Metal–Organic Framework MIL-101(Cr) as an Efficient Heterogeneous Catalyst for Clean Synthesis of Benzoazoles

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Supporting Information

ABSTRACT: A metal–organic framework [MIL-101(Cr)] was used as an efficient heterogeneous catalyst in the synthesis of benzoazoles (benzimidazole, benzothiazole, and benzoxazole), and quantitative conversion of products were obtained under optimized reaction conditions. The catalyst could be simply extracted from the reaction mixture, providing an efficient and clean synthetic methodology for the synthesis of benzoazoles. The MIL-101(Cr) catalyst could be reused without a remarkable decrease in its catalytic efficiency.

INTRODUCTION

Benzoazoles (benzimidazole, benzothiazole, and benzoxazole) are unique motifs that exist in the structure of numerous biologically important compounds, natural products, and advanced materials. ¹ The chemical structure of some of the biologically active molecules containing benzoazole heterocycles are shown in Figure 1.²

In this regard, remarkable efforts have been made to discover novel and well-organized methodologies to prepare these compounds. The most widely used strategy for the synthesis of benzoazoles is condensation reaction of 2-aminophenols/2-aminothiophenol/o-phenylenediamine with aldehydes and carboxylic acid derivatives. For this reaction, different catalyst systems have been developed; however, most of them often suffer from key limitations including low yields, harsh reaction conditions, nonreusability of the catalyst, complicated workup process, unclean synthesis, and limited substrates scope.³

In recent years, incredible growth has been attained in the development of metal–organic frameworks (MOFs) as flexible rational designing materials and readily synthetic catalysts for chemical synthesis.⁴ These materials combine the benefits of clean synthesis with heterogeneous catalysts, which really make simpler workup process and is predominantly attractive from industrial point of view. MOFs are mainly used as supports (catalyst platform) due to their high pore volume, large surface areas, and flexible framework.⁵ Their use in organic synthesis as catalyst is very important and different organic transformations including, Knoevenagel and Aldol condensations, Michael addition, Henry and cycloaddition reactions, and one-pot cascade reaction have been catalyzed with MOFs.⁶

One of the most attractive MOFs is MIL-101(Cr), which was first synthesized by Férey and co-workers. This material has the framework of augmented mobil thirty-nine zeotype building, which consisted of Cr(III)-trimmers cross-linked by 1,4-benzene dicarboxylate. There are two types of mesopore cages with free diameters of 2.9 and 3.4 nm in the structure of this MOF. These cages are available via two micropore windows of 1.2 and 1.6 nm, respectively. The large surface area, high thermal, chemical, and solvent stability and numerous coordinative unsaturated metal sites make MIL-101(Cr) an interesting material in catalysis.⁷

As part of our interest in heterogeneous catalysis,⁸ we report herein the first example of benzoazole synthesis catalyzed by MIL-101(Cr), developing the unique catalytic capability of MOFs in organic synthesis to produce valuable benzoazoles in high yields. This protocol represents the first utilization of MIL-101(Cr) to promote condensation reaction of 2-aminophenols/2-aminothiophenol/o-phenylenediamine with aldehydes, utilizing only catalytic sites exist on the MIL-101(Cr) structure. Our methodology may open up our hand in the industrial synthesis of benzoazoles using MOFs as environmentally friendly and readily available materials. The mild reaction conditions, wide substrate scope, clean synthesis, and good functional group tolerance are main characteristics of this new methodology. We recently developed new catalysts for the synthesis of benzoazoles.⁹ Aware of the importance of benzoazoles and excellent catalytic capability of MOFs, we studied whether MOF can be used as an efficient catalyst to promote the condensation of aldehydes with 2-aminophenols/2-aminothiophenol/o-phenylenediamine.

RESULTS AND DISCUSSION

We set out our study by screening a range of conditions for the condensation of benzaldehyde with o-phenylenediamine in the absence of various MOFs (Table 1).

First, the reaction between benzaldehyde and o-phenylenediamine was checked in the presence of different MOFs as catalyst and maximum yield of the product was obtained with MIL-
As shown in Table 1, in the absence of MOF as catalyst, only 5% of the product was observed (entry 5), demonstrating that MOFs have a key catalytic role in this reaction. By increasing the reaction temperature, the yield was enhanced and optimum temperature for high yield of product (3a) was selected as 55 °C (Table 1, entries 6–8). Then, the optimization of catalyst loading was done, and it seems that 10 mg of MIL-101(Cr) is enough to obtain satisfactory yield (Table 1, entries 9–11). Other reaction media were tested and EtOH was selected as superior solvent for this reaction (Table 1, entries 12–16). Results demonstrate that entry 10 of Table 1 is the best condition optimized for the synthesis of benzimidazole derivatives using MIL-101(Cr) as catalyst.

Using the optimized reaction conditions, we synthesized 2-phenylbenzothiazole and obtained the maximum yield of 87% at a little higher temperature of 60 °C. However, synthesis of benzoxazole derivatives needs a high temperature of 120 °C and the best solvent tested to obtain this product was xylene. Overall, the optimized reaction conditions for the synthesis of benzoxazoles using MIL-101(Cr) as catalyst are shown in Scheme 1.

Before we start to investigate the generality and scope of this new synthetic methodology, some microscopic and spectroscopic analysis from the synthesized MIL-101(Cr) catalyst are

Table 1. Optimization of Reaction Conditions

| entry | catalyst (mg) | solvent | temp (°C) | time (h) | yield 3a (%)b |
|-------|---------------|---------|-----------|----------|---------------|
| 1     | ZIF-8(Zn) (20) | EtOH    | rt        | 8        | 20            |
| 2     | MIL-101(Cr) (20) | EtOH    | rt        | 3        | 60            |
| 3     | MIL-53(Al) (20) | EtOH    | rt        | 8        | 35            |
| 4     | DUT-67(Zr) (20) | EtOH    | rt        | 8        | 40            |
| 5     | none          | EtOH    | rt        | 24       | 5             |
| 6     | MIL-101(Cr) (20) | EtOH    | 40        | 3        | 75            |
| 7     | MIL-101(Cr) (20) | EtOH    | 55        | 2        | 94            |
| 8     | MIL-101(Cr) (20) | EtOH    | 78        | 2        | 94            |
| 9     | MIL-101(Cr) (15) | EtOH    | 55        | 2        | 94            |
| 10    | MIL-101(Cr) (10) | EtOH    | 55        | 2        | 94            |
| 11    | MIL-101(Cr) (5) | EtOH    | 55        | 2        | 60            |
| 12    | MIL-101(Cr) (10) | MeOH    | 55        | 2        | 90            |
| 13    | MIL-101(Cr) (10) | H2O     | 55        | 2        | 84            |
| 14    | MIL-101(Cr) (10) | CH3CN   | 55        | 2        | 85            |
| 15    | MIL-101(Cr) (10) | dioxane | 55        | 6        | 88            |
| 16    | MIL-101(Cr) (10) | CH2Cl2  | 55        | 6        | 40            |

aReaction conditions: 1a (1 mmol), 2a (1.1 mmol), and solvent (5 mL).
bIsolated yields.

Figure 1. Some drugs and biologically active compounds containing benzoazole rings. Nexium (A) is a drug used to treat symptoms of gastroesophageal reflux disease. (B) is used as fatty acid amide hydrolase inhibitor. (C) Showed Ras-PDE delta inhibitor activity. (D) has a DNA-binding property. (E) is used as a potent and selective 5-HT1A serotonin receptor ligand. (F) is introduced as inhibitors of phosphoinositide 3-kinase (PI 3-kinase) delta for the treatment of inflammatory diseases and leukocyte malignancies.
presented. Scanning electron microscopy (SEM) images of the synthetic pristine MIL-101(Cr) is shown in Figure 2. According to the SEM images, the MIL-101(Cr) crystals are formed in the form of discrete octahedron with a smooth surface and have an approximate average of 400 nm.

The Fourier transform infrared (FT-IR) spectrum of our synthesized MIL-101(Cr) corresponds well with that reported in the literature, also confirming the formation of MIL-101(Cr) (Figure 3). For example, according to the FT-IR of MIL-101(Cr), the band at 1392 cm\(^{-1}\) was related to the symmetric (O–C–O) vibrations, implying the existence of dicarboxylate group in the structure of MIL-101(Cr).\(^{10}\) The energy-dispersive X-ray spectra of the synthesized MIL-101(Cr) exposed that the MOFs are composed of C, O, Cr, F, and N (Supporting Information Figure S1). The relative content of Cr in the synthetic MOF was determined to be about 0.35 mmol g\(^{-1}\) of MIL-101(Cr). The amount of Cr is approximately in agreement with the inductively coupled plasma (ICP) analysis results, suggesting that content of Cr as a catalytic site is about 0.36 mmol g\(^{-1}\). The low-angle powder X-ray diffraction (XRD) pattern of the prepared materials matches well with that of the pristine reported MIL-101(Cr) in the literature (Figure 4).\(^{10}\)

The nitrogen adsorption isotherm MIL-101(Cr) is depicted in Figure 5. For the prepared MIL-101(Cr), the specific surface area is calculated by the Brunauer–Emmett–Teller (BET) and the Langmuir methods, which are about 2606 and 2816 m\(^2\) g\(^{-1}\), respectively. The total pore volume and mean pore diameter of the prepared MIL-101(Cr) is estimated to be 1.80 cm\(^3\) g\(^{-1}\) and 2.77 nm, respectively.

Then, different derivatives of benzoazoles, benzimidazoles, and benzothiazoles were synthesized using MIL-101(Cr) catalyst under optimized conditions (Table 2). As shown in Table 2, different benzoazole derivatives were synthesized using the reaction of 2-aminophenols/2-aminothiophenol/\(\alpha\)-phenylenediamine and substituted aldehydes using MIL-101(Cr) as catalyst in high isolated yields and good turnover number (TON). The results indicate that the yield depends to some extent on the electronic nature of the substituent and as well its position in aromatic ring of aldehydes. Overall, aromatic aldehydes having different substituents such as methoxy, nitro, chloro, methyl, etc. tolerated the reaction to afford the corresponding benzoazole derivatives in good to excellent yields. The time of reactions is dependent on the...
position of the substituents on aldehyde, and more time is needed to obtain high yields of ortho-functionalized aldehydes. High yield of para-substituted aldehydes was obtained after 2−4 h. More reaction time is needed for the synthesis of benzoazoles, and this is related to the difficulty in the formation of this heterocycle.

With the aim to prove the synthetic usefulness of MIL-101(Cr) as a catalyst in organic synthesis, we tried to synthesize a novel class of bis-heterocyclic compounds containing benzoazole fragments. Bis-heterocycles are molecules having two linked, fused, or bound heterocyclic compounds.11 This class of molecules has attracted much considerations because of

Table 2. Synthesis of Benzoazole Derivatives Using MIL-101(Cr) as Catalyst

| product | X | R | solvent | temp (°C) | time (h) | yield (%) | TON |
|---------|---|---|---------|-----------|----------|-----------|-----|
| 3a      | NH| H | EtOH    | 55        | 2        | 94        | 261.1 |
| 3b      | O | H | xylene  | 120       | 9        | 87        | 241.6 |
| 3c      | S | H | EtOH    | 60        | 2.5      | 87        | 241.6 |
| 3d      | NH| 4-NO₂| EtOH | 55        | 3.5      | 85        | 236.1 |
| 3e      | O | 4-NO₂| xylene | 120       | 12       | 79        | 219.4 |
| 3f      | S | 4-NO₂| EtOH    | 60        | 4        | 85        | 236.1 |
| 3g      | NH| 4-CH₁| EtOH   | 55        | 2        | 92        | 255.5 |
| 3h      | O | 4-CH₁| xylene  | 120       | 6        | 84        | 233.3 |
| 3i      | S | 4-CH₁| EtOH    | 60        | 2.5      | 89        | 247.2 |
| 3j      | NH| 4-OMe| EtOH   | 55        | 2        | 95        | 263.8 |
| 3k      | O | 4-OMe| xylene  | 120       | 6        | 85        | 231.6 |
| 3l      | S | 4-OMe| EtOH    | 60        | 2.5      | 91        | 252.7 |
| 3m      | NH| 2-Cl| EtOH    | 55        | 3.5      | 85        | 231.6 |
| 3n      | O | 2-Cl| xylene  | 120       | 9        | 80        | 222.2 |
| 3o      | S | 2-Cl| EtOH    | 60        | 4        | 85        | 236.1 |
| 3p      | NH| 4-Cl| ETOH   | 55        | 3        | 87        | 241.6 |
| 3q      | O | 4-Cl| xylene  | 120       | 9        | 82        | 227.7 |
| 3r      | S | 4-Cl| ETOH    | 60        | 3        | 86        | 238.8 |

*Reaction conditions: 1 (1 mmol), 2 (1.1 mmol), MIL-101(Cr) (10 mg = 0.36 mol % Cr). Yields correspond to the isolated product. TON = mmol product/mol % catalyst.

Scheme 2. Synthesis of Some Bromo-Substituted Aldehyde

Figure 5. Nitrogen adsorption−desorption isotherms of the fresh (a) and reused (b) MIL-101(Cr).
their several applications in different fields including organic synthesis, agrochemistry, materials, optics, polymer sciences, and medicinal chemistry. The main reason for the synthesis and investigation of bis-heterocycles is that each used heterocycle has its own activity and in combination with other molecule may have synergetic effect and also create new properties. Thus, two heterocycles that are suitably connected together (directly or via a spacer) to form a complex molecule have high potential to show a new property.

Diverse bis-heterocyclic compounds containing benzoazole fragments were synthesized using MIL-101(Cr) as catalyst under our optimized conditions. The aldehydes for the synthesis of these compounds were prepared according to the synthetic method shown in Schemes 2 and 3. First, compounds 6a−e as bromo-substituted aldehyde were synthesized using the reaction of isovanillin or 4-hydroxybenzaldehyde (4a and 4b) and 1,2-dialkyl bromides (5a−d).

After the synthesis of bromo-substituted aldehyde, they were reacted with selected heterocycles to synthesize new aldehydes containing a heterocycle moiety, which is connected through a carbon chain spacer (7a−g) (Scheme 3).

The synthesized bis-heterocyclic compounds containing benzoazole moieties from the synthetic aldehydes using MIL-101(Cr) catalyst under optimized conditions are shown in Scheme 4.

Compounds 8a−e were synthesized using the reaction of a theophylline-based aldehyde and one of the 2-aminophenols/2-aminothiophenol/α-phenylenediamine coupling partner. These compounds containing a benzoazole ring and also a theophylline heterocycle, both of which are important in medicinal applications. Compounds 8f−h contain an adenine moiety, which it connected to spacer using the sulfur group in 6-position of the adenine ring. In fact, 6-thio adenine (9H-purin-6-thiol) was used as the starting material for the synthesis of these compounds according to the reaction pathway designed in this study. When 6-thio adenine was reacted with bromo-substituted aldehyde 6 (Scheme 3), it underwent reaction by SH group and connected to the aldehyde backbone via the C−S bond. Also, adenine (9H-purin-6-amine) was used to connect aldehyde backbone through the C−N bond from the 9-position of the purin ring. Compounds 8i and 8j were synthesized using the reaction of o-phenylenediamine and 2-aminophenol and aldehyde 7f, respectively.

Synthesis of bis-heterocycles containing two benzoazole moieties is important from the viewpoint of medicinal and photophysical applications, as they have interesting properties. Compounds 8k and 8l are benzimidazole−benzoazole and benzimidazole−benzothiazole bis-heterocycles, respectively, which were synthesized efficiently using this synthetic methodology. These compounds were prepared using the reaction of a benzimidazole-based aldehyde 7g and 2-aminophenol/2-aminothiophenol under optimized conditions.

Overall, this synthetic methodology is suitable for the synthesis of diverse benzoazole derivatives under mild and heterogeneous conditions. Considering the chemical structure of MIL-101(Cr), it is possible to propose a reaction mechanism for the production of benzoazoles over the catalyst (Scheme 5). In the structure of MIL-101(Cr), there are Lewis acidic sites (I) that, originating from Cr(III) and coordination of aldehyde to these catalytic sites (II), can activate it to undergo reaction with amino group and form an imine intermediate (III). The intramolecular nucleophilic addition of the XH group (OH, SH, NH2) afforded a heterocycle intermediate (IV) with a high potential to afford benzoazole product in the presence of MIL-101(Cr).

The reusability of the catalyst was also checked in the reaction of benzaldehyde and 2-aminothiophenol. The MIL-101(Cr) catalyst could be reused at least five times with almost consistent efficiency (Table 3).

Some studies demonstrated the heterogeneity of MIL-101(Cr) as a catalyst in the synthesis of benzoazoles. The reused catalyst from the reaction mixture was characterized and the results show that the structure of MIL-101(Cr) after using in the reaction not alter considerably. For example, after five cycles of reusability, the evaluation of the Cr content of MIL-101(Cr) catalyst using ICP analysis demonstrated that about 5.5% of Cr was removed from the catalyst. Also, the hot filtration test done after the completion of the reaction between benzaldehyde and
2-aminothiophenol showed that only 2.0% of Cr was lost. The FT-IR spectrum of the catalyst after reuse also confirms that the functional group of the catalyst did not change remarkably (Figure 3). Also, the XRD pattern of the catalyst after reuse is same as that of the fresh one (Figure 4). In addition, for the reused MIL-101(Cr), the specific surface area calculated by the BET method was about 2572.8 m$^2$ g$^{-1}$ (compared to 2606 m$^2$ g$^{-1}$ for the fresh one). The total pore volume and the mean pore diameter of the reused MIL-101(Cr) were 1.77 cm$^3$ g$^{-1}$ and 2.75 nm, which are approximately same as those of the fresh one (Figure 5).

A comparison between the catalytic activities of MIL-101(Cr) and other reported catalyst systems in the synthesis of benzoazoles was done, and the results are given in Table 4. As demonstrated in Table 4, the MIL-101(Cr) catalyst shows comparable catalytic activity with other previously reported catalyst systems, and in many cases, it shows superior activity under mild and more sustainable reaction conditions.

**CONCLUSIONS**

In conclusion, MIL-101(Cr) was reported as an efficient catalyst system for the practical synthesis of benzoazole. The reaction conditions for the synthesis of benzimidazoles and benzothiazoles is mild and a range of derivatives were synthesized in ethanol as a green solvent at normal temperature. For the synthesis of benzoxazoles, higher temperature is needed, and the best solvent is xylene. This synthetic methodology is also useful for the synthesis of complex molecules and a range of bis-heterocyclic compounds containing benzoazole moiety were synthesized using MIL-101(Cr) as catalyst. The catalyst can be
reused several times, and can be separated from the reaction mixture by simple filtration. After removing the catalyst, the products were obtained in almost pure form. Moreover, there is no remarkable loss in the catalytic activity of MIL-101(Cr) after five cycles of reuse in the synthesis of benzoazoles.

**Experimental Section**

**General**. All of the starting materials and solvents were supplied from Merck, Acros, and Sigma-Aldrich chemical companies. The chemicals and solvents were used in this study without further purification. To record the $^1$H NMR and $^{13}$C NMR spectra, a Brucker (250 MHz) Avance DRX was used. Pure deuterated DMSO-$d_6$ and CDCl$_3$ were used as solvents and tetramethylsilane as an internal standard. Chemical shifts were reported in ppm ($\delta$) and coupling constants in Hz (J). To characterize the catalyst and also synthetic compounds with FT-IR spectroscopy, a Shimadzu FT-IR 8300 spectrophotometer was employed. The scanning electron micrograph (SEM) for the catalyst was obtained using XL-30 FEG SEM, Philips, at 20 kV. Inductively coupled plasma (ICP) analysis was carried out using an analyzer (Varian, Vista-Pro). The melting points were determined in open capillary tubes in a Buchi melting point B-545. The progress of the reactions was monitored by thin layer chromatography (TLC) on silica gel PolyGram SILG/UV254 plates. Also, to purify synthetic compounds, column chromatography was employed using columns charged with silica gel 60 (70–230 mesh) mesh.

**Procedure for the Synthesis of MIL-101(Cr)**. A 75 mL capacity Teflon-lined stainless steel autoclave was charged with a mixture of 5.4 g of Cr(NO$_3$)$_3$.9H$_2$O, 1.5 g of terephthalic acid, 45 mL of deionized water, and 0.6 mL of hydrofluoric acid (5 mol L$^{-1}$). The mixture was sonicated for 10 min and then heated in an oven at 220 °C for 8 h.$^{34}$ Subsequently, the autoclave was cool down to room temperature and the reaction mixture was filtered and washed with distilled water. The obtained solid was dried in an oven at 80 °C overnight. In this stage, the crude product is a green powder, which contained both formed MIL-101(Cr) and white sharp needle-type crystals as unreacted terephthalic acid. So, the unreacted terephthalic acid should be

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Table 3. Reusability of the MIL-101(Cr) Catalyst in the Reaction of 2-Aminothiophenol and Benzaldehyde under Optimized Conditions

| entry  | yield of product (%) | content of Cr (ppm) |
|--------|----------------------|---------------------|
| fresh catalyst | 87                   | 2.54                |
| run 1  | 87                   | 2.49                |
| run 2  | 86                   | 2.45                |
| run 3  | 86                   | 2.45                |
| run 4  | 85                   | 2.42                |
| run 5  | 84                   | 2.40                |

$^a$Reaction conditions: benzaldehyde (1.1 mmol), 2-aminothiophenol (1 mmol), MIL-101(Cr) (10 mg), and EtOH (5 mL) at 60 °C. $^b$Yields correspond to the isolated product.
repeated another two times and the product dried at 70 °C for 6 h. In the first step, the resulting green powder from the previous step was re-dissolved in two steps. First, the crude product was refluxed overnight in 50 mL ethanol and hot filtration was done. Finally, the material was heated at 80 °C in an oven for 12 h to complete the activation.

**General Procedure for the Synthesis of Benzoazoles**

A canonical flask was charged with ortho-phenylenediamine/or/o-aminophenol/o-aminothiophenol (1.0 mmol), aryl aldehyde (1.1 mmol), solvent (EtOH or xylene; 5 mL), and MIL-101 (0.01 g). The reaction mixture was stirred at specified temperature (55, 60, or 120 °C) for the appropriate time shown in Table 2 and Scheme 4. To monitor the progress of the reaction, TLC with suitable eluent was used. After the reaction was complete, the mixture was filtered, the catalyst washed with ethyl acetate, and the organic solvent evaporated to obtain a concentrated crude product, which was purified using column chromatography on silica gel (eluent of petroleum ether and EtOAc) to give pure products 3a–r and 6a–d.

**Recovery of the Catalyst.** Reusability of the MIL-101(Cr) catalyst was investigated by the reaction of benzaldehyde with 2-aminophenol. Upon completion of the reaction, the MIL-101(Cr) catalyst was separated from the reaction mixture using filtration. The catalyst was then washed with hot ethanol (3 × 5 mL) and then by hot water (3 × 5 mL). After drying under vacuum at 80 °C for 6 h, the catalyst could be reused directly without further purification in the next run. The catalyst could be recycled for five runs without the obvious loss of activity (Table 3).

**General Procedure for the Synthesis of Aldehydes 6a–d.** To synthesize aldehydes 6a–d, p-hydroxybenzaldehyde (0.02 mol, 2.44 g), K$_2$CO$_3$ (2.76 g, 0.02 mol), dibromoalkane (0.06 mol), and a catalytic amount of tetra-$n$-butylammonium bromide (TBAB, 0.1 g) were refluxed in MeCN (50 mL) for 20 h. The progress of the reaction was monitored with TLC; after the completion of the reaction, the reaction temperature was reduced to room temperature and the solvent evaporated. The crude product as a foam was dissolved in CHCl$_3$ (150 mL) and washed with water (3 × 150 mL). Then, the organic layer was dried over anhydrous Na$_2$SO$_4$ and evaporated. To obtain pure product, column chromatography on silica gel [eluting with a mixture of $n$-hexane and EtOAc (10:1)] was used.

**General Procedure for the Synthesis of Theophylline and Benzimidazole and Adenine-Based Aldehyde 7a–g.** A 100 mL double-necked round-bottom flask equipped with a condenser was charged with K$_2$CO$_3$ (1.38 g, 0.01 mol), nuclobase (0.01 mol), aldehydes 6a–d (0.012 mol), a catalytic amount of TBAB (0.1 g), and MeCN solvent (50 mL). The reaction mixture was stirred for 20 h at reflux temperature of acetonitrile. The solvent was evaporated when the reaction was accomplished (monitored by TLC), and the reaction temperature reduced to room temperature. The crude product was dissolved in CHCl$_3$ (150 mL) and then washed with water (3 × 100 mL). Then, the organic solvent was dried over anhydrous Na$_2$SO$_4$ and evaporated. The crude product was purified by column chromatography on silica gel [eluting with a mixture of $n$-hexane and EtOAc (1:1)].

### Table 4. Comparison between the Catalytic Activity of MIL-101 Catalyst and Other Reported Catalysts in the Synthesis of Benzoazoles

| entry | X | reaction conditions | yield (%) | ref |
|-------|---|---------------------|-----------|----|
| 1     | NH| Ag$_2$CO$_3$/celite(25), EtOH, 70 °C, 3 h | 94 | 18 |
| 2     | NH| nano-SZ(10), EtOH, 78 °C, 1 h | 92 | 19 |
| 3     | NH| N,NDMA/graphite, EtOH, 75 °C, 3 h | 67 | 20 |
| 4     | NH| Cu (BHPDPAH)$_2$O$_5$(5), EtOH, 25 °C, 2 h | 95 | 21 |
| 5     | NH| SiO$_2$–OSO$_3$H, EtOH, 80 °C, 0.5 h | 92 | 22 |
| 6     | NH| TiCl$_4$/OTf(10), EtOH, rt, 1.25 h | 84 | 23 |
| 7     | S | Ag$_2$CO$_3$/celite(25), EtOH, 70 °C, 3 h | 95 | 18 |
| 8     | S | Sm(OTf)$_3$(10), EtOH, 60 °C, 2 h | 89 | 24 |
| 9     | S | Pt/Al$_2$O$_3$(1), mesitylene, reflux, 24 h | 55 | 25 |
| 10    | S | Cu(OAc)$_2$/MCM-41, EtOH, rt, 0.5 h | 87 | 26 |
| 11    | S | PIFA–mixed, EtOH, 80 °C, 0.5 h | 87 | 27 |
| 12    | S | Indion 190 resin, EtOH, 70 °C, 4 h | 90 | 28 |
| 13    | O | Ru$_2$Cl$_2$(CO)$_3$, DABCO, toluene, reflux, 12 h | 81 | 9a|
| 14    | O | NaHSO$_4$–SiO$_2$, dioxane, reflux, 12 h | 90 | 29 |
| 15    | O | H$_2$[PMo$_9$V$_2$O$_4$](NH)(0.5), THF, reflux, 10 h | 91 | 30 |
| 16    | O | 4-methylaminophenol, xylene, 120 °C, 5 h | 90 | 31 |
| 17    | O | molecular sieve 5A, xylene, 180 °C, 48 h | 87 | 32 |
| 18    | O | activated carbon-30, xylene, 120 °C, 4 h | 79 | 33 |
| 19    | O | MIL-101(Cr) (10 mg), xylene, 120 °C, 9 h | 87 | this work |
| 20    | NH| MIL-101(Cr) (10 mg), EtOH, 55 °C, 5 h | 94 | this work |
| 21    | S | MIL-101(Cr) (10 mg), EtOH, 60 °C, 2.5 h | 87 | this work |

**ASSOCIATED CONTENT**

## Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.8b02309.
Spectral data and copy of $^1$H NMR and $^{13}$C NMR of synthesized compounds (PDF)

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Notes
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