ELSEVIER

Contents lists available at SciVerse ScienceDirect





journal homepage: www.elsevier.com/locate/molcata

Paal–Knorr reaction catalyzed by metal–organic framework IRMOF-3 as an efficient and reusable heterogeneous catalyst

Nam T.S. Phan*, Tung T. Nguyen, Quang H. Luu, Lien T.L. Nguyen

Department of Chemical Engineering, HCMC University of Technology, VNU-HCM, 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Viet Nam

A R T I C L E I N F O

Article history: Received 13 January 2012 Received in revised form 8 June 2012 Accepted 12 June 2012 Available online 22 June 2012

Keywords: Metal-organic framework IRMOF-3 Paal-Knorr reaction Heterogeneous catalyst Recyclable

1. Introduction

The Paal-Knorr condensation of primary amines with 1,4dicarbonyl precursors has been widely employed in the synthesis of pyrrole, pyrazoles, and their derivatives as important intermediates for pharmaceutical and fine chemical industry [1,2], as well as for the development of organic functional materials [3]. Traditionally, the reaction could effectively proceed in the presence of homogeneous Bronsted or Lewis acids such as H₂SO₄ [4], p-toluene sulfonic acid [5], Bi(NO₃)₃ [6], Al₂O₃ [7], FeCl₃ [3], CoCl₂ [8], Sc(OTf)₃ [9], ZrOCl₂ [10], Yb(OTf)3 [11], indium salts [12], titanium isopropoxide [13], and zinc tetrafluoroborate [14]. However, these homogeneous catalysis procedures suffer a number of serious problems, such as high amounts, toxicity and corrosion of the catalysts, generation of a large amount of wastes, tedious workup and difficult product purification [15,16]. With the increasing emphasis on green chemistry, more environmentally benign processes should be targeted to improve the green aspect of the reaction [17,18]. In this context, several solid catalysts have been investigated for the Paal-Knorr reaction. Indeed, the use of heterogeneous catalysts offers several advantages in terms of facile catalyst recovery and recycling, simple product separation and purification, minimal contamination of the desired products with hazardous or harmful metals [19,20]. Recently, the Paal–Knorr condensation has been carried

ABSTRACT

A highly porous metal–organic framework (IRMOF-3) was synthesized from the reaction of zinc nitrate hexahydrate and 2-amino-1,4-benzenedicarboxylic acid by solvothermal method. Physical characterizations of the material were achieved by using a variety of different techniques, including X-ray powder diffraction (XRD), scanning electron microscope (SEM), transmission electron microscopy (TEM), thermogravimetric analysis (TGA), Fourier transform infrared (FT-IR), atomic absorption spectrophotometry (AAS), and nitrogen physisorption measurements. The IRMOF-3 was used as an efficient heterogeneous catalyst for the Paal–Knorr reaction of benzyl amine with 2,5-hexanedione. Excellent conversions were obtained under mild conditions in the presence of 3 mol% catalyst. The IRMOF-3 catalyst could be reused several times without a significant degradation in catalytic activity.

© 2012 Elsevier B.V. All rights reserved.

out in the presence of a variety of solid catalysts, including layered zirconium phosphate and phosphonate [21], silica sulfuric acid [22], zeolite [23], magnetic nanoparticle-supported glutathione [24,25], nano β -PbO [26], polystyrene-supported aluminum chloride [15], macroporous strongly acidic styrol resin (D001) [27], and cationic exchange resin [28]. Although promising results have been achieved, the development of a more efficient catalyst for the reaction is still in great demand.

Applications of metal-organic frameworks (MOFs), a new family of organic-inorganic hybrid materials, in the field of catalysis have attracted increasing attention during the past few years [29]. Combining some special properties of both organic and inorganic porous materials, MOFs possess several advantages such as high surface areas, well-defined structures, ability to tune pore size, the ease of processability, and structural diversity [30-38]. Very recently, MOFs have been investigated as solid catalysts or catalyst supports for several organic transformations [29,39], including hydrosilylation of 1-hexyne [40], low temperature dehydrogenation [41], nitroaromatic reduction [42], Suzuki cross-coupling [43,44], "click" reaction [45], carbonyl-ene reaction [46], oxidation [47–53], alkene epoxidation [54–57], sequential alkene epoxidation/epoxide ring-opening reactions [58], oxidative cleavage of alkenes [59], cycloaddition of CO₂ with epoxides [60], cyanosilylation [61,62], hydrogenation [63,64], Sonogashira reaction [65], transesterification reaction [66], aldol condensation [67], aza-Michael condensation [68], 1,3-dipolar cycloaddition reactions [45], N-methylation of aromatic primary amines [69], epoxide ring-opening reaction [70-72], hydrolysis of ammonia borane [73], cyclopropanation of alkene [74], Knoevenagel

^{*} Corresponding author. Tel.: +84 8 38647256x5681; fax: +84 8 38637504. *E-mail addresses*: ptsnam@hcmut.edu.vn, ptsnam@yahoo.com, ptsnam@gmail.com (N.T.S. Phan).

^{1381-1169/\$ -} see front matter © 2012 Elsevier B.V. All rights reserved. http://dx.doi.org/10.1016/j.molcata.2012.06.007

condensation [75–77], Henry reaction [78], and Friedel–Crafts alkylation and acylation [79–81]. In this work, we wish to report the utilization of a highly porous metal–organic framework (IRMOF-3) as an efficient heterogeneous catalyst for the Paal–Knorr reaction. High activity was observed, and the IRMOF-3 catalyst could be reused without significant degradation in activity.

2. Experimental

2.1. Materials and instrumentation

All reagents and starting materials were obtained commercially from Sigma-Aldrich and Merck, and were used as received without any further purification unless otherwise noted. Nitrogen physisorption measurements were conducted using a Quantachrome 2200e system. Samples were pretreated by heating under vacuum at 150°C for 3 h. A Netzsch Thermoanalyzer STA 409 was used for thermogravimetric analysis (TGA) with a heating rate of 10°C/min under a nitrogen atmosphere. X-ray powder diffraction (XRD) patterns were recorded using a Cu Ka radiation source on a D8 Advance Bruker powder diffractometer. Scanning electron microscopy studies were conducted on a ISM 740 Scanning Electron Microscope (SEM). Transmission electron microscopy studies were performed using a JEOL JEM 1400 Transmission Electron Microscope (TEM) at 100 kV. The IRMOF-3 samples were dispersed on holey carbon grids for TEM observation. Elemental analysis with atomic absorption spectrophotometry (AAS) was performed on an AA-6800 Shimadzu. Fourier transform infrared (FT-IR) spectra were obtained on a Bruker TENSOR37 instrument, with samples being dispersed on potassium bromide pallets.

Gas chromatographic (GC) analyses were performed using a Shimadzu GC 17-A equipped with a flame ionization detector (FID) and a DB-5 column (length = 30 m, inner diameter = 0.25 mm, and film thickness = $0.25 \,\mu$ m). The temperature program for GC analysis heated samples from 100 to 190 °C at 20 °C/min; then heated them from 190 to 220 °C at 25 °C/min and finally heated them from 220 to 250 °C at 30 °C/min. The inlet and detector temperatures were set constant at 300 °C. n-Dodecane was used as an internal standard to calculate reaction conversions. GC-MS analyses were performed using a Hewlett Packard GC-MS 5972 with a RTX-5MS column (length = 30 m, inner diameter = 0.25 mm, and film thickness = 0. 5 μ m). The temperature program for GC-MS analysis heated samples from 60 to 280 °C at 10 °C/min and held them at 280 °C for 2 min. Inlet temperature was set constant at 280 °C. MS spectra were compared with the spectra gathered in the NIST library.

2.2. Synthesis of IRMOF-3

In a typical preparation [82], a solid mixture of zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O) (0.327 g, 1.1 mmol) and 2-amino-1,4-benzenedicarboxylic acid (H₂NH₂BDC) (0.078 g, 0.43 mmol) was stirred for 10 min in 10 ml of N,N'-dimethylformamide (DMF) in a 20 ml vial. The tightly capped vial was heated at 100 °C in an isothermal oven for 48 h to yield brown block crystals. After cooling of the vial to room temperature, the solid product was removed by decanting with mother liquor and washed in DMF (3×10 ml) for 3 days. After the solid product had been obtained, solvent exchange was carried out with dichloromethane (DCM) (2×10 ml) at room temperature for 2 days. The material was then evacuated under vacuum at 160 °C for 6 h, yielding 0.079 g of IRMOF-3 as Zn₄O(NH₂BDC)₃ in the form of pale yellow crystals (68% based on 2-amino-1,4-benzenedicarboxylic acid).

2.3. Catalytic studies

The Paal-Knorr reaction of benzyl amine with 2,5-hexanedione using the IRMOF-3 catalyst was carried out in a magnetically stirred round-bottom flask. The IRMOF-3 catalyst was activated under vacuum at 160°C for 6h prior to use. In a typical reaction, a solution of benzyl amine (0.22 ml, 2 mmol), 2,5-hexanedione (0.41 ml, 3.4 mmol), and n-dodecane (0.2 ml) as internal standard in 4 ml toluene was added to the flask containing the IRMOF-3 catalyst (0.013 g, 3 mol %). The catalyst concentration was calculated with respect to the zinc/benzyl amine molar ratio. The resulting mixture was stirred at room temperature for 60 min. Reaction conversion was monitored by withdrawing aliquots from the reaction mixture at different time intervals, quenching with diethyl ether, drying over anhydrous Na₂SO₄, analyzing by GC with reference to *n*-dodecane, and further confirming product identity by GC-MS. It should be noted that no further progress of the reaction was observed when the sample in diethyl ether was stored for another 2 h, indicating the aliquots were completely quenched. The IRMOF-3 catalyst was separated from the reaction mixture by simple decantation, washed with copious amounts of anhydrous dichloromethane, dried under vacuum at ambient temperature for 1 h, and reused when necessary. For the leaching test, a catalytic reaction was stopped after 5 min, analyzed by GC, and decanted to remove the solid catalyst. The reaction solution was then stirred for a further 55 min. Reaction progress, if any, was monitored by GC as previously described.

3. Results and discussion

3.1. Catalyst synthesis and characterization

As a member of isoreticular metal-organic framework family, IRMOF-3 consists of Zn₄O clusters and 2-aminobenzenedicarboxylate (NH₂-BDC) linkers, forming an extended three-dimensional cubic porous network as Zn₄O(NH₂BDC)₃ [76,83]. In this work, the IRMOF-3 was synthesized using zinc nitrate hexahydrate and H₂NH₂BDC by a solvothermal method, according to a literature procedure [82]. It was found that the IRMOF-3 was achieved as pale yellow crystals with a yield of 68% (based on 2-amino-1,4-benzenedicarboxylic acid). The IRMOF-3 was then characterized using a variety of different techniques. Elemental analysis with AAS indicated zinc and nitrogen loadings of 4.3 and 3.6 mmol/g, respectively. The XRD diffractogram (Fig. 1) indicated that a highly crystalline material was obtained with a very sharp peak being observed below 10° (with 2θ of 6.8). The overall XRD patterns of the



Fig. 1. X-ray powder diffractogram of the IRMOF-3.



Fig. 2. SEM micrograph of the IRMOF-3.

IRMOF-3 were in good agreement with those previously reported in the literature [84,85]. FT-IR spectra of the IRMOF-3 showed a significant difference as compared to that of the free 2-amino-1,4-benzenedicarboxylic acid, being consistent with the literature [86,87]. TGA result of the IRMOF-3 indicated that the material could be stable up to over 400 °C. The SEM micrograph showed that well-shaped cubic crystals with crystal sizes ranging between approximately 400 and 500 μ m were obtained (Fig. 2). Langmuir specific surface areas of up to 3295 m²/g were observed for the IRMOF-3, as calculated from nitrogen adsorption/desorption isotherm data (Fig. 3). The pore structure of the IRMOF-3 appeared to be complex. Indeed, nitrogen physisorption measurements indicated that the material would contain both microporous (diameter < 20 Å) and mesoporous pores (Fig. 4).

3.2. Catalytic studies

The IRMOF-3 was used as a solid catalyst for the Paal–Knorr reaction of benzyl amine with 2,5-hexanedione to form 1-benzyl-2,5-dimethyl-1*H*-pyrrole as the major product (Scheme 1). Initial studies addressed the effect of reagent molar ratio on the reaction conversion. The Paal–Knorr reaction was carried out in toluene at room temperature in the presence of 2 mol% IRMOF-3 catalyst, using benzylamine: 2,5-hexanedione molar ratio of 1:1, 1:1.5, and 1:1.7, respectively. The catalyst concentration was calculated with



Fig. 4. Pore size distribution of the IRMOF-3.

respect to the zinc/benzyl amine molar ratio. For the reason of simplicity, the zinc content was used as an elemental tag for the catalyst. Farrusseng and co-workers previously employed IRMOFs as solid acid catalysts, and proposed that Zn-OH species, which were formed as structural defects in the synthesis step or upon water adsorption, could contribute to the catalytic activity of the IRMOFs [80,88]. Recently, Corma and co-workers also demonstrated that these defects in IRMOF-3 could be the active sites for acid-catalyzed organic transformations [89]. However, it should be noted that further investigations would be needed to elucidate the real reactive sites on the surface of the IRMOF-3 catalyst in the Paal-Knorr condensation. Aliquots were withdrawn from the reaction mixture at different time intervals and analyzed by GC, giving kinetic data during the course of the reaction. It was found that the reaction rate was significantly affected by the reagent ratio. The Paal-Knorr reaction using one equivalent of 2,5-hexanedione afforded 52% conversion after 60 min, while 60% conversion was observed for that using the reagent ratio of 1:1.5. Increasing the reagent ratio to 1:1.7 led to a dramatic enhancement in reaction rate, with 96% conversion being achieved after 60 min (Fig. 5). It was therefore decided to use benzylamine: 2,5-hexanedione molar ratio of 1:1.7 for further studies.

With this result in mind, we then decided to investigate the effect of catalyst concentration on the reaction conversion, having carried out the Paal–Knorr reaction in toluene at room temperature, using benzylamine: 2,5-hexanedione molar ratio of 1:1.7 in the presence of 2 mol%, 3 mol%, 1 mol%, and 0.5 mol% IRMOF-3 catalyst, respectively. It was observed that decreasing the catalyst concentration to 1 mol% and 0.5 mol% resulted in a significant drop in the



Fig. 3. Nitrogen adsorption/desorption isotherm of the IRMOF-3. Adsorption data are shown as closed circles and desorption data as open circles.



Fig. 5. Effect of benzylamine:2,5-hexanedione molar ratio on reaction conversion.



Scheme 1. The Paal-Knorr reaction using the IRMOF-3 catalyst.

reaction conversion, with 77% and 67% conversions being obtained after 60 min. As expected, increasing the catalyst concentration led to an enhancement in the reaction conversion. The reaction using 3 mol% catalyst afforded 99% conversion after 60 min. It should be noted that a conversion of 16% was observed after 60 min in the absence of the catalyst, indicating the necessity of the IRMOF-3 catalyst for the reaction (Fig. 6). The catalyst concentrations used for the Paal-Knorr reaction in this study were comparable to those in the literature. Indeed, a variety of catalysts were previously employed for the Paal-Knorr reaction, in which the catalyst concentrations could vary from less than 5 mol% to more than 50 mol%, depending on the nature of the catalyst as well as that of the substrate. These catalysts included Bi(NO₃)₃·5H₂O (50–100 mol%) [6], nano lead oxide (20 mol%) [26], polystyrene-supported aluminum chloride (15 mol%) [15], potassium exchanged layered zirconium phosphate (12 mol%), UO2(NO3)2.6H2O (10 mol%) [90], sulfamic acid (10 mol%) [91], zirconium sulfophenyl phosphonate (6 mol%) [21], Yb(OTf)₃ (5 mol%) [11], CoCl₂ (5 mol%) [8], ZrOCl₂·8H₂O (2.5 mol%) [10], and Sc(OTf)₃ (1 mol%) [9].

For liquid-phase organic transformations using solid catalysts, there is a possibility that some of active sites could migrate into the solution phase during the course of the reaction. In several cases, these leached species from the solid phase could contribute significantly to the total conversion of the reaction, thus indicating that the reaction would not proceed under real heterogeneous catalysis conditions [92]. In order to test if active species leached from the solid IRMOF-3 catalyst could play an important role in the catalytic activity for the Paal-Knorr reaction, an experiment was performed using a simple decantation during the course of the reaction. After the solid catalyst was removed from the reaction mixture, if the catalytic reaction continued this would indicate that the reaction occurred either under totally homogeneous or under partially heterogeneous and partially homogeneous conditions. The Paal-Knorr reaction was carried out in toluene at room temperature, using benzylamine: 2,5-hexanedione molar ratio of 1:1.7, in the presence of 3 mol% of fresh IRMOF-3 catalyst. After 5 min reaction time, the toluene phase was separated from the solid IRMOF-3 by simple decantation, transferred to a new reactor vessel, and stirred for an additional 55 min at room temperature with aliquots being sampled at different time intervals, and analyzed by GC. As expected, experimental results showed that no further conversion was observed for the Paal–Knorr reaction after the solid IRMOF-3 catalyst was removed from the reaction mixture. This observation clearly confirmed that the Paal–Knorr reaction could only occur in the presence of the solid IRMOF-3 catalyst, and there was no contribution from leached active species, if any, in the liquid phase (Fig. 7).

To emphasize the advantages of using the solid IRMOF-3 as catalyst for the Paal-Knorr condensation, the catalytic activity of two components of the IRMOF-3 (i.e. Zn(NO₃)₂.6H₂O and 2-amino-1,4benzenedicarboxylic acid) as well as two popular metal-organic frameworks (i.e. MOF-5 and ZIF-8) was investigated for the reaction. The MOF-5 and the ZIF-8 were synthesized and characterized as previously reported [79,93]. The Paal-Knorr reaction was carried out in toluene at room temperature, using benzylamine: 2,5-hexanedione molar ratio of 1:1.7, in the presence of 3 mol% catalyst. It was found that 2-amino-1,4-benzenedicarboxylic acid was totally inactive for the reaction under this condition. with no trace amount of the product being detected by GC. The reaction using 3 mol% Zn(NO₃)₂·6H₂O as catalyst afforded 89% conversion after 60 min, revealing that the metal centers would be the active sites on the solid IRMOF-3 catalyst. Indeed, zinc-based catalyst was previously reported to exhibit high activity in the Paal-Knorr reaction [14]. Fe(NO₃)₃ exhibited similar activity to the IRMOF-3 in the reaction. However, it is apparent that this Lewis acid catalyst cannot be reused. It was found that the ZIF-8 offered lowest activity for the reaction, and a conversion of 83% was obtained after 60 min for the reaction using 3 mol% ZIF-8. Interestingly, the MOF-5 exhibited lower activity than the IRMOF-3, with 93% and 99% conversions being achieved after 60 min for the reaction using the former and the latter, respectively (Fig. 8). It should be noted that the MOF-5 (composition of Zn₄O(BDC)₃ in which BDC = 1,4-benzenedicarboxylate) is topologically similar to IRMOF-3 (composition of Zn₄O(NH₂BDC)₃ in which NH₂BDC is 2-amino-1,4-benzenedicarboxylate), and the MOF-5 possessed



Fig. 6. Effect of catalyst concentration on reaction conversion.



Fig. 7. Leaching test indicated no contribution from homogeneous catalysis of active species leaching into reaction solution.



Fig. 8. Effect of different catalysts on reaction conversion.

higher surface areas $(3800 \text{ m}^2/\text{g})$ than those of the IRMOF-3 $(3295 \text{ m}^2/\text{g})$. These results indicated that the amino groups on the linkers in the MOF structure would play an important role in the catalytic activity for the Paal–Knorr reaction. In this case, the reactants (i.e. benzylamine and 2,5-hexanedione) were significantly more polar than the solvent of the reaction (i.e. toluene). Therefore, the partitioning of the reactants away from the solvent to the catalyst would be enhanced when the polarity of the catalyst surface increased. As the free linker (i.e. 2-amino-1,4-benzenedicarboxylic acid) showed almost no activity for the reaction under identical condition, the higher polarity of the catalyst surface would be one of reasons leading to the higher activity of the IRMOF-3 as compared to that of the MOF-5. However, the role of the amine moiety in the catalyst structure still needs further investigation.

The effect of different solvents on the reaction rate is normally an important issue that should be taken into accounts. A variety of solvents were previously employed for the Paal-Knorr condensation, significantly depending on the nature of the catalyst. Banik et al. carried out the reaction in dichloromethane in the presence of Bi(NO₃)₃·5H₂O as catalyst [6]. Rahmatpour and co-workers used ZrOCl₂.8H₂O catalyst for the reaction and found that the yield increased with the order: tetrahydrofuran < methanol < ethylacetate < chloroform < dichloromethane <acetonitrile<solvent-free condition [10]. Methanol was previously reported to be the solvent of choice for the reaction using $UO_2(NO_3)_2 \cdot 6H_2O$ catalyst, offering higher conversions than that carried out in ethanol, acetonitrile, chloroform, dichloromethane, and solvent-free condition, respectively [90]. For the reaction employing polystyrene-supported aluminum chloride as catalyst, toluene, dichloromethane, dichloroethane, tetrahydrofuran, and solvent-free condition were reported to be totally ineffective, while high yields were observed for the case of acetonitrile [15]. It was therefore decided to investigate the effect of different solvents on the Paal-Knorr reaction using the IRMOF-3 catalyst. The reaction was carried out at room temperature, using benzylamine: 2,5-hexanedione molar ratio of 1:1.7, in the presence of 3 mol% catalyst. It was found that polar solvents like methanol and ethanol were not suitable for the process, as the IRMOF-3 crystals were broken into fine powders in these solvents. Experimental results showed that the reaction rate of the Paal-Knorr condensation using the IRMOF-3 catalyst decreased in the order of solvents: toluene > anisole > p-xylene > ethylbenzene > chloroform (Fig. 9). The reaction carried out in toluene could proceed to completion after 60 min, while 88%, 81%, 76%, and 47% conversions were observed for the case of anisole, *p*-xylene, ethylbenzene, and chloroform, respectively. However, the effect of different solvents



Fig. 9. Effect of different solvents on reaction conversion.

on the rate of the Paal-Knorr reaction using the IRMOF-3 catalyst is complex, and needs further investigation.

The study was then extended to the condensation reaction of several reagents in the presence of the IRMOF-3 as catalyst. The reactions of 2,5-hexanedione with eight amines, including benzylamine, 1,2-phenylenediamine, p-toluidine, aniline, phenylhydrazine, *p*-anisidine, 4-florobenzylamine, 4-methylbenzylamine, respectively, were carried out at room temperature using the reagent molar ratio of 1:1.7, in the presence of 3 mol% IRMOF-3 catalyst. The reaction of benzylamine with 2,5-hexanedione proceeded to completion after 60 min under this condition. However, it was observed that the effect of substituents in the aromatic ring on the Paal-Knorr condensation was unclear. The presence of either an electron-donating group (i.e. 4-methylbenzylamine) or an electron-withdrawing group (i.e. 4-florobenzylamine) in benzylamine both accelerated the reaction rate, with quantitative conversions being achieved after 20 min and 10 min, respectively. Indeed, Chen et al. previously reported similar observation for the Paal-Knorr condensation, in which high conversions were obtained for both benzylamines containing electron-withdrawing or electron-donating groups [9]. It was also found that the IRMOF-3 catalyst could be suitable for the condensation of 2,5-hexanedione with phenylhydrazine to form a pyrazole derivative, where the reaction could afford more than 99% conversion after 30 min. Although the IRMOF-3 exhibited high activity in the Paal-Knorr reaction of benzylamine, it was observed that the condensation reaction of aniline with 2,5-hexanedione using this catalyst proceeded with difficulty. Conversions of 12%, 28%, and 39% were obtained after 60 min for the case of aniline, p-toluidine, and panisidine, respectively (Fig. 10). Curini et al. previously carried out the Paal-Knorr reaction using zirconium-based catalysts and found that benzylamine was significantly more reactive than aniline [21]. Aniline also exhibited lower reactivity than benzylamine in the Paal-Knorr reaction using ZrOCl₂ 8H₂O [10], and silica sulfuric acid [22] as catalysts. However, it was previously reported that the Paal-Knorr reaction of aniline afforded higher yields than the case of benzylamine in the presence of other catalysts, including CoCl₂ [8], ZrCl₄ [94], UO₂(NO₃)2·6H₂O [90], nano β-PbO [26], Bi(NO₃)₃·5H₂O [6], and macroporous strongly acidic styrol resin (D001) [27]. With this result in mind, we then decided to carry out the Paal-Knorr reaction of benzylamine with different diketones, including 2,5-hexadione, 1-phenyl-1,4-pentandione, and 1,2-dibenzoylethane, respectively. It was found that the reaction occurred slowly for the case of 1-phenyl-1,4-pentandione and 1,2dibenzoylethane, while quantitative conversion was achieved for the reaction of 2,5-hexadione under the same condition (Fig. 11). The issue still needs further studies, though it could be proposed



Fig. 10. Effect of different amines on reaction conversion.

that the bulky phenyl groups on the diketone might have a negative effect on the transformation.

As mentioned earlier, the replacement of traditional homogeneous Lewis acids with solid catalysts would offer several advantages, including easy catalyst recovery and recycling. In the best case the solid catalyst can be recovered and reused several times before it eventually deactivates completely. It was therefore decided to investigate the recoverability and reusability of the IRMOF-3 catalyst in the Paal-Knorr reaction of benzylamine with 2,5-hexadione by repeatedly separating the IRMOF-3 from the reaction mixture, washing it and then reusing it. The reaction was carried out in toluene at room temperature using the reagent molar ratio of 1:1.7, in the presence of 3 mol% IRMOF-3 catalyst. After each run, the catalyst was separated from the reaction mixture by simple decantation, then washed with copious amounts of dichloromethane to remove any physisorbed reagents. The recovered IRMOF-3 was dried under vacuum at room temperature for 1 h, and then reused in further reactions under identical conditions to those of the first run. It was found that the IRMOF-3 could be recovered and reused several times without a significant degradation in catalytic activity. Indeed, a conversion of 92% was still achieved in the 8th run (Fig. 12a). In a second experiment, aliquots were withdrawn from the reaction mixture at different time intervals and analyzed by GC, giving kinetic data during the course of the reaction



Fig. 11. Effect of different diketones on reaction conversion.



Fig. 12. Catalyst recycling studies.

using the fresh and recycled catalyst, respectively. It was observed that the activity of the IRMOF-3 catalyst in the Paal–Knorr reaction decreased slightly after each run. However, it was apparent that the catalyst could still be recycled and reused (Fig. 12b). Although it was previously reported that almost no loss of activity was observed for reused solid catalysts in the Paal–Knorr reaction, no kinetic data was provided [15,22,25,27]. Indeed, only conversions at the end of the experiment were mentioned. However, stable activity should not be demonstrated by reporting only similar reaction conversions at long times. Kinetic studies are the true test of catalyst deactivation [92].



Fig. 13. FT-IR spectra of the fresh (a) and reused (b) IRMOF-3.



Fig. 14. X-ray powder diffractogram of the fresh (a) and reused (b) IRMOF-3.

In order to support the recoverability and reusability of the IRMOF-3 in the Paal-Knorr reaction, the recovered catalyst was also characterized by FT-IR and XRD. The C=O stretching vibration of free –COOH group was not observed on the FT-IR of the reused IRMOF-3. Indeed, the spectra of the reused catalyst after the first run revealed a similar absorption as compared to that of the fresh IRMOF-3 (Fig. 13). Furthermore, XRD result of the reused IRMOF-3 after the first run showed that the crystallinity of the material could be maintained during the course of the reaction, though a slight difference in the overall structure was observed for the reused catalyst (Fig. 14). The recyclability of the IRMOF-3 catalyst in the Paal-Knorr reaction still needs further investigation. In a control experiment, it was observed that the IRMOF-3 catalyst was stable in toluene at room temperature for at least 1 week. The presence of a small amount of a base in the reaction mixture (i.e. benzylamine) might have a negative effect on the stability of the catalyst. This could be one of the reason leading to the low signal in the XRD result of the recycled catalyst (Fig. 14). Indeed, Saha and Deng previously reported a significant loss in crystallinity after MOF-5 was fully exposed to ammonia [95]. However, Savonnet [68], Zhang [96] and co-workers demonstrated that IRMOF-3 catalyst could be recycled and reused several times in the presence of amines as reactants.

4. Conclusions

In summary, highly crystalline porous IRMOF-3 was synthesized from the reaction of zinc nitrate hexahydrate and 2-amino-1,4benzenedicarboxylic acid by a solvothermal method. The IRMOF-3 was characterized using a variety of different techniques, including FT-IR, TEM, SEM, XRD, TGA, AAS, and nitrogen physisorption measurements. The material was used as an efficient heterogeneous catalyst for the Paal-Knorr reaction of benzyl amine with 2,5-hexanedione to form 1-benzyl-2,5-dimethyl-1*H*-pyrrole as the major product. Excellent conversions were obtained under mild conditions in the presence of 3 mol% catalyst, and the IRMOF-3 catalvst could be reused several times without significant degradation in activity. Moreover, the Paal-Knorr reaction could only occur in the presence of the solid IRMOF-3 catalyst, and there was no contribution from leached active species, if any, in the solution phase. The presented results demonstrate that the application of this porous metal-organic framework could be expanded to the catalysis field, which would be interested to the chemical industry.

References

 M. Biava, G.C. Porretta, G. Poce, S. Supino, D. Deidda, R. Pompei, P. Molicotti, F. Manetti, M. Botta, J. Med. Chem. 49 (2006) 4946–4952.

- [2] S.K. Vooturi, C.M. Cheung, M.J. Rybak, S.M. Firestine, J. Med. Chem. 52 (2009) 5020–5031.
- [3] N. Azizi, A. Khajeh-Amiri, H. Ghafuri, M. Bolourtchian, M.R. Saidi, Synlett 14 (2009) 2245–2248.
- 4] S.E. Drewes, C.J. Hogan, Synth. Commun. 19 (1989) 2101–2107.
- [5] S. Raghavan, K. Anuradha, Synlett (2003) 711–713.
- [6] B.K. Banik, I. Banik, M. Renteriaa, S.K. Dasgupta, Tetrahedron Lett. 46 (2005) 2643–2645.
- [7] R. Ballini, L. Barboni, G. Bosica, M. Petrini, Synlett (2000) 391-393
- [8] S.K. De, Heteroatom Chem. 10 (2008) 592–595.
- [9] J. Chen, H. Wu, Z. Zheng, C. Jin, X. Zhang, W. Su, Tetrahedron Lett. 47 (2006) 5383–5387.
- [10] A. Rahmatpour, Appl. Organometal. Chem. 25 (2011) 585–590.
- B.Zuo, J.X. Chen, M.C. Liu, H.Y. Wu, W.K. Su, Chin. Chem. Lett. 20 (2009) 423–426.
 J.X. Chen, M.C. Liu, X.L. Yang, J.C. Ding, H.Y. Wu, J. Braz. Chem. Soc. 19 (2008) 877–883.
- [13] S.-X. Yu, P.W.L. Quesne, Tetrahedron Lett. 36 (1995) 6205–6208.
- [14] B.C. Ranu, S. Ghosh, A. Das, Mendeleev Commun. 16 (2006) 220-221.
- [15] A. Rahmatpour, J. Aalaie, Heteroatom Chem. 22 (2011) 85-90.
- [16] R.G.d. Noronha, A.C. Fernandes, C.C. Romão, Tetrahedron Lett. 50 (2009) 1407-1410.
- [17] M.J. Gracia, E. Losada, R. Luque, J.M. Campelo, D. Luna, J.M. Marinas, A.A. Romero, Appl. Catal. A 349 (2008) 148–155.
- [18] G.D. Yadav, G. George, Micropor. Mesopor. Mater. 96 (2006) 36-43.
- [19] K. Mantri, K. Komura, Y. Kubota, Y. Sugi, J. Mol. Catal. A 236 (2005) 168-175.
- [20] N.E. Leadbeater, M. Marco, Chem. Rev. 102 (2002) 3217-3274.
- [21] M. Curini, F. Montanari, O. Rosati, E. Lioy, R. Margarita, Tetrahedron Lett. 44 (2003) 3293–3295.
- [22] H. Veisi, Tetrahedron Lett. 51 (2010) 2109-2114.
- [23] R. Sreekumar, R. Padmakumar, Synth. Commun. 28 (1998) 1661–1665.
- [24] V. Polshettiwar, R.S. Varma, Tetrahedron 66 (2010) 1091-1097.
- [25] V. Polshettiwar, B. Baruwati, R.S. Varma, Chem. Commun. (2009) 1837–1839.
 [26] S.K. Pasha, V.S.V. Satyanarayana, A. Sivakumar, K. Chidambaram, L.J. Kennedy, Chin. Chem. Lett. 22 (2011) 891–894.
- [27] S.Z. Yuan, L.X. Jin Liu, Chin. Chem. Lett. 21 (2010) 664–668.
- [28] Y.-H. He, G.-Q. Wang, Z. Guan, J. Heterocycl. Chem. 47 (2010) 486-489.
- [29] A. Dhakshinamoorthy, M. Alvaro, A. Corma, H. Garcia, Dalton Trans. 40 (2011) 6344-6360.
- [30] H.K. Chae, D.Y. Siberio-Perez, J. Kim, Y. Go, M. Eddaoudi, A.J. Matzger, M. O'Keeffe, O.M. Yaghi, Nature 427 (2004) 523–527.
- [31] D.J. Tranchemontagne, M.O.k.Z. Ni, O.M. Yaghi, Angew. Chem. Int. Ed. 47 (2008) 5136–5147.
- [32] S.S. Kaye, A. Dailly, O.M. Yaghi, J.R. Long, J. Am. Chem. Soc. 129 (2007) 14176–14177.
- [33] H. Furukawa, N. Ko, Y.B. Go, N. Aratani, S.B. Choi, E. Choi, A.O. Yazaydin, R.Q. Snurr, M. O'Keeffe, J. Kim, O.M. Yaghi, Science 239 (2010) 424–428.
- [34] P. Horcajada, T. Chalati, C. Serre, B. Gillet, C. Sebrie, T. Baati, J.F. Eubank, D. Heurtaux, P. Clayette, C. Kreuz, J.S. Chang, Y.K. Hwang, V. Marsaud, P.N. Bories, L. Cynober, S. Gil, G. Férey, P. Couvreur, R. Gref, Nat. Mater. 9 (2010) 172–178.
- [35] R.J. Kuppler, D.J. Timmons, Q.-R. Fang, J.-R. Li, T.A. Makal, M.D. Young, D. Yuan, D. Zhao, W. Zhuang, H.-C. Zhou, Coord. Chem. Rev. 253 (2009) 3042–3066.
- [36] H. Li, M. Eddaoudi, M. O'Keeffe, O.M. Yaghi, Nature 402 (1999) 276-279.
- [37] J.L.C. Rowsell, O.M. Yaghi, Micropor. Mesopor. Mater. 73 (2004) 3-14.
- [38] Z.-Q. Li, L.-G. Qiu, T. Xu, Y. Wu, W. Wang, Z.-Y. Wu, X. Jiang, Mater. Lett. 63 (2009) 78–80.
- [39] M. Ranocchiari, J.A.v. Bokhoven, Phys. Chem. Chem. Phys. 13 (2011) 6388–6396.
 [40] T. Kamegawa, M. Saito, T. Watanabe, K. Uchihara, M. Kondo, M. Matsuoka, M.
- Anpo, J. Mater. Chem. 21 (2011) 12228–12231.
- [41] W. Sun, S. Li, J. Mao, Z. Guo, H. Liu, S. Dou, X. Yu, Dalton Trans. 40 (2011) 5673–5676.
- [42] R.F. D'Vries, M. Iglesias, N. Snejko, S. Alvarez-Garcia, E. Gutiérrez-Puebla, M.A. Monge, J. Mater. Chem. 22 (2012) 1191–1198.
- [43] F.X.L.i. Xamena, A. Abad, A. Corma, H. Garcia, J. Catal. 250 (2007) 294-298.
- [44] Y. Huang, Z. Zheng, T. Liu, J. Lü, Z. Lin, H. Li, R. Cao, Catal. Commun. 14 (2011) 27–31.
- [45] I. Luz, F.X.L.i. Xamena, A. Corma, J. Catal. 276 (2010) 134-140.
- [46] K.S. Jeong, Y.B. Go, S.M. Shin, S.J. Lee, J. Kim, O.M. Yaghi, N. Jeong, Chem. Sci. 2 (2011) 877–882.
- [47] A. Dhakshinamoorthy, M. Alvaro, H. Garcia, ACS Catal. 1 (2011) 48-53.
- [48] F.X.Li. Xamena, O. Casanova, R.G. Tailleur, A.C.H. Garcia, J. Catal. 255 (2008) 220–227.
- [49] H. Liu, Y. Liu, Y. Li, Z. Tang, H. Jiang, J. Phys. Chem. C 114 (2010) 13362-13369.
- [50] W. Kleist, M. Maciejewski, A. Baiker, Thermochim. Acta 499 (2010) 71-78.
- [51] A. Dhakshinamoorthy, M. Alvaro, H. Garcia, J. Catal. 267 (2009) 1-4.
- [52] W. Wang, Y. Li, R. Zhang, D. He, H. Liu, S. Liao, Catal. Commun. 12 (2011) 875–879.
- [53] A. Dhakshinamoorthy, M. Alvaro, H. Garcia, Catal. Sci. Technol. 1 (2011) 856–867.
- [54] F. Song, C. Wang, J.M. Falkowski, L. Ma, W. Lin, J. Am. Chem. Soc. 132 (2010) 15390–15398.
- [55] S.-H. Cho, B. Ma, S.T. Nguyen, J.T. Hupp, T.E. Albrecht-Schmitt, Chem. Commun. 42 (2006) 2563–2565.
- [56] K. Brown, S. Zolezzi, P. Aguirre, D. Venegas-Yazigi, V. Paredes-García, R. Baggio, M.A. Novak, E. Spodine, Dalton Trans. 38 (2009) 1422–1427.
- [57] S. Bhattacharjee, D.-A. Yang, W.-S. Ahn, Chem. Commun. 47 (2011) 3637–3639.
- [58] F. Song, C. Wang, W. Lin, Chem. Commun. 47 (2011) 8256-8258.

- [59] Z. Saedi, S. Tangestaninejad, M. Moghadam, V. Mirkhani, I. Mohammadpoor-Baltork, Catal. Commun. 17 (2012) 18–22.
- [60] J. Song, Z. Zhang, S. Hu, T. Wu, T. Jiang, B. Han, Green Chem. 11 (2009) 1031–1036
- [61] K. Schlichte, T. Kratzke, S. Kaskel, Micropor. Mesopor. Mater. 73 (2004) 81–88.
- [62] M. Gustafsson, A. Bartoszewicz, B. Martn-Matute, J. Sun, J. Grins, T. Zhao, Z. Li, G. Zhu, X. Zou, Chem. Mater. 22 (2010) 3316–3322.
- [63] S. Opelt, S. Turk, E. Dietzsch, A. Henschel, S. Kaskel, E. Klemm, Catal. Commun. 9 (2008) 1286–1290.
- [64] Y. Zhao, J. Zhang, J. Song, J. Li, J. Liu, T. Wu, P. Zhang, B. Han, Green Chem. 13 (2011) 2078–2082.
- [65] S. Gao, N. Zhao, M. Shu, S. Che, Appl. Catal. A: Gen. 388 (2010) 196-201.
- [66] Y. Zhou, J. Song, S. Liang, S. Hu, H. Liu, T. Jiang, B. Han, J. Mol. Catal. A 308 (2009) 68-75.
- [67] F. Vermoortele, R. Ameloot, A. Vimont, C. Serre, D.D. Vos, Chem. Commun. 47 (2011) 1521–1523.
- [68] M. Savonnet, S. Aguado, U. Ravon, D. Bazer-Bachi, V. Lecocq, N. Bats, C. Pinel, D. Farrusseng, Green Chem. 11 (2009) 1729–1732.
- [69] A. Dhakshinamoorthy, M. Alvaro, H. Garcia, Appl. Catal. A: Gen. 378 (2010) 19-25.
- [70] K. Tanaka, S. Oda, M. Shiro, Chem. Commun. 44 (2008) 820-822.
- [71] K.K. Tanabe, S.M. Cohen, Inorg. Chem. 49 (2010) 6766–6774.
- [72] A. Corma, H. García, F.X.L.i. Xamena, Chem. Rev. 110 (2010) 4606–4655.
 [73] P. Song, Y. Li, W. Li, B. He, J. Yang, X. Li, Int. J. Hydrogen Energy 36 (2011) 10468–10473
- [74] F.-N. Shi, A.R. Silva, J. Rocha, J. Solid State Chem. 184 (2011) 2196–2203.
- [75] S. Neogi, M.K. Sharma, P.K. Bharadwaj, J. Mol. Catal. A 299 (2009) 1-4.
- [76] J. Gascon, U. Aktay, M.D. Hernandez-Alonso, G.P.M.v. Klink, F. Kapteijn, J. Catal. 261 (2009) 75–87.

- [77] G.A.E. Oxford, D. Dubbeldam, L.J. Broadbelt, R.Q. Snurr, J. Mol. Catal. A: Chem. 334 (2011) 89–97.
- [78] L.-X. Shi, C.-D. Wu, Chem. Commun. 47 (2011) 2928–2930.
- [79] N.T.S. Phan, K.K.A. Le, T.D. Phan, Appl. Catal. A: Gen. 382 (2010) 246–253.
- [80] U. Ravon, M. Savonnet, S. Aguado, M.E. Domine, E. Janneau, D. Farrusseng, Micropor. Mesopor. Mater. 129 (2010) 319–329.
- [81] L.T.L. Nguyen, C.V. Nguyen, G.H. Dang, K.K.A. Le, N.T.S. Phan, J. Mol. Catal. A: Chem. 349 (2011) 28–35.
- [82] A.R. Millward, O.M. Yaghi, J. Am. Chem. Soc. 127 (2005) 17998-17999.
- [83] C.J. Doonan, W. Morris, H. Furukawa, O.M. Yaghi, J. Am. Chem. Soc. 131 (2009) 9492-9493.
- [84] Z.Q. Wang, S.M. Cohen, J. Am. Chem. Soc. 129 (2007) 12368-12369.
- [85] M.J. Ingleson, J.P. Barrio, J.-B. Guilbaud, Y.Z. Khimyak, M.J. Rosseinsky, Chem. Commun. 44 (2008) 2680–2682.
- [86] C.H. Specht, F.H. Frimmel, Phys. Chem. Chem. Phys. 3 (2001) 5444-5449.
- [87] S.K. Papageorgiou, E.P. Kouvelos, E.P. Favvas, A.A. Sapalidis, G.E. Romanos, F.K. Katsaros, Carbohydr. Res. 345 (2010) 469–473.
- [88] U. Ravon, M.E. Domine, C.G. Re, A. Desmartin-Chomel, D. Farrusseng, New J. Chem. 32 (2008) 937–940.
- [89] F.X.Li. Xamena, F.G. Cirujano, A. Corma, Micropor. Mesopor. Mater. 157 (2012) 112–117.
- [90] V.S.V. Satyanarayana, A. Sivakumar, Ultrason. Sonochem. 18 (2011) 917–922.
- [91] H. Luo, Y. Kang, Q. Li, L. Yang, Heteroatom Chem. 19 (2008) 144–148.
- [92] N.T.S. Phan, C.W. Jones, J. Mol. Catal. A: Chem. 253 (2006) 123-131.
- [93] U.P.N. Tran, K.K.A. Le, N.T.S. Phan, ACS Catal. 1 (2011) 120–127.
- [94] Z.-H. Zhang, J.-J. Li, T.-S. Li, Ultrason. Sonochem. 15 (2008) 673-676.
- [95] D. Saha, S. Deng, J. Colloid Interface Sci. 348 (2010) 615-620.
- [96] X. Zhang, F.X.L.i. Xamena, A. Corma, J. Catal. 265 (2009) 155-160.