

Document downloaded from:

<http://hdl.handle.net/10251/110928>

This paper must be cited as:

Rapeyko, A.; Arias Carrascal, KS.; Climent Olmedo, MJ.; Corma Canós, A.; Iborra Chornet, S. (2017). Polymers from biomass: one pot two-step synthesis of furilydenepropanenitrile derivatives with MIL-100(Fe) catalyst. *Catalysis Science & Technology*. 7(14):3008-3016. doi:10.1039/c7cy00463j



The final publication is available at

<http://doi.org/10.1039/c7cy00463j>

Copyright The Royal Society of Chemistry

Additional Information

# Catalysis Science & Technology

Accepted Manuscript



This article can be cited before page numbers have been issued, to do this please use: A. Corma, A. Rapeyko, K. S. Arias, M. J. Climent and S. Iborra, *Catal. Sci. Technol.*, 2017, DOI: 10.1039/C7CY00463J.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [author guidelines](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the ethical guidelines, outlined in our [author and reviewer resource centre](#), still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

## Polymers from biomass: One pot two steps synthesis of furilydenepropanenitrile derivatives with MIL-100 (Fe) catalyst

Anastasia Rapeyko, Karen S. Arias, Maria J. Climent, Avelino Corma\*, Sara Iborra\*

Instituto de Tecnología Química, Universitat Politècnica de València-Consejo Superior de Investigaciones Científicas,  
Avenida de los Naranjos s/n, 46022 Valencia, (Spain)  
Fax: (+34) 963877809  
E-mail: acorma@itq.upv.es  
siborra@itq.upv.es

### Abstract

Furilydenepropanenitrile derivatives, useful as monomers, has been obtained in high yields by coupling the oxidation of 5-hydroxymethylfurfural (HMF) to 2,5-diformylfuran (DFF) and the Knoevenagel condensation of DFF with methylene active compounds in a one pot process. The oxidation step was studied using a Fe containing metal-organic framework (MIL-100(Fe), and Fe(BTC)), Cu containing MOF ( $\text{Cu}_3(\text{BTC})_2$ ) a Fe exchanged HY zeolite and homogeneous Fe salts in the presence of 2,2,6,6-tetramethylpiperidine-1-oxide (TEMPO) as cocatalyst,  $\text{NaNO}_2$  as an additive and oxygen as the terminal oxidant. The results showed that the synthesis post treated MIL-100(Fe) with  $\text{NH}_4\text{F}$  was the most active catalyst that can achieve 100 % HMF conversion with 100 % selectivity to DFF and can be reused with good success. Additionally, the catalytic system has been applied to the oxidation of different primary and secondary alcohols to aldehydes and ketones under mild reaction conditions with good success. The second step, the Knoevenagel condensation of the obtained DFF with malononitrile or ethyl cyanoacetate was performed taking advantage of the basicity of the reaction medium.

**Keywords:** biomass, HMF oxidation, Diformylfuran, MIL-100 (Fe), TEMPO, furilydenepropanenitrile derivatives, one pot process

### Introduction

Transformation of biomass into valuable chemicals has become an attractive area of research. In particular, biomass-derived 5-hydroxymethylfurfural (HMF), which can be easily obtained by dehydration of hexoses, has attracted much attention as a valuable intermediate to produce other important derivatives such as 2,5-diformylfuran (DFF), 2,5-dihydroxymethylfuran, 2,5dimethylfuran, 2,5dimethyltetrahydrofuran, 2,5-furandicarboxylic acid, and levulinic acid.<sup>1</sup>

In this work, our attention has been focused on the selective oxidation of HMF into DFF, an important derivative, which can be used as a monomer for polymeric materials<sup>2</sup> and as an intermediate for pharmaceuticals,<sup>3</sup> fungicides,<sup>4</sup> cross-linking agents or macrocyclic ligands.<sup>5</sup>

DFF has been first synthesized from the oxidation of HMF using conventional oxidants such as pyridinium chlorochromate,<sup>6</sup> BaMnO<sub>4</sub>,<sup>7</sup> and NaOCl.<sup>8</sup> However these methods use stoichiometric amounts of oxidants and produce large amounts of wastes. Therefore, recently there has been an increased interest to produce DFF from HMF oxidation using more environmental friendly methodologies. Thus, a variety of heterogeneous catalytic systems that can be reused and that use oxygen or air as the terminal oxidant have been developed. For instance, Co/Mn/Zn/Br,<sup>9</sup> Ru/HT,<sup>10</sup> Ru/C<sup>11</sup> vanadium-based catalysts,<sup>12</sup> Ag-OMs-2,<sup>13</sup> and MOF-derived magnetic hollow Fe-Co nanocatalyst<sup>14</sup> have been recently used with different success in the selective aerobic oxidation of HMF into DFF. However, most of these protocols require the utilization of expensive metals, and high reaction temperature and/or high oxygen pressure to obtain high selectivity to DFF at high conversion of HMF.

The catalytic systems based in transition metals (typically Cu and Fe salts) and 2,2,6,6-tetramethylpiperidine-1-oxide (TEMPO) for the oxidation of primary and secondary alcohols to aldehydes and ketones respectively, have attracted great attention due to the use of cheap transition metals, molecular oxygen as the terminal oxidant and milder reaction conditions.<sup>15,16,17,18,19,20</sup> These catalytic systems have been applied to the oxidation of HMF to DFF. For instance Cottier et al.<sup>21</sup> performed the oxidation of HMF to DFF using CuCl and dioxygen assisted by TEMPO achieving a 65 % DFF yield. Hansen et al.<sup>22</sup> reported 95 % yield of DFF after 24 h, using CuCl and TEMPO by working at room temperature and ambient oxygen pressure in the presence of

nitrogen containing promoters. More recently Fang et al.<sup>23</sup> showed that Fe(III) salts assisted by TEMPO catalyzed the selective oxidation of HMF into DFF in 1,2-dichloroethane at room temperature and ambient oxygen pressure achieving 92 % yield of DFF after 4h. These catalytic systems based on Cu or Fe salts, in spite of their good performances in the HMF oxidation, they can not address the catalyst recyclability, therefore the development of a truly heterogeneous recyclable catalyst would be of interest for the green production of DFF from HMF.

MOFs are a type of coordination polymers which structure is defined by metal ions or clusters acting as lattice nodes that are held in place by rigid bi- or multipodal organic linkers.<sup>24</sup> The outstanding high porosity and high surface area of the MOFs, their tunable composition and topology as well as, the presence in their structure of transition metals with free coordination positions make them potential candidates as heterogeneous catalysts.<sup>25</sup>

As a precedent of the use of MOFs combined with TEMPO as cocatalyst for alcohol oxidation, Dhakshinamoorthy et al.<sup>26</sup> reported the aerobic oxidation of benzyl alcohols to aldehydes catalyzed by the  $\text{Cu}_3(\text{BTC})_2$  MOF (BTC: 1,3,5-benzenetricarboxylate)(trimesate) under mild temperature at atmospheric pressure. However, as we will show later this catalytic system exhibits very low performances in the oxidation of HMF to DFF.

In the present work, we have found that the iron containing metal-organic framework MIL-100 (Fe) in the presence of piperidinyloxy as cocatalyst is an efficient and reusable catalyst to promote the selective aerobic oxidation of HMF into DFF as well as the oxidation of different primary and secondary alcohols to the corresponding carbonyl compounds under mild reaction conditions. Moreover, taking advantage of the basicity of the reaction media, we have coupled the production of DFF with the Knoevenagel condensation with methylene active compounds in a one pot process to produce the corresponding Knoevenagel adducts with potential applications as monomers.

Particularly, the mesoporous MIL-100 (Fe) is built up from iron oxo-centred trimers connected by trimesate anions (1,3,5-benzenetricarboxylate) resulting in hybrid

supertetrahedra, further delimiting two sets of mesoporous cages.<sup>27</sup> The catalytic properties of MIL-100 (Fe) are attributed to the presence of coordinatively unsaturated iron centers that can act as Lewis acid or redox sites.<sup>28,29,30</sup>

## Experimental section

### Synthesis of MOFs

Fe(BTC), under the name of Basolite F 300, and  $\text{Cu}_3(\text{BTC})_2$  under the name of Basolite C 300, were purchased from Sigma Aldrich as well as other chemicals used in this work. The sample of MIL-100 (Fe) was synthesized by microwave-assisted hydrothermal method as reported by Márquez et al.<sup>31</sup> Then it was modified in a post synthesis purification with  $\text{NH}_4\text{F}$  solution as described below. In the general procedure, Iron (III) chloride hexahydrate (2.43 g, 9 mmol) was dissolved in distilled water (30 mL) under stirring. After that trimesic acid (0.84 g, 4 mmol) was added to the solution and heated in microwave to 130 °C over 1 min (1400 W) and maintained at this temperature for 5.5 min. Then the reacting mixture was cooled down to room temperature and centrifuged at 10500 rpm for 25 min. A solid (2.5g) with orange colour was obtained that was washed first with distilled water (30 mL) at 70 °C under stirring during 3 h and then with ethanol at 65 °C for 3 h. After that the catalyst was dried in the oven at 100 °C overnight and treated with a solution of  $\text{NH}_4\text{F}$  (38 mM, 20 mL) at 70 °C for 3 h. After cooling, the precipitate was filtered and washed five times with 200 mL of hot water (60 °C) to remove traces of  $\text{NH}_4\text{F}$ .<sup>32</sup>

### Synthesis of HY-Fe

HY-Fe zeolite was prepared following the method described in the literature.<sup>29</sup> Typically, the 0.7 g of the commercially available HY zeolite (Si/Al=2.6) was stirred at room temperature with 7 mL of 0.2M aqueous solution of  $\text{Fe}(\text{NO}_3)_3$  at pH 3. After that, the solid was filtered, washed exhaustively with milliQ water and dried at 100 °C overnight. Then the HY-Fe zeolite was dehydrated at 150 °C under reduced pressure. ICP analysis showed that the catalyst contains 5.3 wt% of Fe.

### Typical procedure for oxidation of HMF

A 10 mL round-bottomed flask was charged with required amount of catalyst, TEMPO and sodium nitrite. To this mixture, 5 mL of acetonitrile was added followed by the appropriate quantity of HMF. The reaction was stirred vigorously under atmospheric pressure of oxygen at 75 °C. The reaction was followed by taking samples at regular time periods that were analyzed by gas chromatography with a FID detector and capillary column (HP5, 30 m × 0.25 mm × 0.25 μm) using dodecane as internal standard. When the reaction was finished the catalyst was removed by filtration, the acetonitrile was eliminated by vacuum distillation and the reaction mixture was dissolved in ethyl acetate. This solution was extracted with water to remove TEMPO and NaNO<sub>2</sub> and then, the solvent was removed by rotary evaporation and the resulting product was analyzed by NMR analysis.

#### *Spectroscopic data (<sup>1</sup>H-NMR, <sup>13</sup>C-NMR, and MS)*

The chemical shifts are given in ppm and the *J* values are given in Hz. Abbreviations were defined as follows: s=singlet, t=triplet, q=quadruplet.

2,5-diformylfuran: <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 9.85 (s, 2H, CHO), 7.33 (s, 2H, ArH). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>): δ 179.1 (CHO), 154.2 (C), 119.1 ppm (CH). MS *m/z* (%) 124 (M<sup>+</sup>, 100), 123 (70), 97 (100), 95 (24), 67 (5), 39 (27), 38 (14).

#### **One pot two steps synthesis of furilydenepropanenitrile derivatives**

Typically, a 10 mL round-bottomed flask was charged with required amount of catalyst, TEMPO and sodium nitrite. To this mixture, 5 mL of acetonitrile was added followed by the appropriate quantity of HMF. The reaction was stirred vigorously under atmospheric pressure of oxygen at 75 °C until the total conversion of HMF to DFF. Then, the catalyst was removed by filtration and the methylene active compound (MAC) (malononitrile or ethyl cyanoacetate) with MAC/HMF molar ratio of 2 was added to the reaction mixture. The reaction was monitored by taking samples at regular time periods that were analyzed by gas chromatography with a FID detector and capillary column (HP5, 30 m × 0.25 mm × 0.25 μm) using dodecane as internal standard. When the reaction was finished, the solvent was removed by distillation and the reaction mixture was dissolved in ethyl acetate and extracted with water. After that, the solvent was removed by rotary evaporation and the resulting solid product

was purified by crystallization from ethanol and was characterized by NMR analysis and GC-MS.

*Spectroscopic data (<sup>1</sup>H-NMR, <sup>13</sup>C-NMR, and MS)*

**2,2'-(2,5-Furandiyl)dimethylidyne)-bis-propanedinitrile (2a)**

<sup>1</sup>H NMR (300 MHz, DMSO-*d*<sub>6</sub>): δ 8.45 (=CH, s, 2H), 7.66 (s, 2H, ArH). <sup>13</sup>C NMR (75 MHz, DMSO-*d*<sub>6</sub>): δ 151.6 (CH), 143.7 (C), 124.9 (CH), 113.7, 112.3, 81.4 ppm (C). MS *m/z* (%) 220 (M<sup>+</sup>, 100), 193 (9), 157 (6), 105 (15), 77 (12).

**Diethyl 3,3'-(2,5-furandiyl)(2*E*,2'*E*)-bis(2-cyanoacrylate) (2b)**

<sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 8.07 (=CH, s, 2H), 7.62 (s, 2H, ArH), 4.38 (CH<sub>2</sub>, q, 4H, *J* = 7.1 Hz), 1.39 (CH<sub>3</sub>, t, 6H, *J*=7.1 Hz); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>): δ 161.4 (C=O), 151.7 (C), 138.0 (=CH), 121.9 (CN), 114.5 (CH), 103.6 (C-CN), 63.1 (O-CH<sub>2</sub>), 14.1 ppm (CH<sub>3</sub>). MS *m/z* (%) 314 (M<sup>+</sup>, 100), 286 (17), 269 (55), 240 (58), 214 (26), 196 (14), 170 (14), 142 (17), 114 (16), 89 (12), 29 (22).

<sup>1</sup>H-NMR and <sup>13</sup>C-NMR spectra of products are provided in Supplementary Information.

### Catalyst regeneration and reuse

When the oxidation reaction was completed, the catalyst was collected by vacuum filtration and washed with ethyl acetate to remove organic species. Then the catalyst was washed with water milliQ during 24 h using Dean Stark apparatus and dried at 100 °C overnight. It was activated at 150 °C under vacuum before each reuse.

### Characterization techniques

Conversion and yields of final products were determined by Gas chromatography using a FID detector and capillary column (HP5, 30 m × 0.25 mm × 0.25 μm). The products were identified by GC-MS and NMR analysis. IR spectra of MIL-100 (Fe) fresh and recovered after Soxhlet extraction were recorded with KBr pellets in a Nicolet 710 FT spectrophotometer. Surface area measurements were obtained with a Micrometrics ASAP 2000 apparatus following the BET procedure by means of nitrogen and argon adsorption at 77 and 85 K, respectively. The structure and crystallinity of materials were determined by X ray diffraction analysis. XRD patterns analysis was obtained by X-ray powder diffraction (XRD) on a Panalytical CUBIX diffractometer using monochromatic Cu Kα radiation. Metal content was determined



by inductively coupled plasma–atomic emission spectrometry (ICP–AES). The content of C, N, O and H was determined by elemental analysis. The particle size and morphology were visualized by using a JEOL6300 SEM at typical conditions of 10 mA emission current and 20 kV operating voltage. The nonconductive samples were coated with a thin layer of gold by using a BAL-TEC SCD 005 sputter apparatus. The physical and chemical properties of the different catalysts are given in Table S1 and the SEM and XRD analysis of the MOFs are presented in Figures S1 and S2 respectively in Supplementary information.  $^1\text{H-NMR}$  and  $^{13}\text{C-NMR}$  spectra of products are provided in Supplementary information.

## Results and discussion

It is known that some bonds in MOFs can be selectively broken either during post-synthesis modifications or during reaction which enhance the catalytic activity of these materials.<sup>33</sup> Additionally, during the synthesis of MOFs, another important factor that can modify their catalytic activity is the level of purification of the MOF.<sup>34</sup> Thus, the BET surface area, pore volume and catalytic properties of a MOF can be affected by the presence of residual impurities such as non-reacted carboxylic acids in the pores, inorganic cations or anions from starting metal salts and/or coordinated carboxylates.<sup>31</sup> We have recently showed that the catalytic activity of MIL-100(Fe) in the dehydration of aldoximes to nitriles can be considerably enhanced by a post-treatment with aqueous  $\text{NH}_4\text{F}$  solution at 70 °C.<sup>29</sup> It was presented that this treatment produces the removal of non reacted iron complexes and organic compounds located inside and outside the pores. As consequence, BET surface area as well as pore volume increase by a factor of 1.5 and 1.2 respectively which lead to an enhanced accessibility of the reactant and their interaction with framework iron species.

Taking into account these previous results, the oxidation of HMF to DFF was performed using of MIL-100 (Fe)- $\text{NH}_4\text{F}$  (post-treated with  $\text{NH}_4\text{F}$  according the experimental section) using TEMPO, oxygen as the terminal oxidant and  $\text{NaNO}_2$  as an additive (Scheme 1). We selected  $\text{NaNO}_2$  because it has been previously showed that this additive activates TEMPO-iron as well as TEMPO-copper catalytic systems for aerobic oxidation of alcohols.<sup>18</sup> The reactions were performed at 75 °C in acetonitrile

as solvent and the results obtained are presented in Table 1. A blank experiment in which the reaction was performed in the presence of MIL-100 (Fe)-NH<sub>4</sub>F under oxygen at atmosphere pressure (Table 1, entry 1) showed that no reaction takes place. The same results were obtained in the absence of TEMPO, MIL-100 (Fe) or NaNO<sub>2</sub> (Table 1, Entry 2-4). To select the most adequate composition of the catalytic system, the amount of catalyst and TEMPO were varied. Results obtained with the conditions of entry 5, showed that high yield and selectivity to DFF (100 % conversion and 100% selectivity) could be achieved in 6h reaction time (Figure S3). When the amount of TEMPO was decreased to one half (entry 6) the yield considerably decreased up to 40% after 6h, although 98 % DFF yield could be achieved by prolonging the reaction time to 20 h. Meanwhile the results in Table 1, entry 7 show the importance of the Fe catalyst for this transformation. The results clearly indicate that every component of the catalytic system plays a crucial role in the reaction mechanism and that DFF can be obtained in high yield and selectivity using catalytic amounts of TEMPO together with the MIL-100 (Fe)-NH<sub>4</sub>F catalyst (see entries 5 and 6).

Taking into account the proposed mechanism for the oxidation of alcohols using the catalytic system Fe salts/TEMPO/NaNO<sub>2</sub>, previously reported,<sup>18,20</sup> an oxidation mechanism of HMF into DFF with the MOF is presented in Scheme 2. Thus, in the first step TEMPO should couple with Fe<sup>3+</sup> unsaturated sites of MIL-100 (Fe)- NH<sub>4</sub>F to form an intermediate I (Scheme 2). Then, HMF would react with complex I to form an intermediate II by releasing one proton. After the abstraction of β-H from the alcohol by TEMPO, a reductive elimination occurs producing DFF, Fe<sup>2+</sup> and TEMPOH. Reduction of NO<sub>2</sub> to NO would reoxidize the Fe<sup>2+</sup> to Fe<sup>3+</sup> while TEMPOH would be reoxidized to TEMPO by reaction with Fe<sup>3+</sup>. Finally, NO<sub>2</sub> would be regenerated by the reaction of O<sub>2</sub> with NO.

#### **Comparison of catalytic activity of different iron catalysts for the oxidation of HMF to DFF**

For comparative purposes other iron containing heterogeneous catalysts such as a NH<sub>4</sub>F non post treated MIL-100(Fe), a commercially available Fe(BTC), and a Fe exchanged HY zeolite as well as homogeneous iron salts such FeCl<sub>3</sub>·6H<sub>2</sub>O and Fe-

trimesate were employed for oxidation of 5-HMF. As can be observed from the results presented in Table 2, Fe(BTC) catalyst (entry 3) presents lower catalytic activity than MIL-100 (Fe)-NH<sub>4</sub>F (entry 1) for this reaction, obtaining only 56 % of conversion after 6 hours. Although the crystal size and chemical composition of Fe(BTC) and MIL-100(Fe)-NH<sub>4</sub>F are similar (both are constituted by iron ions and 1,3,5-benzenetricarboxylate:BTC), the lower catalytic activity of the Fe(BTC) can be attributable to its lower surface area and pore volume which limits the accessibility of the TEMPO and HMF to the active sites (see Table S1). The same explanation can be given for the lower catalytic activity exhibited by the non post-treated MIL-100(Fe) (entry 2) compared with MIL-100(Fe)-NH<sub>4</sub>F. Additionally, high yield and selectivity to DFF were also achieved using a Fe exchanged HY zeolite.

On the other hand, homogeneous Fe salts such as Fe-trimesate showed similar activity to MIL-100(Fe)-NH<sub>4</sub>F while the activity of FeCl<sub>3</sub>·6H<sub>2</sub>O was considerably lower. These results agree with the results reported by Wang et al.<sup>18</sup> who found that counter anion of Fe salts is critical for the alcohol oxidation, being chloride salts more active than nitrates and sulfates. In fact, taking into account the proposed oxidation mechanism the modulation of the Lewis acidity of Fe sites by the counter anion should have an impact on the interaction of the TEMPO and HMF on the Fe sites and for hence on the activity of the catalyst for the alcohol oxidation.

Finally, Cu<sub>3</sub>(BTC)<sub>3</sub> was used as catalyst in the aerobic oxidation of HMF into DFF since this catalyst combined with TEMPO had showed good activity in the oxidation of a variety of benzyl alcohols.<sup>26</sup> However, as showed in Table 2 (entry 7), only 28 % conversion of HMF with 100 % selectivity to DMF was achieved after 6 h, indicating that Fe-based MOFs are considerably more active for this transformation.

### Reusability of Fe-HY zeolite and MIL-100 (Fe)-NH<sub>4</sub>F

At this point we have showed that Fe-HY zeolite and the post-treated MIL-100(Fe)-NH<sub>4</sub>F are active solid catalysts to perform the selective oxidation of HMF into DMF. However, an important issue to be addressed for the potential application of these catalysts to produce DFF is their stability and the possibility to be regenerated and reused. Thus, after a first cycle, the Fe-HY zeolite recovered by filtration and

washed thoroughly with milliQ water, was dried and used in a second cycle. The results showed an important loss of activity, achieving only 10 % conversion of HMF after 6h. In order to determine if the deactivation was due to the strong adsorption of organic material, the catalyst was calcined at 540 °C in air and used again in reaction, however the catalytic activity was not recovered at all. Then, the irreversible catalyst deactivation points into the leaching of iron species from the catalyst to the reaction media during the first cycle of reaction as the main cause of catalyst deactivation. To check that, ICP analysis of the recovered zeolite was performed, showing that the amount of iron remaining on the zeolites was less than 1wt % (from 5.3 wt %). These results suggest that in the case of Fe-HY, Fe leached species in the reaction media would be the active species.

In a similar way, to check the stability and reusability of MIL-100 (Fe)-NH<sub>4</sub>F, after the first reaction cycle, the catalyst was exhaustively washed with water in a Soxhlet apparatus, dried and after activation at 150 °C, it was used in a second and third run (see Table 3). As can be observed some deactivation of catalyst during reuses occurs (see Figure S4), although prolonging the reaction time complete HMF conversion was achieved with the reused catalyst.

To understand the cause of catalyst deactivation BET surface area and pore volume of MIL-100 (Fe)-NH<sub>4</sub>F were analyzed before and after reuse. In Table 4 can be observed that these parameters slightly decrease during the reuses but they remain still high. The carbon content of fresh and reused sample of MIL-100 (Fe)-NH<sub>4</sub>F after washing it with water, is maintained practically unchanged, indicating the absence of organic material generated during the reaction that remains strongly adsorbed on the catalyst surface. Moreover, this was corroborated by the IR analysis of the fresh and used catalyst (after Soxhlet extraction) (see Figure S5), where only the absorption bands of the MOF were observed. Moreover, the Fe content of fresh and reused samples of MIL-100 (Fe)-NH<sub>4</sub>F remains almost unchanged suggesting that there is no leaching of Fe<sup>3+</sup> during the reaction and washing. Nevertheless an additional experiment was carried out by doing the reaction under optimized conditions and the MIL-100 (Fe)-NH<sub>4</sub>F was separated from the reaction media in hot when the conversion of HMF was 34 %. After that, the filtrated, now without solid catalyst, was again

stirred during 12h and no further product formation was observed in absence of solid (Figure S6), indicating that no conversion by any possible homogeneous Fe species occurs. Finally, comparing the powder XRD pattern of fresh and reused MIL-100 (Fe)-NH<sub>4</sub>F catalyst (Figure 1) it was observed a small loss of crystallinity of the catalyst with the reuses which can be responsible for the loss of activity. We speculated that the small loss of the crystallinity and the changes the XRD at low angles, could be explained by a very small amount of reactants and/or product that could be remain adsorbed.

### Scope of the reaction

In order to expand the scope of the aerobic oxidation of alcohols using the MIL-100(Fe)-NH<sub>4</sub>F/TEMPO/NaNO<sub>2</sub> as catalytic system, the oxidation of various alcohols has been performed. Reactions were performed in conditions comparable to those previously reported using Cu<sub>3</sub>(BTC)<sub>2</sub><sup>26</sup> and the results are presented in Table 5. As can be observed benzyl alcohols bearing electron-donating and electron withdrawing groups give the corresponding benzaldehyde with high yields and selectivity, although benzyl alcohols with electron withdrawing groups are less reactive and required longer reaction time as was already observed by other authors.<sup>[18,26]</sup> Aerobic oxidation of cinnamyl alcohol and 1-phenyl ethanol resulted in good to moderate yield, while the oxidation of furfuryl alcohol to furfural was complete. The oxidation of 1-octanol gives lower yield of octanal which is attributable to the low reactivity of primary aliphatic alcohols,<sup>35</sup> however it is interesting to point out that under homogeneous catalysis using FeCl<sub>3</sub> this alcohol could not be oxidized.<sup>18</sup>

From the results presented above, we can conclude that our catalytic system based on MIL-100(Fe)-NH<sub>4</sub>F/TEMPO/NaNO<sub>2</sub> exhibits high activity in the aerobic oxidation of a variety of alcohols, being superior to previously reported Cu-MOF catalysts.

### One pot two steps synthesis of furilydenepropanenitrile derivatives.

As it was mentioned before 2,5-diformylfuran (DFF) is one of the valuable biomass derivatives that can be used as a monomer for polymer manufacturing.

Furthermore DFF contains two reactive carbonyl groups that can be transformed into other functionalities giving compounds of interests in the field of polymers. For instance, DFF has been used to prepare polymeric Schiff bases<sup>36</sup> (or polyimines) and diformylfuran-urea resins.<sup>2</sup> Although there is a growing interest in renewable polymeric materials only few examples of furanic dialdehyde based polymers have been synthesized until now. This may be related with the high cost of monomer DFF which limits its field of applications.

Here, we have found that DFF can be obtained in quantitative yield from the aerobic oxidation of HMF using MIL-100(Fe)-NH<sub>4</sub>F/TEMPO/NaNO<sub>2</sub>, and taking into consideration the basicity of the components of this catalytic system (namely TEMPO and NaNO<sub>2</sub>) we envisaged that the oxidation reaction could be coupled with the base catalyzed Knoevenagel condensation of DFF with methylene active compounds (malononitrile and ethyl cyanoacetate). This should allow, for instance to produce furilydenepropanenitrile derivatives with potential applications as monomers for new polymeric materials.

In a first approach, we attempted the synthesis of the Knoevenagel adduct (2,2'-(2,5-furandiylidimethyldiylidene)-bis-propanedinitrile (**2a**) directly from 5-HMF and malononitrile using the same catalytic system as for oxidation of HMF to DFF. In this way, the DFF would be formed as an intermediate by catalytic oxidation of HMF and then would couple with malononitrile to form the final Knoevenagel adduct (**2a**). Unfortunately, it was observed that the presence of malononitrile completely inhibits the HMF oxidation, and the Knoevenagel adduct formed was not the desired one but the resultant from the condensation of HMF and malononitrile (**1a**) (99 % yield).

Then, the synthesis of **2a** by one pot two step process with DFF as an intermediate was attempted. In the first step, the oxidation of HMF to DFF was performed and when the yield of DFF was 100%, the MIL-100(Fe)-NH<sub>4</sub>F was removed by filtration and 2 mmol of malononitrile were added to the filtrate and the reaction continued at 75 °C. As can be observed in Figure 2, the intermediate **1a** (Scheme 3) coming from the condensation of one molecule of malononitrile with DFF appears as a primary product that subsequently reacts with another molecule of malononitrile to give the Knoevenagel adduct (**2a**) in 100% yield after 0.5 h reaction time. Additionally, the reaction was also

performed using as methylene active compound ethyl cyanoacetate, and in this case a total conversion of DFF into the corresponding Knoevenagel adduct (**2b**) was also achieved although longer reaction time (7h) was required due to the lower acidity of ethyl cyanoacetate compared with malononitrile.<sup>37</sup>

From these results we can conclude that it is possible to couple HMF oxidation with Knoevenagel condensation of the DFF intermediate with methylene active compounds through a one pot two step process to produce furilydenepropanonitrile derivatives in high yields.

### Conclusions

We have showed that by coupling the oxidation of 5-hydroxymethylfurfural (HMF) to diformylfuran (DFF) with the Knoevenagel condensation of DFF with methylene active compounds, furilydenepropanonitrile useful as monomers, have been obtained in high yields through a one pot two step process under mild reaction conditions.

The oxidation step was studied using Fe (MIL-100(Fe), Fe(BTC)) and Cu ( $\text{Cu}_3(\text{BTC})_2$ ) containing MOFs, a Fe exchanged HY zeolite and homogeneous Fe salts in the presence of 2,2,6,6-tetramethylpiperidine-1-oxide (TEMPO) as cocatalyst,  $\text{NaNO}_2$  as additive and oxygen as the terminal oxidant. The results showed that Fe containing catalysts (homogeneous and heterogeneous) were more active than  $\text{Cu}_3(\text{BTC})_2$ , while a post treated MIL-100(Fe) with  $\text{NH}_4\text{F}$  was the most active catalyst achieving 100 % HMF conversion with 100 % selectivity to DFF. The high activity of this catalyst was attributed to the enhanced accessibility of reactants (HMF and TEMPO) to the active Fe sites due to their higher surface area and pore volume compared with the non post-treated MIL-100(Fe). Additionally, the catalytic system has been applied to the oxidation of different primary and secondary alcohols to the corresponding carbonyl compounds under mild reaction conditions with good success. The second step, the Knoevenagel condensation of the obtained DFF with malononitrile and ethyl cyanoacetate was performed taking advantage of the basicity of the reaction medium.

### Acknowledgements

Spanish MICINN Project (CTQ-2015-67592-P), Generalitat Valenciana (Prometeo Program), Severo Ochoa Program and the EU-Japan Project NOVACAM are gratefully acknowledged.

## References

- 1 a) A.A. Rosatella, S.P. Simeonov, R.F.M. Frade, C.A.M. Afonso) *Green Chem.* **2011**, *13*, 754-793; b) R.J. van Putten, J.C. van der Waaal, E. de Jong, C.B. Rasrendra, H.J. Heeres, J.G. de Vries, *Chem. Rev.*, 2013, **113**, 1499-1597; c) M.J. Climent, A. Corma, and S. Iborra, *Green Chem.*, 2014, **16**, 516-547.
- 2 A. S. Amarasekara, D. Green, L. D. Williams, *Eur. Polym. J.*, 2009, **45**, 595–598.
- 3 K. T. Hopkins, W. D. Wilson, B. C. Bender, D. R. McCurdy, J. E. Hall, R. R. Tidwell, A. Kumar, M. Bajic, D. W. Boykin, *J. Med. Chem.*, 1998, *41*, 3872–3878.
- 4 M. Del Poeta, W. A. Schell, C. C. Dykstra, S. Jones, R. R. Tidwell, A. Czarny, M. Bajic, , A. Kumar, D. Boykin, R. J. Perfect, *Antimicrob. Agents Chemother.* 1998, **42**, 2495–2502.
- 5 D. T. Richter, T. D. Lash, *Tetrahedron Lett.*, 1999, **40**, 6735–6738.
- 6 T. Shimo, S. Ueda, T. Suishu, K. Somekawa, *J. Heterocycl. Chem.*, 1995, **32**, 727-730.
- 7 F. W. Lichtenthaler, *Acc. Chem. Res.*, 2002, **35**, 728-737.
- 8 A.S. Amarasekara, D. Green, E. McMillan, *Catal. Commun.*, 2008, **9**, 286-288.
- 9 W. Partenheimer, V.V. Grushin, *Adv. Synth. Catal.*, 2001, **343**, 102-111.
- 10 A. Takagaki, M. Takahashi, S. Nishimura, K. Ebitani, *ACS Catal.*, 2011, **1**, 1562-1565.
- [11] J. Nie, J. Xie, H. Liu, *J. Catal.* **2013**, *301*, 83-91.
- 12 a) C. Carlini, P. Patrono, A.M. Raspolli, G. Sbrana, V. Zima, *Appl. Catal. A: General*, 2005, **289**, 197-204.; b) O. Casanova, A. Corma, S. Iborra, *Top. Catal.*, 2009, **52**, 304-314; c) I. Sadaba, Y.Y. Gorbanev, S. Kegnaes, S.S.R. Putluru, R.W. Berg, A. Riisager, *ChemCatChem*, 2013, **5**, 284-293.
- 13 G.D. Yadav, R.V. Sharma, *Appl. Catal. B*, 2014, **147**, 293-301.
- 14 R. Fang, R. Luque, Y. Li, *Green Chem.*, 2016, **18**, 3152-3157.
- 15 R. Ben-Daniel, P. Alsters, R. Newmann, *J. Org. Chem.*, 2001, **66**, 8650-8653.
- 16 I. A. Ansari, R. Gree, *Org. Lett.*, 2002, **4**, 1507-1509.



17 P. Gamez, I.W.C.E. Arends, J. Reedijk, R. A. Sheldon, *Chem. Commun.*, 2003, 2414-2415.

18 N. Wang, R. Liu, J. Chen, X. Liang, *Chem. Commun.*, 2005, 5322-5324.

19 W. Yin, C. Chu, Q. Lu, J. Tao, X. Liang, R. Liu, *Adv. Synth. Catal.*, 2010, **352**, 113–118.

20 S. Ma, J. Liu, S. Li, B. Chen, J. Cheng, J. Kuang, Y. Liu, B. Wan, Y. Wang, J. Ye, Q. Yu, W. Yuan, S. Yu, *Adv. Synth. Catal.*, 2011, **353**, 1005–1017.

21 L. Cottier, G. Descotes, J. Lewkowski, R. Skowronski, E. Viollet, *J. Heterocyclic Chem.*, 1995, **32**, 927-930.

22 T.S. Hansen, I. Sadaba, E.J. Garcia-Suarez, A. Riisager, *Appl. Catal. A*, 2013, **456**, 44-50.

23 C. Fang, J. J. Dai, H. J. Xu, Q. X. Guo, Y. Fu, *Chinese Chem. Lett.*, 2015, **26**, 1265-1268.

24 a) G. Ferey, *Chem. Soc. Rev.* 2008, **37**, 191-214; b) S. Natarajan, P. Mahata, *Chem. Soc. Rev.*, 2009, **38**, 2304-2318.

25 a) A. Corma, H. Garcia, F.X. Llabres I Xamena, *Chem.Rev.* 2010, **110**, 4606-4655; b) J. Liu, L. Chen, H. Cui, J. Zhang, L. Zhang, C. Y. Su, *Chem. Soc. Rev.*, 2014, **43**, 6011-6061.

26 A. Dhakshinamoorthy, M. Alvaro, H. Garcia, *ACS Catal.*, 2011, **1**, 48–53.

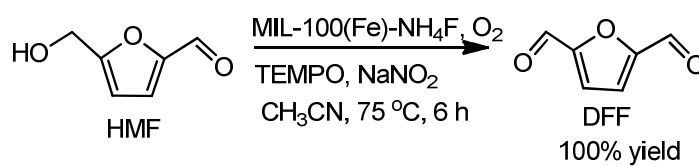
27 R. Canioni, C. Roch-Marchal, F. Secheresse, P. Horcajada, C. Serre, M. Hardi-Dan, G. Ferey, J. M. Greneche, F. Lefebvre, J. S. Chang, Y. K. Hwang, O. Lebedev, S. Turner, G. Van Tendeloo, *J. Mater. Chem.* 2011, **21**, 1226–1233.

28 P. Wang, H. Zhao, H. Sun, H. Yu, S. Chen, X. Quan, *RSC Advances*, 2014, **4**, 48912-48919.

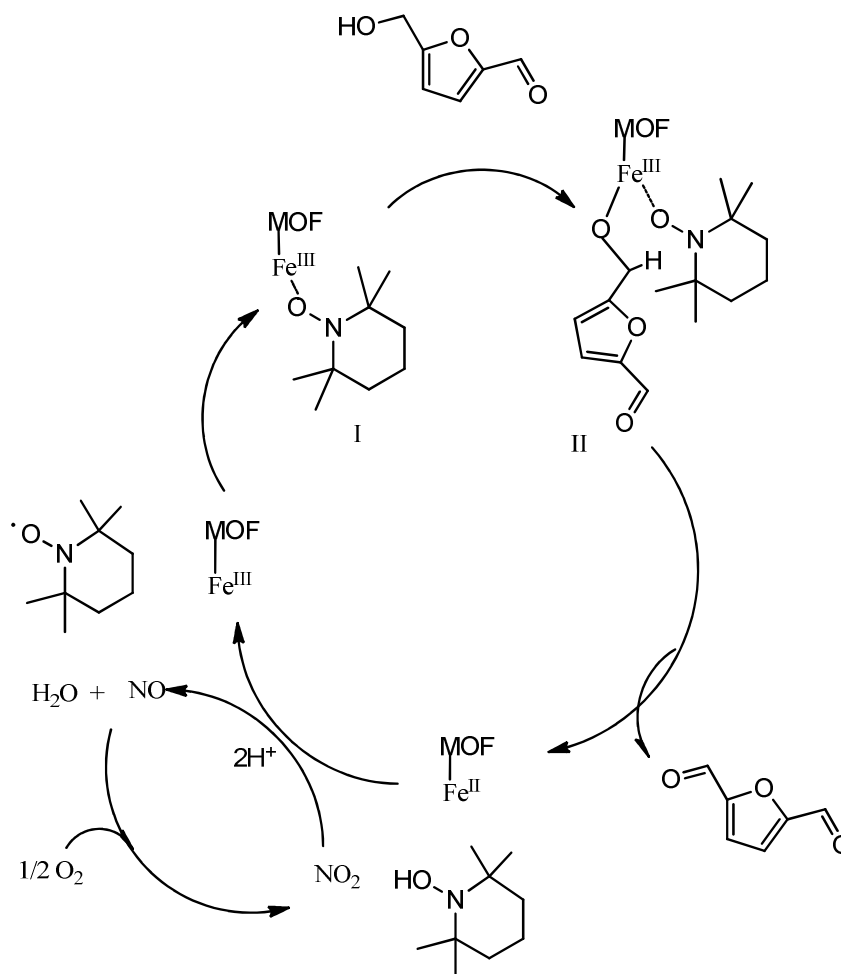
29 A. Rapeyko, M. J. Climent, A. Corma, P. Concepcion, S. Iborra, *ChemSusChem* 2015, **8**, 3270-3282.

[30] A. Dhakshinamoorthy, M. Alvaro, Y. K. Hwang, Y. K. Seo, A. Corma, H. Garcia, *Dalt. Trans.*, 2011, **40**, 10719–10724.

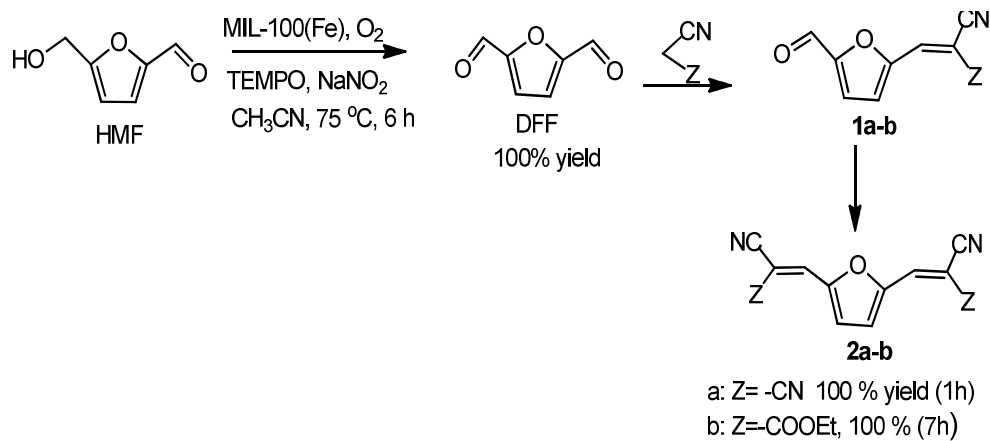
- 31 A. García Marquez, A. Demessence, A. E. Platero-Prats, D. Heurtaux, P. Horcajada, C. Serre, J. S. Chang, G. Férey, V. A. de la Peña-O'Shea, C. Boissiere, D. Grosso, C. Sanchez, *Eur. J. Inorg. Chem.*, 2012, **2012**, 5165–5174.
- 32 Y. K. Seo, J. W. Yoon, J. S. Lee, U. H. Lee, Y. K. Hwang, C. H. Jun, P. Horcajada, C. Serre, J. S. Chang, *Microporous Mesoporous Mater.*, 2012, **157**, 137–145.
- 33 a) M. Polozij, M. Rubes, J. Cejka, P. Nachtigall, *ChemCatChem*, 2014, **6**, 2821–2824;  
b) R. E. Morris, J. Čejka, *Nature Chemistry*, 2015, **7**, 381–388.
- 34 D. Y. Hong, Y. K. Hwang, C. Serre, G. Férey, J. S. Chang, *Adv. Funct. Mater.*, 2009, **19**, 1537–155.
- 35 K. keresszegi, D. Ferri; T. Mallat, A. Baiker, *J. Catal.*, 2005, **234**, 64–65.
- 36 Z. Hui, A. Gandini, *Eur. Polym. J.* 1992, **28**, 1461–1469.
- 37 M. J. Climent, A. Corma, S. Iborra, A. Velty, *J. Mol. Catal. A*, 2002, **182-183**, 327–342.



**Scheme 1.** Oxidation of HMF to DFF



**Scheme 2.** Proposed mechanism for the selective oxidation of HMF to DFF using MIL-100 (Fe)-NH<sub>4</sub>F/TEMPO/NaNO<sub>2</sub> catalytic system



**Scheme 3.** One pot two steps process for the preparation of furilydenepropanenitrile derivatives

**Table 1.** Aerobic oxidation of HMF into DFF in the presence of MIL-100 (Fe)-NH<sub>4</sub>F under various reaction conditions.

Entry	TEMPO (mmol)	NaNO <sub>2</sub> (mmol)	Time (h)	HMF Conversion <sup>c</sup> (%)	DFF Yield <sup>c</sup> (%)
1	-	-	21	0	0
2	-	0.14	21	0	0
3	0.076	-	21	0	0
4 <sup>a</sup>	0.076	0.14	21	0	0
5	0.076	0.14	6	100	100
6	0.040	0.14	<u>6 (20)</u>	40(98)	40(98)
7 <sup>b</sup>	0.076	0.14	20	20	20

Reaction Conditions: 5-HMF (1 mmol, 126 mg), catalyst (45 mg. 0.17 mmol Fe); CH<sub>3</sub>CN (5 mL); at 75 °C at atmospheric pressure of oxygen.<sup>a</sup> Without catalyst. <sup>b</sup> With 23 mg of catalyst. <sup>c</sup> Determined by GC.

Table 2. Oxidation of HMF with different iron containing catalysts

Entry	Catalyst	Time (h)	Metal/HMF mol ratio	Conversion HMF (%) <sup>a</sup>	Yield DFF (%) <sup>a</sup>
1	MIL-100 (Fe)-NH <sub>4</sub> F	6	0.17	100	100
2	MIL-100(Fe)	6	0.17	57	57
3	Fe(BTC)	6	0.17	56	56
4	HY-Fe (5.3 wt.%)	6	0.043	100	100
5	FeCl <sub>3</sub> ·6H <sub>2</sub> O	6	0.17	63	63
6	Fe-Trimesate	6	0.17	90	90
7	Cu <sub>3</sub> (BTC) <sub>2</sub>	6	0.20	28	28

Reaction Conditions: HMF (1 mmol, 126 mg); TEMPO (0.076 mmol; 12 mg); NaNO<sub>2</sub> (0.14 mmol, 10 mg), in CH<sub>3</sub>CN (5ml) at 75 °C under atmospheric pressure of oxygen.<sup>a</sup>

Determined by GC.

Table 3. Results of reuses of MIL-100 (Fe)-NH<sub>4</sub>F catalyst

Entry	cycles	Time (h)	Conversion 5-HMF (%) <sup>a</sup>	Yield 2,5-DFF (%) <sup>a</sup>
1	1st	6	100	100
2	2nd	6	73	73
		10	100	100
3	<u>3rd</u>	6	55	55
		16	99	99

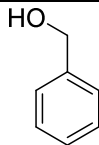
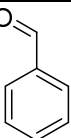
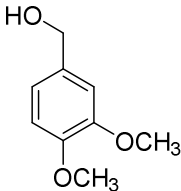
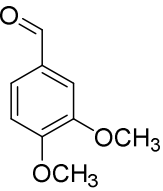
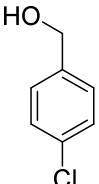
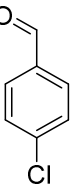
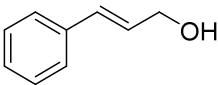
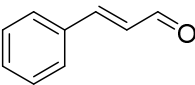
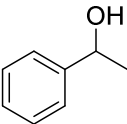
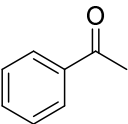
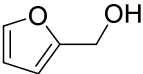
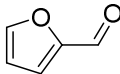
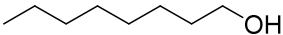
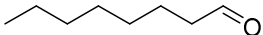
Reaction Conditions: 5-HMF (1 mmol, 126 mg); catalyst MIL-100(Fe)-NH<sub>4</sub>F 45 mg; TEMPO (0.076 mmol; 12 mg); NaNO<sub>2</sub> (0.14 mmol, 10 mg) at 75 °C in CH<sub>3</sub>CN (5ml) under atmospheric pressure of oxygen. <sup>a</sup> Determined by GC. Catalyst regeneration procedure: After reaction the catalyst was collected by vacuum filtration and washed with ethyl acetate and then with water milliQ during 24 h using Dean Stark apparatus, and dried at 100 °C overnight. It was activated at 150 °C under vacuum before each reuse.



**Table 4.** BET surface area and total pore volume ( $V_{\text{total}}$ ) of MIL-100 (Fe)- $\text{NH}_4\text{F}$  before and after reuses

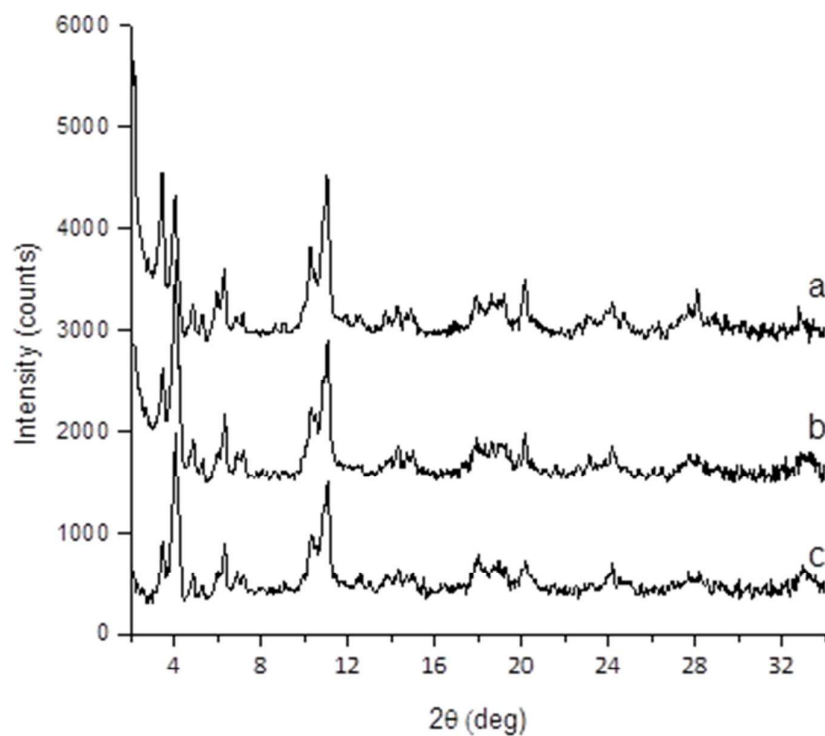
Catalyst	BET ( $\text{m}^2/\text{g}$ )	$V_{\text{total}}$ ( $\text{cm}^3/\text{g}$ )
Fresh	1370	0.84
After 1 <sup>st</sup> cycle	1293	0.82
After 2 <sup>nd</sup> cycle	1058	0.72

**Table 5.** Oxidation of different alcohols using MIL-100 (Fe)-NH<sub>4</sub>F as catalyst

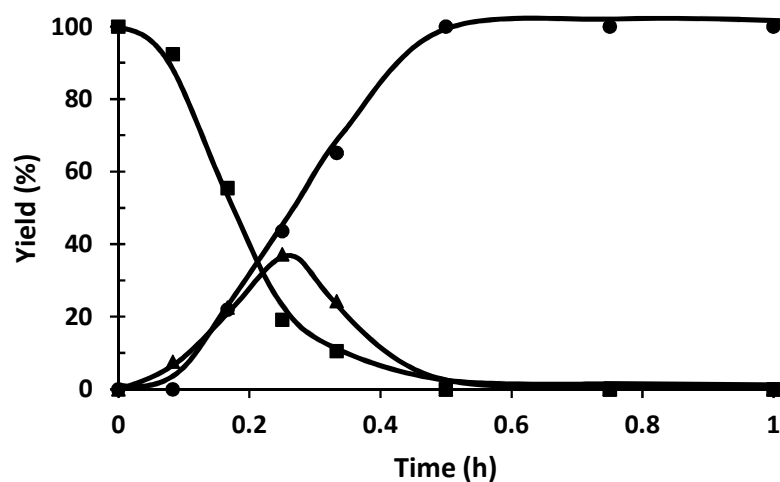
Substrate	Product	Time (h)	Yield (%) <sup>a</sup>	Selectivity (%)
		5	100 (89) <sup>b</sup>	100
		2.5	100 (8) <sup>b</sup>	100
		8	100	100
		22	87 (62) <sup>b</sup>	92
		22	67 (14) <sup>b</sup>	100
		5	100 (21) <sup>b</sup>	100
		5	59 (3) <sup>b</sup>	89

Reaction conditions: alcohol (1 mmol), MIL-100(Fe)-NH<sub>4</sub>F (150 mg), TEMPO (0.5 meq), NaNO<sub>2</sub> (1 meq), acetonitrile (5 mL), at 75 °C under atmospheric pressure of oxygen. <sup>a</sup>

Determined by GC. <sup>b</sup> In brackets yields reported in ref.(26) after 22h using Cu<sub>3</sub>(BTC)<sub>2</sub> as heterogeneous catalyst.

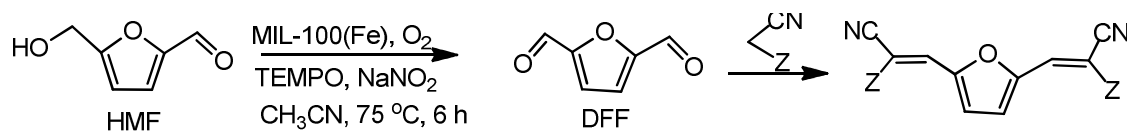


**Figure 1.** XRD patterns of fresh and reused MIL-100(Fe)-NH<sub>4</sub>F catalyst a) Fresh; b) after 1<sup>st</sup> cycle; c) after 2<sup>nd</sup> cycle.



**Figure 2.** Kinetic plot of the Knoevenagel condensation of DFF with malononitrile. (■) DFF; (▲) intermediate **1a**; (●) Knoevenagel adduct (**2a**). Reaction conditions: DFF (1mmol); malononitrile (2mmol); TEMPO (0.076 mmol; 12 mg); NaNO<sub>2</sub> (0.14 mmol, 10 mg) at 75 °C in CH<sub>3</sub>CN (5ml)

## Graphical Abstract



Monomers from biomass have been prepared from HMF and methylene active compounds through one pot process using MIL-100(Fe)/TEMPO/NaNO<sub>2</sub> as catalytic system.