

VIETNAM NATIONAL UNIVERSITY - HO CHI MINH CITY
HO CHI MINH CITY UNIVERSITY OF TECHNOLOGY

NGUYEN THI LE LIEN

**METAL-ORGANIC FRAMEWORKS IRMOF-8, ZIF-9, MOF-199 AND
IRMOF-3 AS CATALYSTS FOR THE FRIEDEL-CRAFTS
ACYLATION, KNOEVENAGEL, AZA-MICHAEL AND PAAL-KNORR
REACTIONS**

Major: Organic chemical Technology

Major code: 62527505

PhD THESIS SUMMARY

HO CHI MINH CITY 2013

The dissertation was completed in Ho Chi Minh city University of Technology - Vietnam National University – Ho Chi Minh city

Supervisor : Assoc Professor Phan Thanh Son Nam

Independent opponent 1:

Independent opponent 2:

Opponent 1:

Opponent 2:

Opponent 3:

The dissertation will be defended before thesis committee at

.....
.....

On

The thesis information can be looked at following libraries:

- General Science Library – Ho Chi Minh city
- Library of Ho Chi Minh University of Technology– VNU-HCMC

INTRODUCTION

MOFs are extended porous structures composed of transition metal ions or clusters that are linked by organic bridges. Compared to conventionally used microporous and mesoporous inorganic materials, these metal-organic structures have the potential for more flexible rational design, through control of the architecture and functionalization of the pores.

Employing MOFs as catalysts is a young research area, as compared with the field of gas capture and storage. Indeed, MOFs have emerged as a hot topic in heterogeneous catalysis. Similarly to zeolites, the large surface area and open porosity of MOFs allows the access of substrates to the active sites present inside the crystal structure. One of the advantages of MOFs compared to zeolites is the large diversity of transition metals and organic linkers that can be used for the synthesis of MOFs.

The necessity of the study

With the increasing emphasis on green chemistry, environmentally benign processes should be developed to improve the green credentials of the reaction. For the development of greener processes, moisture-insensitive and easy handling solid acid catalysts are desired. Furthermore, the use of solid acid catalysts offers easy catalyst recovery and recycling, as well as product separation. At the same time, the catalyst recovery also decreases contamination of the desired products with hazardous or harmful metals.

The utilization of highly porous MOFs as efficient heterogeneous catalysts for liquid organic reactions should be examined and investigated.

CHAPTER 1. LITERATURE REVIEWS

1.1 Metal organic framework

The MOFs consists of organic ligand and metal active site with extremely high porosity. One of the outstanding properties of porous materials in the comparison with other material is their high surface areas. Which can be obtained from 1000 to 8000m²/g. MOFs are stable with the temperature that ranges from about 400 °C to 500 °C.

Their application is mostly in gas storage, separation and catalysis. MOFs also exhibit the physical properties usually encountered in dense inorganic solids: fluorescence, magnetic susceptibility, conductivity, optical properties.

Zeolitic imidazolate frameworks (ZIFs) are a new class of porous materials that potentially have the advantages of both inorganic zeolites (for example, high stability) and MOFs (for example, high porosity and organic functionality).

MOFs are synthesized by mixing organic ligands and metal salts under solvothermal reaction conditions at relatively low temperatures (typically, below 300°C). MOFs are also synthesized by diffusion method, and gel methods.

1.2 The application of MOFs in catalysis

In all MOF compounds, three different parts can be clearly differentiated: (i) the metallic component, (ii) the organic ligand, and (iii) the pore system. Potential catalytic activity of MOFs can be envisaged from a direct inspection of their structure, like those containing, e.g., redox active centers in a given coordination environment, organic groups with basic properties (such as amides or amines), or metal sites with potential coordinative unsaturations, which could behave as active centers for certain Lewis catalyzed processes. MOFs can be of interest since they allow high density of catalytic sites, in particular when these active sites are transition metals.

In the field of catalysis, several MOFs have been used as solid catalysts or catalyst supports for a variety of organic transformations such as Knoevenagel condensation, aldol condensation, oxidation, epoxidation, hydrogenation, Suzuki cross-coupling, transesterification reaction, Friedel-Crafts alkylation, epoxide ring-opening reaction, methylation of aromatic amines, activation of alkynes, domino coupling and cyclization reactions, and alkene cyclopropanation. As in the case of zeolites, the application of MOFs in catalysis is undoubtedly an area that will attract further research in the near future.

1.3 Aim and objectives of the study

The Friedel Craft acylation reaction

Friedel–Crafts acylation reactions of aromatic compounds with acid chlorides are considered as fundamental and important processes in organic synthesis as well as in industrial chemistry. Traditionally, these reaction require the presence of more than stoichiometric amounts of anhydrous strong Lewis acids such as AlCl_3 , TiCl_3 , FeCl_3 , or SnCl_4 . These methods suffer from high amounts, toxicity and corrosion of the catalysts, generation of a large amount of waste, and difficult purification of products. Moreover, these catalysts are highly moisture sensitive and hence moisture-free reaction conditions are required to achieve the optimal yields of the desired aromatic ketones. Several solid acid catalysts have been investigated for the Friedel-Crafts acylation reactions, such as metal triflate loaded SBA-15, mesoporous superacid catalyst, zeolite, hybrid zeolitic-mesostructured materials, modified clay, nafion/silica composite materials, mesoporous sulphated zirconia, and mesoporous sieve AIKIT-5. Although interesting results have been achieved for the Friedel-Crafts acylation reaction, they have not led to any very important industrial application.

The Knoevenagel reaction

The Knoevenagel reaction of aldehydes with compounds containing activated methylene groups has been widely employed in the synthesis of several fine chemicals as well as heterocyclic compounds of biological significance. This reaction is conventionally catalyzed by alkali metal hydroxides or by organic bases like primary, secondary and tertiary amines under homogeneous conditions with the attendant difficulties in catalyst recovery and recycling. Over the last few years, a wide range of solid catalysts have been investigated for this reaction such as amino-functionalized mesoporous silica, diamine-functionalized mesopolymers, amine-functionalized mesoporous zirconia, superparamagnetic mesoporous Mg–Fe bi-metal oxides, mesoporous titanasilicate, basic MCM-41 silica, acid-base bifunctional mesoporous MCM-41 silica, nanocrystalline ceria–zirconia, zeolites exchanged with alkylammonium cations, amine-functionalized superparamagnetic nanoparticles, chitosan hydrogel, acrylic resin immobilized lipase, organic-inorganic hybrid silica materials containing imidazolium and dihydroimidazolium salts, IRMOF-3, and ZIF-8

The Aza-Michael reaction

The aza-Michael reaction of amines and α,β -unsaturated carbonyl compounds has attracted significant attention as one of the most effective methods to prepare β -amino carbonyl compounds and their derivatives. These structures serve as essential intermediates in the synthesis of a variety of biologically important natural

products, antibiotics, peptide analogues, chiral auxiliaries, and other nitrogen-containing compounds. Traditionally, stoichiometric or catalytic amounts of several Lewis acids have been employed for the process, including AlCl_3 , HgCl_2 , TiCl_4 , $\text{Bi}(\text{NO}_3)_3$, $\text{CeCl}_3 \cdot 7\text{H}_2\text{O} \cdot \text{NaI}$, $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, LiClO_4 , Na_2SnO_3 , $\text{Ni}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$, $\text{Cu}(\text{OTf})_2$, and boric acid. Employing these Lewis acids required aqueous workup for the catalyst separation, generating of a large amount of waste, and also suffering from difficult product purification. Several solid catalysts have been investigated for the aza-Michael reaction, including glutathione supported on magnetic nanoparticles, graphene oxide, modified IRMOF-3, Amberlyst-15, Co(II) complex supported on mesoporous SBA-15, AlSBA-15, nanocrystalline copper(II) oxide, copper nanoparticles, polyaniline supported CuI, azaphosphatranate nitrate salt immobilized on Merrifield resin, Cu-Al hydrotalcite, silica gel, $\text{KF}/\text{Al}_2\text{O}_3$, and $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$ immobilized on montmorillonite K10. Although interesting results have been achieved for the aza-Michael reaction, the development of simple and environmentally benign approaches for the reaction is still the target of further research in the near future.

The Paal Knorr reaction

The Paal-Knorr condensation of primary amines with 1,4-dicarbonyl precursors has been widely employed in the synthesis of pyrrole, pyrazoles, and their derivatives as important intermediates for pharmaceutical and fine chemical industry, as well as for the development of organic functional materials. Traditionally, the reaction could effectively proceed in the presence of homogeneous Bronsted or Lewis acids such as H_2SO_4 , *p*-toluene sulfonic acid, $\text{Bi}(\text{NO}_3)_3$, Al_2O_3 , FeCl_3 , CoCl_2 , $\text{Sc}(\text{OTf})_3$, ZrOCl_2 , $\text{Yb}(\text{OTf})_3$, indium salts, titanium isopropoxide, and zinc tetrafluoroborate. Recently, the Paal-Knorr condensation has been carried out in the presence of a variety of solid catalysts, including layered zirconium phosphate and phosphonate, silica sulfuric acid, zeolite, magnetic nanoparticle-supported glutathione, nano β -PbO, polystyrene-supported aluminum chloride, macroporous strongly acidic styrol resin (D001), and cationic exchange resin. Although promising results have been achieved, the development of a more efficient catalyst for the reaction is still in great demand.

❖ Objectives of this study:

- Synthesis of four different MOF materials: IRMOF-8, ZIF-9, MOF-199, IRMOF-3
- Characterization of the four MOF materials by modern analysis techniques
- Catalytic study of the four tested reactions, Friedel -Craft acylation, Knoevenagel reaction, aza-Michael reaction and Paal-Knorr reaction, by IRMOF-8, ZIF-9, MOF-199, IRMOF-3, respectively.

CHAPTER 2. EXPERIMENTAL

2.1 Synthesis of MOF catalysts

Four types of MOFs- IRMOF-8, ZIF-9, MOF-199, and IRMOF-3 have been synthesized by solvothermal methods.

- Pale-yellow cubic-shaped crystals (71% based on 2,6-naphthalenedicarboxylic acid) was collected as IRMOF-8.
- Purple cubic crystals (25% based on benzimidazole) was collected as ZIF-9.
- Deep purple crystals (88% based on 1,3,5-benzenetricarboxylic acid) was collected as MOF-199
- Pale yellow crystals (68% based on 2-amino-1,4-benzenedicarboxylic acid) was collected as the synthesized IRMOF-3.

The synthesized MOFs were characterized by modern analysis technologies such as XRD, SEM, TEM, TGA, nitrogen adsorption/desorption isotherm, FT-IR, and AAS

2.2 Application of MOF in catalysis

The IRMOF-8 was assessed for its activity as a solid acid catalyst in the Friedel-Crafts acylation of toluene with benzoyl chloride to form *p*-benzoyltoluene as the major product and *o*-benzoyltoluene as the minor one.

The ZIF-9 catalyst was assessed for its activity in the Knoevenagel reaction by studying the condensation of benzaldehyde with malononitrile to form benzylidene malononitrile as the principal product.

The reaction aza-Michael reaction of benzylamine with ethyl acrylate to form ethyl 2-(benzylamino)acetate (A) as the principal product was catalyzed by MOF-199.

The Paal-Knorr reaction of benzyl amine with 2,5-hexanedione using the IRMOF-3 catalyst was carried out to define its catalytic efficiency.

All reactions were carried out in a magnetically stirred round-bottom flask at various conditions. Samples were taken every one hour. Reaction conversions were analyzed by GC system.

CHAPTER 3. RESULT & DISCUSSION

3.1 Catalyst characterization

The four MOFs were characterized by XRD, SEM, TEM to confirm their crystalline and porous structure. Surface areas are determined by nitrogen adsorption/desorption isotherm as followed:

Catalyst	Surface area, m ² /g
IRMOF-8	2110
ZIF-9	1144
MOF-199	1970
IRMOF-3	3295

The high surface areas and porous structure make the four synthesized MOFs attractive candidate for application in catalysis.

Thermal stability of MOFs was defined by TGA analysis, and the results shown that the MOFs were stable from 300 to 500°C.

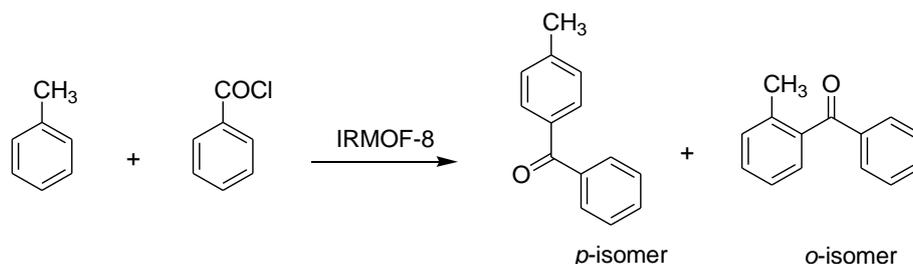
Metal loading are determined by AAS techniques, given results as followed:

- Zn loading in IRMOF-8 is 4.38 mmol/g
- Co loading in ZIF-9 is 4.17 mmol/g
- Cu loading in MOF-199 is 4.61 mmol/g
- Zn loading in IRMOF-3 is 4.3 mmol/g

FT-IR spectra of the IRMOF-8 exhibited a significant difference as compared to that of their corresponding ligands. The significant features observed were to confirm the deprotonation in the carboxylate group when linked with the metal sites during the formation of MOF structures

3.2 Catalytic studies

3.2.1 Friedel-Crafts acylation reaction



Scheme 3.1. Friedel-Craft acylation of toluene with benzoyl chloride using IRMOF-8 catalyst

Initial studies addressed the effect of temperature on the reaction conversion, having carried out the reaction using 5 mol% IRMOF-8 catalyst and benzoyl chloride:toluene molar ratio of 5 : 1 at 80 °C, 90 °C, and 100 °C, respectively. It was found that increasing the reaction temperature from 80 °C to 90 °C led to a significant enhancement in reaction rate.

It was found in this research that the Friedel-Crafts acylation reaction of toluene with benzoyl chloride using the IRMOF-8 catalyst could occur under solventless condition, and that the reagent molar ratio had a profound effect on the reaction conversion. Interestingly, decreasing the benzoyl chloride: toluene molar ratio from 5 : 1 to 1.5 : 1 resulted in a significant enhancement in reaction rate,. From experimental points of view, it should be noted that using a benzoyl chloride: toluene molar ratio of less than 1.5 : 1 could cause difficulty in stirring the reaction mixture containing the solid catalyst.

The effect of catalyst concentration on reaction conversion was investigated. The catalyst concentration, with respect to the zinc content in the IRMOF-8, was studied in the range of 1-5 mol% relative to toluene. It was found that the Friedel–Crafts acylation of toluene and benzoyl chloride proceeded readily in the presence of a catalytic amount of the IRMOF-8. Conversions of 95%, 90%, and 88% were achieved after 6 h at the catalyst concentration of 5 mol%, 3 mol%, and 1 mol%, respectively.

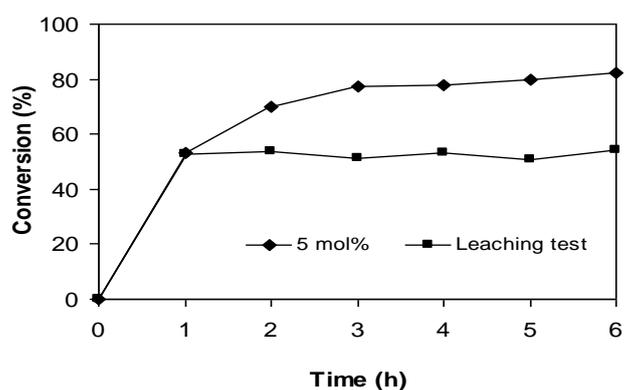


Fig. 3.1. Leaching test

In order to determine if leaching was a problem for the Friedel-Crafts acylation reaction using the IRMOF-8 catalyst, an experiment was performed to estimate the contribution of leached active species to the total reaction conversion by performing a

simple centrifugation during the course of the reaction to remove the solid catalyst. Within experimental error, no further reaction was observed after the solid IRMOF-8 was removed, proving that there was no contribution from leached active species and that conversion was only being possible in the presence of the solid IRMOF-8 catalyst.

The replacement of environmentally unacceptable homogeneous Lewis acids with solid acids offers several advantages including easy catalyst recovery and recycling. The IRMOF-8 catalyst was therefore investigated for recoverability and reusability in the Friedel-Crafts acylation reaction over five successive runs. It was found that the IRMOF-8 catalyst could be recovered and reused in further reactions without a significant degradation in activity. Conversions of 95%, 95%, 96%, 90%, and 82% were achieved after 6 h for the 1st, 2nd, 3rd, 4th, and 5th run, respectively.

The study was then extended to the Friedel-Crafts acylation reaction of benzoyl chloride with several aromatic hydrocarbon having different substituents, including anisole, toluene, *p*-xylene, and ethylbenzene, respectively. Reactions were carried out at 100 °C with 3 mol% catalyst loading and at the benzoyl chloride: aromatic hydrocarbon molar ratio of 1.5 : 1. As expected, the anisole benzylation using the IRMOF-8 catalyst proceeded with a higher reaction rate than that of toluene.

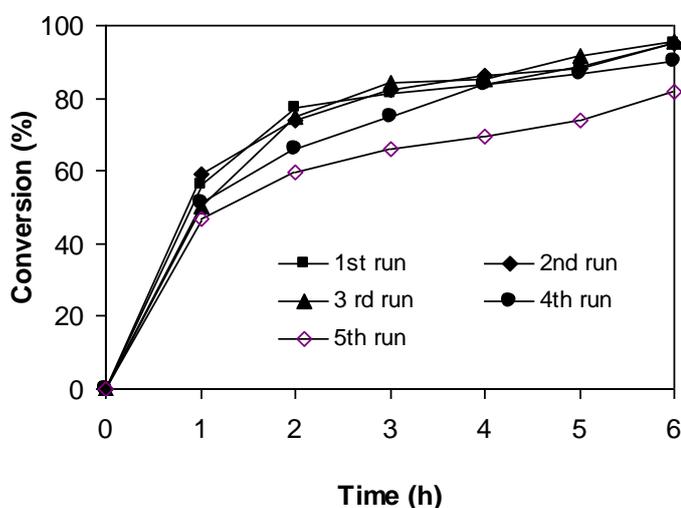
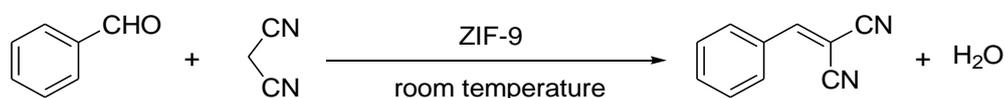


Fig. 3.2 Catalytic recycling studies

The effect of different acylation reagents on the Friedel-Crafts acylation reaction of toluene was also studied, having carried out the reaction using benzoyl chloride, 4-methoxybenzoyl chloride, and 4-chlorobenzoyl chloride, respectively.

3.2.2 Knoevenagel reaction



Scheme 3.2 Knoevenagel reaction of benzaldehyde with malononitrile using the ZIF-9 catalyst

The reagent ratio is normally an important factor that should be taken into consideration in the case of the Knoevenagel condensation. The effect of the benzaldehyde : malononitrile molar ratio on reaction conversions was therefore investigated, having carried out the reaction at molar ratios of 1:1, 1: 2, 1: 3, and 1 : 4, respectively. Experimental results showed that 99% conversion was obtained after 4 h for the reaction using the reagent molar ratio of 1 : 3. The reaction at the reagent molar ratio of 1: 4 occurred more readily. The malononitrile:benzaldehyde molar ratio to 1 : 2 resulted in a significant drop in the reaction rate. The reaction using one equivalent of malononitrile proceeded slowly, with only 49% conversion being observed after 6 h.

The catalyst concentration, with respect to the cobalt content in the ZIF-9, was then studied in the range of 1-8 mol% relative to benzaldehyde. It was found that decreasing the catalyst concentration to 3 mol% led to a significant drop in the reaction rate. The results indicated that the ZIF-9 catalyst was quite active in the Knoevenagel reaction. Furthermore, it exhibited higher activity than some previously reported Lewis acid catalysts, where longer reaction time or/and higher catalyst loading were required for the same reaction. However, the ZIF-9 was slightly less active for the Knoevenagel condensation as compared to some solid base catalysts such as amine-functionalized superparamagnetic nanoparticles and amine-functionalized mesoporous zirconia.

In this research, it was found that the homogeneous benzimidazole linker exhibited higher activity in the Knoevenagel reaction than the ZIF-9 catalyst, with quantitative conversion being obtained after 3 h. As expected, cobalt nitrate hexahydrate showed very low activity in the Knoevenagel condensation under similar reaction condition.

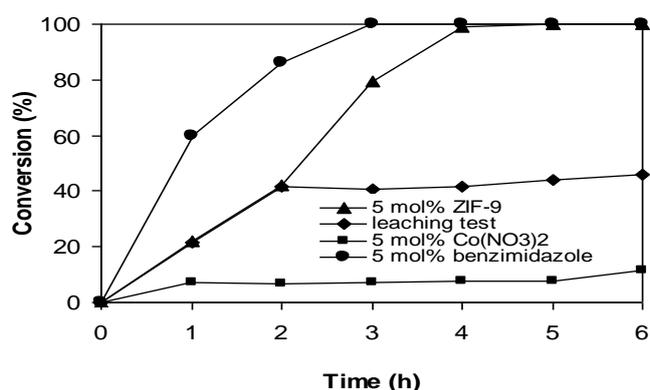


Fig. 3.3 Leaching test

In order to determine if the benzimidazole linker leached from the solid ZIF-9 catalyst could play a significant role in the catalytic activity for the Knoevenagel reaction, an experiment was performed using a simple centrifugation during the course of the reaction. After the solid catalyst was removed, if the catalytic reaction continued this would indicate that the active species were from the solution rather than from the solid ZIF-9 catalyst.

No further reaction was observed after the solid ZIF-9 catalyst was separated from the reaction mixture. This result indicated that the Knoevenagel reaction could only occur in the presence of the solid ZIF-9 catalyst, and there was no contribution from leached active species in the reaction solution.

To investigate the solvent effect in the Knoevenagel reaction, using 5 mol% of the ZIF-9 catalyst at room temperature. Experimental results showed that the reaction rate of the Knoevenagel condensation using the ZIF-9 catalyst decreased in the order of solvents: tetrahydrofuran > toluene > ethyl acetate > dichloromethane.

The ZIF-9 catalyst was therefore investigated for recoverability and reusability in the Knoevenagel reaction over five successive runs. It was observed that over 99% conversions were achieved in the 1st, the 2nd and the 3rd runs, with no trace amount of benzaldehyde being detected by GC. The study was then extended to the Knoevenagel condensation of several benzaldehyde derivatives having different substituents with malononitrile using the ZIF-9 catalyst. The reaction of 4-methylbenzaldehyde and 2-methylbenzaldehyde, respectively, with malononitrile proceeded readily in the presence of the ZIF-9 catalyst to give quantitative conversions after 2 h. Although methyl is an electron-donating group, both 4-methylbenzaldehyde and 2-methylbenzaldehyde were found to be more reactive than the benzaldehyde. The Knoevenagel reaction of 4-nitrobenzaldehyde and 4-chlorobenzaldehyde also proceeded readily, with quantitative conversion being obtained within 1 h.

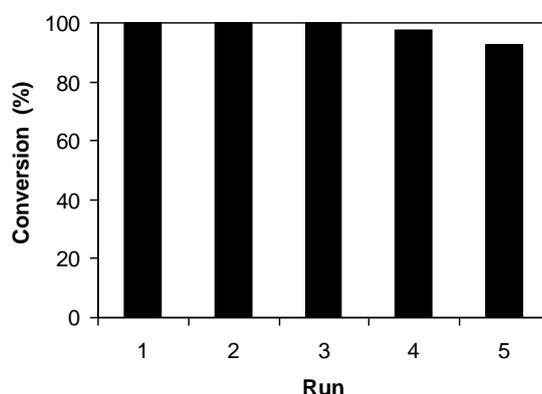
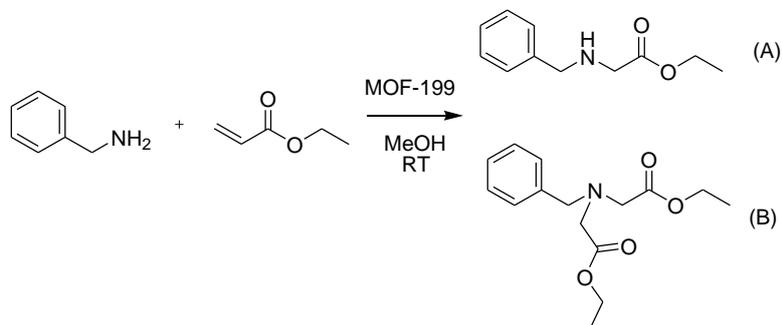


Fig. 3.4. Recycling test

3.2.3 Aza-Michael reaction



Scheme 3.3 The aza-Michael reaction using MOF-199 catalyst

The MOF-199 was assessed for its catalytic activity in the aza-Michael reaction by studyi

Initial studies addressed the effect of catalyst concentration on the reaction conversion, having carried out the aza-Michael reaction at room temperature in methanol, using one equivalent of ethyl acrylate in the presence of 1 mol%, 2.5 mol%, and 5 mol% catalyst, respectively. As expected, decreasing the catalyst concentration resulted in a drop in the reaction rate, though the reaction could still afford 88%, and 84% conversion after 60 min at the catalyst concentration of 2.5 mol%, and 1 mol%, respectively.

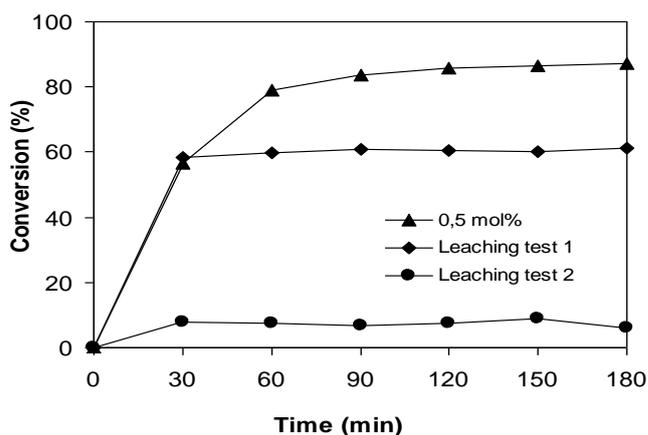


Fig. 3.5 Leaching test

In order to confirm the role of Lewis acid present in the MOF-199 structure as catalytically active sites, a control reaction was carried out using 5 mol% MOF-199

catalyst in conjunction with pyridine as a catalyst poison, at the copper:pyridine molar ratio of 1:1. It was found that the presence of pyridine in the reaction mixture led to a dramatic drop in the reaction rate, with only 46% conversion being achieved after 60 min. This observation was consistent with the poisoning of the MOF-199 catalyst by the strong interaction of pyridine with the Lewis acid sites.

Reaction were carried out the reaction in methanol at room temperature, using 5 mol% MOF-199 with the benzylamine:ethyl acrylate molar ratio of 1:1, 1:1.5, and 1:2, respectively.

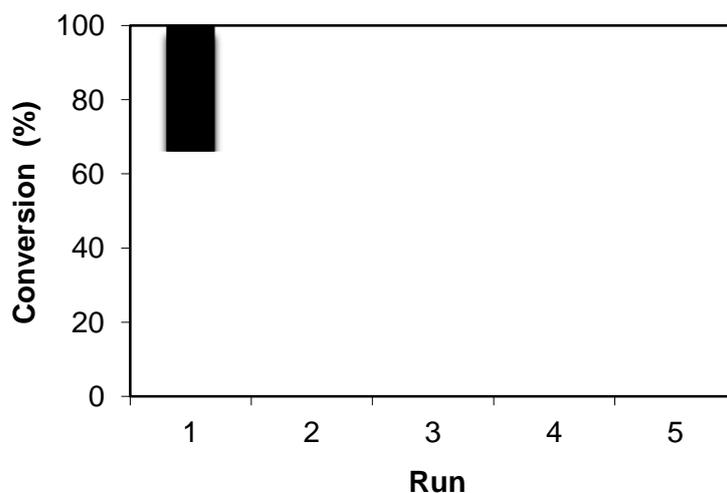


Fig 3.6 Recycling test

As expected, increasing the reagent ratio from 1:1 to 1:1.5 led to a significant improvement in the reaction rate. However, it was observed that the reaction rate was not enhanced dramatically when the reagent ratio increased from 1:1.5 to 1:2. In order to determine if active species leached from the solid MOF-199 catalyst could play a significant role in the catalytic activity for the aza-Michael reaction, an experiment was performed using a simple centrifugation during the course of the reaction. Experimental results revealed that no further conversion was observed for the aza-Michael transformation after the solid MOF-199 catalyst was separated from the reaction mixture. These results confirmed that the aza-Michael reaction could only proceed in the presence of the solid MOF-199 catalyst, and there was no contribution from leached active species in the liquid phase.

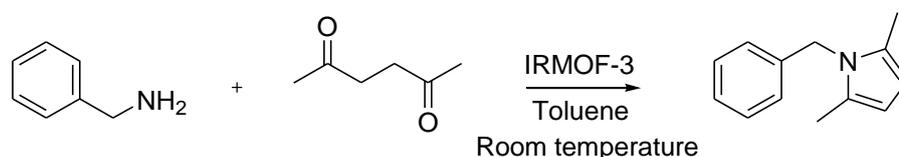
The effect of different solvents on the rate of a reaction using solid catalyst could normally be of extreme importance. The experimental results showed that the reaction rate of the aza-Michael reaction using the MOF-199 catalyst increased in the order of solvents: tetrahydrofuran, toluene, ethylacetate < dichloromethane < acetonitrile < chloroform < DMF < nitromethane < methanol. Tetrahydrofuran was

previously reported to be able to coordinate with copper centers in MOF-199, completely blocking Lewis acid sites of the catalyst. However, the effect of different solvents on the rate and the selectivity of the reaction is complex, and needs further investigation.

The MOF-199 catalyst was investigated for recoverability and reusability in the aza-Michael reaction over eight successive runs. Conversion of more than 99% was still achieved in the 8th run. The FT-IR spectra of the reused MOF-199 after the first run exhibited a similar absorption as compared to that of the fresh catalyst. Moreover, XRD result of the reused catalyst after the first run revealed that the MOF-199 could maintain its crystallinity during the course of the reaction. These results indicated that the MOF-199 exhibited excellent reusability in the aza-Michael reaction, thus offering a route to green chemistry for this reaction.

The study was extended to the aza-Michael reaction of ethyl acrylate with several amines in the presence of the MOF-199 as catalyst, including benzylamine, 4-methylbenzylamine, 4-florobenzylamine, cyclohexylamine, piperidine, 3-aminomethylpyridine, and imidazole. It was also observed that 4-methylbenzylamine was slightly more reactive than benzylamine.

3.2.4 Paal-Knorr reaction



Scheme 3.4. The Paal-Knorr reaction using the IRMOF-3 catalyst.

The Paal-Knorr reaction was carried out in toluene at room temperature in the presence of 2 mol% IRMOF-3 catalyst, using benzylamine.

The effect of catalyst concentration on the reaction conversion was investigated 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 reaction conversion. As expected, increasing the catalyst concentration led to an enhancement in the reaction conversion.

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. 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.

The effect of different solvents on the Paal-Knorr reaction using the IRMOF-3 catalyst were investigated. 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. However, the effect of different solvents 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. 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. 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. 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. The Paal-Knorr reaction of benzylamine with different diketones, including 2,5-hexadione, 1-phenyl-1,4-pentandione, and 1,2-dibenzoylthane, respectively.

It was found that the reaction occurred slowly for the case of 1-phenyl-1,4-pentandione and 1,2-dibenzoylthane, while quantitative conversion was achieved for the reaction of 2,5-hexadione under the same condition. The issue still needs further studies, though it could be proposed that the bulky phenyl groups on the diketone might have a negative effect on the transformation.

The recoverability and reusability of the IRMOF-3 catalyst in the Paal-Knorr reaction of benzylamine with 2,5-hexadione was studied by repeatedly separating the IRMOF-3 from the reaction mixture, washing it and then reusing it.

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 97% was still achieved in the 8th run.

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.

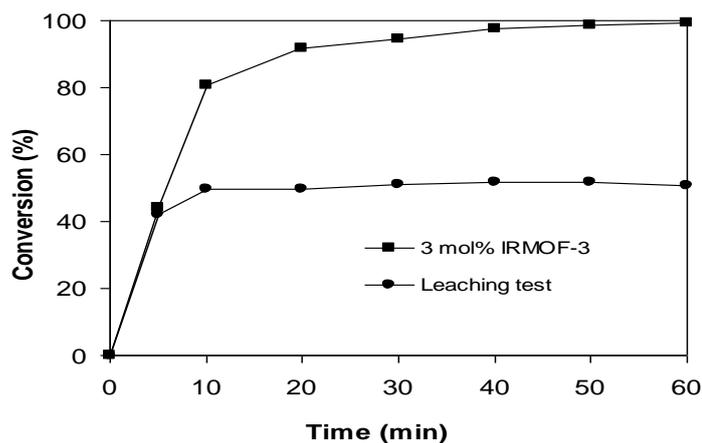


Fig. 3.7 Leaching test

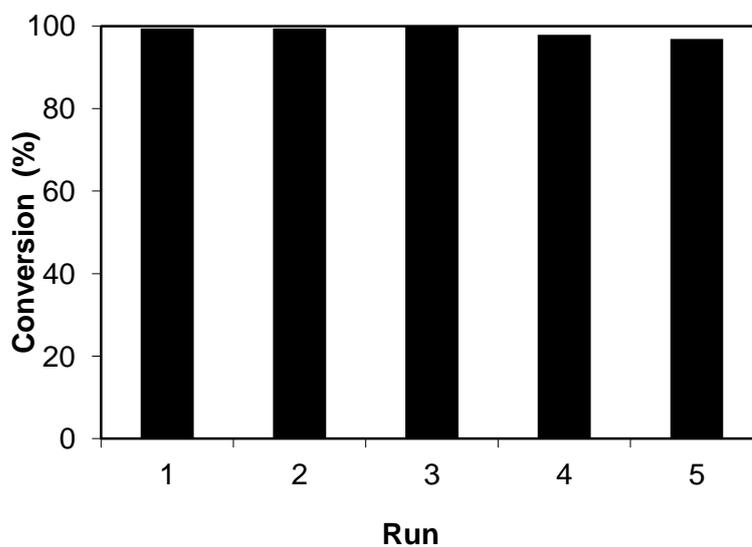


Fig. 3.8 Catalyst recycling study

Indeed, the spectra of the reused catalyst revealed a similar absorption as compared to that of the fresh IRMOF-3. Furthermore, XRD result of the reused IRMOF-3 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. These results confirmed that the IRMOF-3 exhibited an excellent reusability in the Paal-Knorr reaction.

CONCLUSIONS

Highly crystalline porous IRMOF-8, ZIF-9, MOF-199, and IRMOF-3 were achieved by a solvothermal method, following previous studies of Yaghi and coworkers. The four self-synthesized MOFs were characterized using a variety of different techniques, including XRD, TEM, SEM, FT-IR, TGA, AAS, and nitrogen physisorption measurements. Experimental results show that they are highly crystalline with high porous structure and surface areas, which make them efficient to be used as heterogeneous catalysts.

The IRMOF-8 catalyst clearly exhibited advantages over conventional Lewis acid catalysts for the Friedel-Crafts acylation reaction of toluene and benzoyl chloride. The ZIF-9 was also used as an efficient heterogeneous catalyst for the Knoevenagel reaction between benzaldehyde with malononitrile to form benzylidene malononitrile as the principal product. Excellent conversions were obtained in the presence of 5 mol% catalyst. The MOF-199 was, similarly, used as an efficient heterogeneous catalyst for the aza-Michael reaction of benzylamine with ethyl acrylate to form ethyl 2-(benzylamino)acetate as the principal product. The IRMOF-3 was able to be 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.

All reactions under catalysis of MOF materials in our study occurred in mild conditions without the need for an inert atmosphere which is required if conventional Lewis acid is used. This advantage make the reaction work is simpler in practice. Another advantage is that the MOF solid catalysts could be facilely separated from the reaction mixture by simple centrifugation or filtration, and could be reused without a significant degradation in catalytic activity. Therefore, less toxic catalysts are to be discharged to the environment as well as economic benefit being achieved. Leaching test confirmed that no contribution from homogeneous catalysis of active acid species leaching into the reaction solution during the course of the reaction was detected, and the MOF catalyst is purely heterogeneous.

Based on the obtained results in this study and other researches in literature reviews, it could be concluded that the MOF catalysts clearly exhibited advantages over conventional Lewis acid or base catalysts and could be used as an alternative to other solid acid catalysts for organic synthesis reaction. This would help to expand applications of this porous metal-organic framework from the gas separation and storage to the catalysis field. Prospective research in our laboratory will be directed to the design and synthesis of several MOF-based catalysts for a wide range of organic transformations.

LIST OF PUBLICATIONS

1. Lien T.L. Nguyen, Chi V. Nguyen, Giao H. Dang, Ky K.A. Le, Nam T.S. Phan. “Towards applications of metal–organic frameworks in catalysis: Friedel–Crafts acylation reaction over IRMOF-8 as an efficient heterogeneous catalyst”. *Journal of Molecular Catalysis A: Chemical* 349 (2011) 28– 35
2. Lien T. L. Nguyen, Ky K. A. Le, Hien X. Truong and Nam T. S. Phan. “Metal–organic frameworks for catalysis: the Knoevenagel reaction using zeolite imidazolate framework ZIF-9 as an efficient heterogeneous catalyst”. *Catalysis Science & Technology* 2 (2012), 521-528
3. Lien T.L. Nguyen, Tung T. Nguyen, Khoa D. Nguyen, Nam T.S. Phan. “Metal–organic framework MOF-199 as an efficient heterogeneous catalyst for the aza-Michael reaction”. *Applied Catalysis A: General* 425– 426 (2012) 44– 52
4. Nam T. S. Phan, Tung T . Nguyen, Quang H. Luu, Lien T. L. Nguyen. « Paal-Knorr reaction catalyzed by metal-organic framework IRMOF-3 as an efficient and reusable heterogeneous catalyst”. *Journal of Molecular Catalysis A: Chemical*, 363–364 (2012), 178–185