow incorporation of more PTA molecules in MIL-101 cages and/or facilitate ordering of PTA. This hypothesis is further elucidated below with the crystal structure analysis on the MIL101/PTA composites.

To understand the configurations of PTA molecules in the composites, we investigated several models of the composite structures and refined the models against the MIL/PTA_{imp} diffraction pattern (Figure 6(b)) using the Rietveld refinement technique. The models were tested to address the questions whether the PTA molecules are aligned with respect to the MIL-101 framework or randomly oriented, and what the spatial distribution of PTA molecules is. These questions are important because they are pertinent to the stability of the composite and the maximum catalyst loading in MIL-101.

We first surmise that there are five PTA molecules residing in the large cages of MIL-101, according to findings from previous studies.²⁹ Two models were constructed based on this assumption: one with disordered PTA, and the other with an ordered PTA assembly. Given the difficulty to model precisely disorder of the large PTA molecules, we represented PTA molecules as a diffuse electron cloud within a MIL-101 cage. We modeled the ordered PTA assembly as a tetrahedron, wherein one PTA molecule lies at the center of the MIL-101 large cage, and four PTA molecules face the four six-carbon rings constituting the MIL-101 large cage (Figure 7b,c). This configuration is sensible because it is highly symmetric, and more importantly, it may naturally form since PTA molecules are likely to diffuse through the six-carbon-ring window during impregnation as opposed to the five-carbon ring window. The simulated X-ray diffraction patterns of the two models are compared against experimental patterns (Figure 6d,e). Both simulated patterns show intensified peaks between 6° and 8° compared with those of MIL-101 (Figure 6a); however, the relative peak intensities are much lower than observed experimentally. The ordered PTA model is a closer match with the experimental data because only the calculated pattern based on this model produced new peaks of observable intensity matching the experimentally observed peaks between 6 and 8° 2 θ . The pattern calculated from the disordered PTA model exhibited many other intensified peaks not seen in the experimental data between 6 and 8 and 9 and 12°, suggesting that the PTA guest molecules are more likely to exist in an ordered fashion. This hypothesis could help to explain the high thermal stability of the MIL101/PTA composites (Figure 5),



Figure 7. Proposed crystal structure of (a) MIL-101 and (b-e) MIL101/PTA composites. (a) MIL-101 crystal structure with the boundary of the large cage highlighted green and that of the small cage highlighted yellow. The Cr polyhedrons are colored pink. (b, c) The PTA tetrahedron in a multicolored large cage of MIL-101, which corresponds to the model with ordered PTA. Views from two directions are presented, b is viewed from the same direction as in a, and c is viewed facing a six-carbon ring. Each of the four six-carbon rings is colored differently, each aligned with a PTA molecule. (d, e) A possible configuration of three PTA molecules in a small cage of MIL101 viewed (d) from the front, which is the same direction as in a, and (e) from the top. The three PTA molecules were allowed to rotate around their shared axis.

because an ordered guest molecule would be expected to be more tightly bound to the MOF structure.

The discrepancy in the relative peak intensities between the calculated diffraction pattern with ordered PTA in the MIL-101 large cage and the experimental pattern implies that there might be more PTA incorporated in the MIL-101 structure. This hypothesis is corroborated by the elemental and EDX analysis of the MIL101/PTA composites, which indicate that the actual PTA content is 1.5–2 times greater than the amount predicted by the models discussed above. The EDX analysis yielded a higher fraction of PTA than indicated by the elemental analysis, which may result from the enrichment of PTA near the surface of the MIL101/PTA composite. There are two hypotheses to explain this discrepancy: the large cage of the MIL-101

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structure may contain more than five PTA molecules or the small cage of the MIL-101 may also contain PTA. Previous studies postulate that the large cage may not be able to accommodate more than five PTA molecules.²⁹ In addition, the coordinated water molecules (not included in our model) are expected to take up a significant portion of the cage. Therefore, we surmise that the small cages are also occupied with PTA (Figure 7d, e). Accordingly, the model with five ordered PTA in the large cage was modified by adding three PTA in the small cage. This model yields a Cr: W mass ratio of 1:4.6, which is close to the experimental EDX results. In addition, three PTA molecules occupy approximately half the volume of the small cage, which is about the same volume occupancy as five PTA in the large cage. We could not produce a proposed model of ordered PTA in the small cage of the MIL-101 structure; therefore, we took a simplified approach by putting the PTA molecules in the center of the small cage and giving them large isotropic thermal displacement parameters, and the simulated diffraction pattern is shown in Figure 6f. This model produced a calculated diffraction pattern that was a much better match with the experimental patterns (Figure 6b, c), compared to the model with PTA in only the large cage, particularly in the highlighted regions $(4-5^\circ, 6-8^\circ)$. This result provides evidence that PTA is present in both cages and is ordered in at least the larger cage and possibly also in the smaller cage. However, even this model is not an adequate description of the MIL101/PTA composite. Specifically, the two peaks at 5.2 and 5.7° in the simulated pattern exhibit much higher intensities than actually observed, which indicates the PTA in the small cage may assume a more ordered configuration. The proper solution of this structure will require additional work, most likely combining neutron scattering experiments and firstprinciples computer modeling.¹⁶

Interestingly, in the HTXRD experiment, the two peaks at 5.2 and 5.7° exhibited much higher intensity once the temperature increased beyond 200° and before the collapse of the entire structure at 375° (Figure 5). At the same time, the new peaks between 6 and 8° decreased significantly in intensity. These features seem to be captured by the simulated diffraction pattern based on the model with ordered PTA in the large cage and disordered PTA in the small cage (Figure 6f), which indicates that the MIL101/PTA composite may go through a "phase transition" at around 200° when the PTA assembly in the small cage transitions from an ordered to a disordered state, whereas the PTA assembly in the large cage may remain ordered, since the "new" peaks between $6-8^{\circ}$ weakened but did not disappear in this temperature range. The fact that these 'new' peaks persisted until the collapse of the entire crystalline structure may help explain why MIL101/PTA is more stable than pure MIL-101 as indicated by the TGA results (see the Supporting Information, S-10). It is possible that the PTA molecules in small cages become disordered at a lower temperature than those in the large cages, if the PTA in small cages possesses lower degrees of order in the first place in MIL101/PTA as synthesized. For instance, in the small cage, the PTA may have higher rotational degrees of freedom while having little translational degree of freedom.

To summarize the structural studies of the MIL101/PTA composites, we infer from the XRD analysis that there are ordered PTA assemblies residing in both the large cages and small pores of MIL-101, and the PTA assemblies in the small pores or cages may possess higher degrees of freedom than those in the large cages, or a lower degree of order. In contrast,

previous researchers reported loading of PTA only in the large cages, 22,29,35 and, correspondingly, they did not observe the significant changes in XRD pattern that we did on incorporation of PTA. This distinction may result from the absence of the HF in the crystal structure of MIL-101 synthesized by the HF-free method, which enables catalyst payloads 1.5–2 times higher than previously achieved.

Reaction Catalysis by MIL-101 and MIL101/PTA **Composites.** The catalytic performance of the MIL101/PTA composites was assessed in the Baeyer condensation of benzaldehyde and 2-naphthol, in the 3-component condensation of benzaldehyde, 2-naphthol and acetamide, and in the epoxidation of caryophyllene by aqueous hydrogen peroxide (Table 3). In all experiments, no detectable product formation was observed without the catalysts. With PTA present, all experiments showed almost complete conversion of the reactants, demonstrating the effectiveness of PTA as a catalyst. Notably, PTA dissolved in either benzaldehyde or water in these reactions, which then proceeded at given temperatures in the homogeneous catalysis regime. Upon equilibration at room temperature, precipitation of PTA was observed only in one reaction - the benzaldehyde, 2-naphthol and acetamide condensation. However, the catalyst recovery by filtering was low (<30 wt % of initial loading). Although PTA recovery has been claimed in previous studies,57 no sufficiently detailed description of the catalyst recovery process was given. In the benzaldehyde -2-naphthol condensation and oxidation reactions, no PTA precipitation was observed. In contrast, in the heterogeneous reactions with MIL-101 or MIL101/PTA composite solids present, we observed excellent catalyst recovery yields, as detailed below.

Initial loadings of the PTA in our experiments (Table 3), when this polyoxometalate alone was applied as a catalyst, were comparable to the effective PTA loading when the MIL101/ PTA composites were used, considering that PTA comprised approximately 30 wt % composites (Table 2). Replacement of the MIL101/PTA heterogeneous catalyst with 1-3% effective equivalent concentration of the homogeneous catalyst, PTA resulted in the yields less than 15% of those observed with the regular loading of MIL101/PTA. The reaction yields with PTA and MIL101/PTA at otherwise identical temperature and time were similar. It is interesting to note that small particles of MIL101/PTA_{imp} (~400 nm size) afforded essentially the same, within experimental error $(\pm 5 \text{ wt } \%)$, yields as their larger MIL101/PTA_{ia} counterparts with sizes up to 10 μ m (Figure 4). This is an indication of the absence of transport limitations of the substrate and product molecules in the catalyst pores. Because of the rapid conversion of the reactants into products under MW heating, we were unable to measure the observed reaction rate constants. Nevertheless, an estimate of the turnover frequency (TOF) could be calculated as TOF = (moles of substrate consumed)/(moles of PTA \times time), wherein the overall reaction time is taken into consideration with the assumption that the reaction time is approximately the reciprocal of the observed reaction rate constant. The TOF estimates with the MIL101/PTA composites were 200-420 min⁻¹ in the reaction of dibenzoxanthene, 220 min⁻¹ in the reaction of 1-amidoalkyl-2-naphthol, and 30 min^{-1} in the reaction for β -caryophyllene oxide syntheses. The high yields, within minutes observed in the present work with MIL101/ PTA correspond well to analogous condensation reactions conducted under MW irradiation with catalysts such as molecular iodine,⁶⁸ sulfamic acid,⁴⁴ and ceric sulfate.^{56,69}

Table 3. Baeyer Condensations and Epoxidation of Caryophyllene Catalyzed by MOF MIL-101 and Its Polyoxometalate Composites with PTA under Microwave Heating

reaction	catalyst (loading, wt % or mol %) ^a	Т (°С)	MW ^c time (min)	yield (wt %) ^d
synthesis of dibenzoxanthene from	no catalyst	60	2	0
benzaldehyde (B) and 2-naphthol	no catalyst	90	10	<3
(N). Initial B:N mol ratio, 1:2.	MIL- 101 (4.8) ^e	80	2	5-10
	MIL- 101 (9.2)	90	10	32
	MIL101/ PTA _{imp} (4.8)	60	2	83
	MIL101/ PTA _{imp} (9.2)	60	2	92
	MIL101/ PTA _{imp} (9.2)	90	2	96
	MIL101/ PTA _{ja} (4.8)	60	2	80
	MIL101/ PTA _{ja} (9.2)	90	2	96
	PTA $(2.4/0.11)^b$	90	2	96
synthesis of l-amidoalkyl-2-naphthol	no catalyst	130	5	0
from 2-naphthol (N), benzaldehyde (B), and acetamide	MIL- 101 (5.1)	130	5	25
(A). Initial B:N:A ratio, 1:1:1.4.	MIL101/ PTA _{imp} (5.1)	130	5	88
	MIL101/ PTAja(5.1)	130	5	92
	PTA $(1.8/0.08)^b$	130	5	95
synthesis of caryophyllene oxide	no catalyst	75	5	<3
from p-caryophyllene and aqueous	MIL-101 (1)	55	5	<3
H ₂ O ₂ .	MIL101/ PTA _{imp} (l)	55	5	79
	MIL101/ PTA _{imp} (1.7)	55	5	93
	MIL101/ PTA _{ja} (l)	55	5	84
	MIL101/ PTA _{ja} (1.7)	55	5	92
	PTA $(1/0.013)^{b}$	55	5	95

^{*a*}In all cases, except for catalysis with phosphotungstic acid (PTA), the catalyst loading is given in wt %. The loading is calculated as 100 × catalyst weight/sum of weight of all components in the initial reaction mixture . ^{*b*}PTA loading is given in wt %/mol %. The content in mol % is calculated as 100 × mols of catalyst/sum of mols of each component in the initial reaction mixture. ^{*c*}MW is the time of microwaving, wherein specified temperature is held within the reaction tube. ^{*d*}Series of independent experiments conducted in triplicate demonstrated standard deviations of the yield determination to be within ±5 wt %. ^{*c*}MIL-101 samples prepared using autoclaving method are used throughout. No significant differences in reactivity of MIL-101 samples prepared by either MW or conventional oven heating in dibenzox-anthene and caryophyllene oxide syntheses were observed in the control series of experiments.

Syntheses of dibenzoxanthene derivatives using heterogeneous acidic catalysts under conventional heating required several hours to arrive at high yields, with the TOF being ca. 100-fold lower than in the present work.⁷⁰

In addition, MIL-101 itself was observed to be mildly active in both condensation reactions due to the presence of its acidic sites. Similarly, many other heterogeneous and homogeneous acidic catalysts ranging from strong acids such as *p*-toluene

Table 4. Recovery and	Reuse of MIL101/PTA	Composite Cat	alysts in Four	Consecutive (Lycles of Dil	benzoxanthene an	d
Caryophyllene Oxide Sy	ntheses						

MIL101/PTA _{imp}				MIL101/PTA _{ja}					
cycle no.	total catalyst recovery ^c	Keggin ion content ^d	reaction yield	cycle no.	rotal catalyst recovery	Keggin ion content	reaction yield		
Dibenzoxanthene Synthesis ^a									
1	93	30.9	96	1	94	30.5	96		
2	88	29.4	95	2	87	28.3	95		
3	82	24.5	95	3	80	27.1	91		
4	77	21.1	94	4	76	22.5	94		
Caryophyllene Oxide Synthesis ^b									
1	94	30.9	93	1	94	30.5	92		
2	85	28.1	92	2	87	27.5	95		
3	81	22.6	93	3	80	22.6	93		
4	75	19.3	94	4	76	21.4	91		

^{*a*}Synthesis conducted at 90 °C for 2 min at catalyst loading of 9.2 wt %. ^{*b*}Synthesis conducted at 55 °C for 5 min at catalyst loading of 1.7 wt %. ^{*c*}Total catalyst recovery is measured by weighing the recovered catalyst after each consecutive cycle, with reference to the catalyst weight initially utilized in the first cycle. ^{*d*}Keggin ion content is calculated as weight fraction of Keggin ions ($H_3PW_{12}O_{40}$, obtained from average elemental analysis) in the total catalyst recovered in each cycle.

sulfonic acid⁴⁰ or acetic/sulfuric acid blends⁵³ to Lewis acids like strontium triflate⁶⁷ or $K_5CoW_{12}O_{40}$ · $3H_2O^{42}$ were shown to catalyze analogous aldehyde-naphthol condensations, including under solvent-free conditions.^{40,53,67,42} It is of significance to note that the MIL101/PTA composites, however, appear to possess much higher catalytic activity than does MIL-101.

The enhancement of the caryophyllene oxide yield and reaction rate in the presence of MIL101/PTA was quite dramatic, with the TOF estimates approximately 22-fold higher than the TOF measured in the identical reaction catalyzed by titanium-monosubstituted Keggin heteropolyanions loaded into MIL-101 cages.^{31,71} Undoubtedly, such an acceleration under otherwise similar conditions and analogous catalysts is due to utilization of the MW heating herein vs the conventional heating supply used in the previous reports. At variance with the previous work,³¹ we observed no significant yield of caryophyllene oxide in the presence of MIL-101 alone despite its acidic properties. This can be explained by the differences in the product yield measurement. Herein, we used recrystallization to recover the product, whereas Maksimchuk et al.³¹ analyzed the liquid reaction mixture identifying the products by GC-MS. Low selectivity of the caryophyllene oxidation with MIL-101 was observed, with the overoxidation coproducts comprising more than half of the products. As a result, caryophyllene oxide would not crystallize in our experiments due to the presence of large amounts of oily liquid coproducts such as clovenol and the like.^{72,73} However, selectivity of the caryophyllene oxidation improved dramatically, reaching 100% in the presence of MIL101/PTA hybrids, and therefore high yields of the caryophyllene oxide were observed. It was hypothesized³¹ that such an improvement in the reaction selectivity in the presence of PTA supported on solid MOF is due to deprotonation of the (Ti-susbstituted) PTA anion on immobilization within the MIL-101 cages via anion exchange, which protected the acid-sensitive epoxide from undergoing the ring-opening reaction. We find this hypothesis to be credible, given the predominantly electrostatic interaction of the Keggin ions and MIL-101 framework,⁷¹ which shields the acidic character of the immobilized PTA.

Catalyst Recovery and Reuse. As described in the Experimental Section, by filtering the catalysts at the reaction temperature before completion of the reaction and testing the filtrate for activity,⁷⁴ we obtained a rigorous proof that the

MIL101/PTA composite materials behaved as heterogeneous catalysts in the reactions studied. The MIL101/PTA composites were further tested for recovery and reuse using parameters such as catalyst and product recovery in four consecutive cycles, in reactions of dibenzoxanthene and caryophyllene oxide syntheses. The catalyst recovery was measured by the total weight of the recovered particles as well as Keggin ion content in the recovered catalyst, calculated using average elemental analysis results (Table 4). Excellent yields of the product and catalyst recovery were maintained in both processes for at least 4 cycles. Washing of the catalyst with methanol in the process of recovery (see the Experimental Section) resulted in loss of approximately 10 wt % of the Keggin PW₁₂ from either type of catalyst. The removed fraction of PTA was identified as chemically intact using ³¹P NMR ($\delta = -14.8$ ppm, see the Supporting Information, S-9).⁷⁵ Such PTA removal did not result in any appreciable decrease in the product yields, however (Table 4). In addition, XRD of the MIL101/PTA composites recovered in four cycles of either dibenzoxanthene or caryophyllene oxide syntheses did not indicate any changes in the crystalline structure of the recovered catalyst (Figure 8). Such a stability in the presence of an aqueous medium containing hydrogen peroxide is somewhat surprising, given that an analogous reaction (but conducted using conventional heating at longer times) did result in the MIL101/PTA crystal structure degradation.³¹ The



Figure 8. XRD patterns of MIL101/PTA_{imp} composite as synthesized (1, black line), the composite that underwent four cycles of dibenzoxanthene synthesis (2, blue line), and the composite that underwent four cycles of caryophyllene oxide synthesis in water in the presence of hydrogen peroxide (3, red line). For experimental details, see the Experimental Section and Table 4.

difference can be explained by the kinetics of such degradation, which is minimal in short, 5 min heating cycles. Overall, we believe the newly obtained MIL101/PTA composites possessed exceptional stability in the reactions studied.

CONCLUDING REMARKS

The present work focused on the well-known and important type of metal organic framework, MIL-101, which possesses exceptionally high surface area and relatively large pores. We simplified the synthesis procedure for the preparation of MIL-101 by avoiding the use of hydrofluoric acid; the resulting MOF possessed indistinguishable structure and equal stability to the compound that included HF. Furthermore, by simply impregnating the already prepared MIL-101 or by adding phosphotungstic acid to the aqueous MIL-101 recipe followed by heating by either a conventional oven or microwave, we obtained MII101/PTA composites capable of facile catalysis of Baeyer condensations and epoxidation reactions, with high turnover numbers. To explain high PTA loadings and XRD results, we proposed a structural model that includes PTA incorporated not only in the large cavities, but also in smaller pores. The exceptional stability and reactivity of the novel composites prompted our concurrent inquiry into applications of these catalytic matrices in a multitude of catalytic reactions and engineering processes.

ASSOCIATED CONTENT

S Supporting Information

Schematic of the acid-catalyzed Baeyer condensation reaction, mechanism of the acid-catalyzed Baeyer condensation reaction of 2-napthol and benzaldehyde, hydrodynamic diameter and Langmuir surface area of MOF MIL-101 particles synthesized using a microwave oven as functions of pH, SEM images of MIL101/PTA_{ja} particles, EDX mapping analysis of a MIL101/PTA_{ja} particle interior, BET nitrogen adsorption isotherms for MIL-101 and MIL101/PTA hybrid material, thermogravimetric analysis of MIL-101 particles and MIL-101/PTA hybrid materials, ³¹P NMR spectrum of the wash-outs resulting from the MIL101/PTA_{imp} recovery process after the dibenzoxanthene synthesis reaction (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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