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# Fe(MIL-53) metal–organic framework as a facile and sustainable Lewis acidic catalyst for the one-pot synthesis of xanthene derivatives

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The catalytic application of the easily preparable Fe(MIL-53) MOF was demonstrated as a sustainable solid Lewis acidic catalyst in synthesising pharmaceutically essential xanthenes under mild conditions. The Fe(MIL-53) MOF catalyst was synthesised and characterised using various analytical tools such as PXRD, FTIR, SEM, TGA and ICP-OES. The presence of a high concentration of coordinatively unsaturated Fe<sup>3+</sup> sites in Fe(MIL-53) can efficiently catalyse the formation of xanthenes in the presence of a catalytic amount (1.36 mg) of MOF using environmentally friendly, non-toxic and renewable ethanol as the medium. A series of substituted xanthenes were synthesised in good to excellent yield with wide functional group tolerance. The present methodology avoids the usage of any strong reagents and uses stoichiometric amounts of the catalyst. The catalytic comparison studies with other homogeneous and heterogeneous catalytic systems proved the efficiency of the present Fe(MIL-53) MOF catalyst. The hot-filtration test and reusability profile prove the stability and sustainability of this catalyst, which were also supported by PXRD, FTIR and SEM analysis of the reused catalyst.

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## Sustainability spotlight

Iron is one of the most abundant metals in nature, and iron-based metal–organic frameworks (MOFs) have garnered significant attention due to their remarkable reactivity, stability, ease of handling, relatively low toxicity, and environmental friendliness while being cost-effective. Earlier-generation catalysts were largely based on precious metals, often homogeneous, and suffered from significant recyclability challenges. Xanthenes are a crucial class of organic compounds with diverse pharmacological properties. However, their synthesis presents challenges, particularly due to their acid-sensitive groups. The use of iron-based MOFs offers a sustainable approach to overcoming these limitations. This work aligns with the United Nations Sustainable Development Goals (SDGs) 7 and 12, which emphasize affordable and clean energy as well as sustainable consumption and production patterns, promoting a more environmentally responsible approach to catalysis.

## 1. Introduction

Xanthenes are an important class of organic compounds with several pharmacological properties, such as anti-coagulant, spasmolytic, anticancer, antiviral, anti-inflammatory, antibacterial, antifungal, antiproliferative, antioxidant, and specific IK<sub>Ca</sub> channel blocking activities.<sup>1–7</sup> These compounds were widely used as synthetic precursors for many valuable organic compounds,<sup>8</sup> dyes,<sup>9</sup> and photoactive materials<sup>10</sup> and in laser technologies<sup>11</sup> and fluorescent materials for the visualisation of biomolecules<sup>12</sup> and detection of metal ions.<sup>13</sup> Tetraketones and their tautomeric enol forms are also considered to be important biologically active compounds, being assessed as tyrosinase

inhibitors, and also leading intermediates in the preparation of fused heterocyclic systems such as xanthendione, acridindione and 4*H*-1-benzopyran derivatives.<sup>14</sup> Xanthene derivatives can be prepared generally *via* the condensation between aldehydes and 1,3-dicarbonyl compounds. To obtain xanthenes, this type of condensation reactions has been reported in the literature using homogeneous catalysts, including protonic acids,<sup>15</sup> Lewis acids such as InCl<sub>3</sub>·4H<sub>2</sub>O,<sup>16</sup> indium triflate,<sup>17</sup> FeCl<sub>3</sub>·8H<sub>2</sub>O,<sup>18</sup> CuCl<sub>2</sub>,<sup>19</sup> and NaHSO<sub>4</sub>,<sup>20</sup> and heterogeneous catalysts, such as Dowex-50W,<sup>21</sup> polyaniline *p*-toluenesulfonate,<sup>22</sup> *p*-toluenesulfonic acid,<sup>23</sup> sulfamic acid@MCM-41,<sup>24</sup> PPA-SiO<sub>2</sub>,<sup>25</sup> TiO<sub>2</sub>/SO<sub>4</sub>,<sup>26</sup> nano-Fe<sub>3</sub>O<sub>4</sub>-TiO<sub>2</sub>-SO<sub>3</sub>H,<sup>27</sup> Fe<sub>3</sub>O<sub>4</sub>@NFC@NNSM-Mn(III),<sup>28</sup> Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>@APTES@MPIB-Mn(II),<sup>29</sup> TMP-PECH-COOH,<sup>30</sup> CuCeO<sub>2</sub> NPs,<sup>31</sup> ZrO<sub>2</sub> NPs,<sup>32</sup> Fe<sub>3</sub>O<sub>4</sub> NPs,<sup>33</sup> Cu(II) NPs,<sup>34</sup> CuS quantum dots,<sup>35</sup> and Amberlyst-15.<sup>36</sup> In general, heterogeneous solid acid catalysts have more advantages over homogeneous acid catalysts as they can be easily recovered from the reaction mixture by simple filtration and can be reused several times

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without loss of their active sites, thereby making the process more economically and environmentally feasible.<sup>37</sup>

Metal-organic frameworks (MOFs) are of immense interest as a new class of synthetic porous materials in various applications.<sup>38</sup> MOFs contain coordinatively unsaturated metal centres/sites (CUS), which act as Lewis acidic centres,<sup>39</sup> or functionalities suspended on their organic linkers, which act as either Brønsted basic<sup>40</sup> or acidic<sup>40b,c,41</sup> sites, promoting sustainable catalytic processes. The combination of abundant metal content and porosity makes MOFs promising heterogeneous catalysts for several organic transformations.<sup>42</sup> Besides the field of catalysis, due to their fascinating features, which include structural diversity, flexibility and alterability, intrinsic porosity, and desirable chemical functionality, MOFs have been used in diverse fields such as gas storage and separation, sensors, drug delivery and bioimaging.<sup>43</sup>

Among the reported popular MOFs, iron-based organic frameworks have attracted considerable attention<sup>44</sup> owing to their remarkable reactivity, stability, ease of handling, relatively non-toxic and environment-friendly nature, and low cost. Various iron-based MOFs such as Fe(BTC),<sup>45</sup> Fe(MIL-100),<sup>46</sup> Fe(MIL-53),<sup>47</sup> Fe(MIL-101),<sup>48</sup> NH<sub>2</sub>-MIL-101(Fe),<sup>49</sup> MOF-235,<sup>50</sup> Fe<sub>3</sub>O(BDC)<sub>3</sub>,<sup>51</sup> Fe<sub>3</sub>O(BPDC)<sub>3</sub>,<sup>52</sup> and VNU-20 (ref. 53) have been used for different applications. Amongst them, Fe(MIL-53) MOF is a reliable iron-MOF that is explicitly used in photocatalysis,<sup>55</sup> sensors,<sup>56</sup> drug delivery,<sup>54</sup> *etc.* Centred in the middle of the d-block elements and able to support formal oxidation states varying from -II to +VI, iron-based catalysts can be widely applied in the field of organic synthesis. Iron-based metal-organic frameworks show comparable or superior catalytic activity, along with improved stability and sustainability, when used as catalysts for organic transformations. Further, the Lewis acidity of iron varies from fairly modest to very high, and this property is strongly associated with its oxidation state, and hence tunable not only based on the choice of ligands. However, although Fe(MIL-53) MOF possesses promising characteristics for catalysis such as high porosity, thermal stability, and Lewis acidic sites, its application as a heterogeneous catalyst in organic synthesis has been relatively underexplored. To date, only a limited number of organic transformations has been reported using Fe(MIL-53), including Fenton-type oxidation<sup>57</sup> and the synthesis of heterocyclic frameworks such as pyrano [2,3-*c*]pyrazoles,<sup>58</sup> 2-aryl-1H-benzimidazoles,<sup>59</sup> and pyrimido [4,5-*d*]pyrimidine derivatives.<sup>60</sup> In contrast, other Fe-based MOFs, such as Fe-BTC and Fe-MOF-74, have been more widely studied for diverse catalytic applications. However, to our knowledge, there have been no reports on the iron-MOF-catalysed synthesis of xanthenes *via* condensation reactions. Therefore, our current study offers a novel contribution by demonstrating the efficiency of Fe(MIL-53) MOF in catalysing the synthesis of xanthenes, further expanding its catalytic utility in organic transformations.

## 2. Results and discussion

In this study, we aim to explore the catalytic efficiency of Fe(MIL-53) MOF as a heterogeneous iron catalyst for synthetic

organic applications. Specifically, we have utilized this catalyst for the synthesis of pharmaceutically active xanthene molecules. The Fe(MIL-53) MOF was synthesised and systematically characterised using various spectroscopic and microscopy techniques. The FTIR (Fig. 7) and PXRD (Fig. 8) analyses confirmed the formation Fe(MIL-53) as a framework, not as a coordination polymer. Further, the crystalline nature of the synthesised Fe(MIL-53) MOF (**1**) was proven by the SEM analysis, which showed the formation of highly crystalline rod-shaped Fe (MIL-53) (Fig. 9). After confirming the structure of the prepared MOF (**1**), it was used as a solid Lewis acid catalyst for the synthesis of xanthene from benzaldehyde (**2**) and dimedone (**3**) as model substrates. To obtain the optimum reaction conditions, the catalytic reaction parameters such as solvent, time, temperature and catalyst loading were screened. When employing MOFs as catalysts in heterocyclic synthesis, owing to the presence of multiple catalytic sites within their pores, the role of solvent is highly inevitable. In the present study, a spectrum of non-polar solvents was screened using 20 wt% of the Fe(MIL-53) MOF catalyst (Table 1) at the reflux temperature of the respective solvent and arbitrarily fixing 3 h as the reaction time.

The analysis of the solvent screening results clearly reveals that the solvent played a notable role in the formation of the product. In general, MOF catalysts are not more compatible with non-polar solvents. This behaviour was reflected in the present study. When non-polar solvents like toluene, dichloromethane, and dichloroethane were employed as the solvent, a moderate yield (64–72%) was observed. Meanwhile, polar solvents such as tetrahydrofuran, chloroform, 1,4-dioxane, acetonitrile and DMF resulted in moderate to good

**Table 1** Solvent optimisation for Fe(MIL-53) MOF-catalysed synthesis of xanthene (**4a**)<sup>a</sup>



S. no.	Solvent	Yield <sup>b</sup> (%)
1	Methanol	85
2	Ethanol	98
3	IPA	89
4	Dioxane	80
5	ACN	58
6	DMF	88 <sup>c</sup>
7	Toluene	64 <sup>c</sup>
8	THF	82
9	CHCl <sub>3</sub>	74
10	Water	23 <sup>d</sup>
11	DCM	72
12	DCE	70

<sup>a</sup> Reaction conditions: benzaldehyde (0.71 mmol, 1.0 eq.), dimedone (1.42 mmol, 2.0 eq.), Fe(MIL-53) (25 wt%), solvent (2 mL), reflux, 3 h. <sup>b</sup> Isolated yield. <sup>c</sup> 100 °C. <sup>d</sup> MOF catalyst decomposed.







Fig. 3 Optimisation of catalyst (Fe(MIL-53) (1)) load for the synthesis of xanthene (4a).

under reflux conditions. With this mild and the reliable optimised reaction conditions in hand, to further unlock the potential of this catalyst for the synthesis of xanthene, its scope was extended to various aldehydes under the above-optimised condition, and the results are depicted in Table 2. Under the optimised reaction conditions, a series of aldehydes with different electronic natures was reacted with dimedone in the presence of 20 wt% of Fe(MIL-53) (1) as the catalyst in ethanolic medium. All the studied aryl aldehydes gave the respective xanthenes in good to excellent yield, and the products are presented in Table 2. Aldehydes containing electron-releasing substituents like methyl, methoxy, ethoxy, isopropyl and hydroxy (4c–4f and 4h) at the *para* position gave excellent yield of the corresponding xanthenes (94–97%), respectively; meanwhile, aldehydes possessing methyl and hydroxyl substituents on the *ortho* position (4b and 4g) resulted in a slight drop in the yield (89% and 92%, respectively) owing to steric factors. Similarly, aldehydes containing electron-withdrawing groups such as fluoro, chloro, bromo, nitro and cyano (4i–4k, 4n, and 4o) at the *para* position gave moderate to good yield (82–91%), while the same groups present at the *ortho* (4l) and *meta* (4m) positions showed a slight drop in the yield to 84% and 87%, respectively. In the case of di-substituted aldehydes (4p) with methoxy groups at the *para* and *meta* positions, they also resulted in good yield (91%). Fused ring systems like naphthyl (4q) and aryl aldehyde substituted with a reactive functional group such as boronic acid (4r) underwent the reactions smoothly and gave the respective xanthene derivatives in good yields of 90% and 92%, respectively.

Next, the scope was extended to aldehydes containing heterocyclic atoms like oxygen (4s), which underwent the reaction readily and produced oxygen-rich xanthene derivatives in moderate yield (85%); meantime, aldehydes containing nitrogen did not give the respective xanthene. The poor or no

reaction of the nitrogen-containing aldehyde is rationalised due to the coordination of the nitrogen atom with the active metal sites ( $\text{Fe}^{3+}$ ) present in the catalyst, which prevents the progress of the reaction. Notably, the optimised catalytic system was also compatible with aliphatic aldehyde, which gave the corresponding product 4t in good yield (93%). Further, to understand the efficiency of the catalyst in bulk production, the synthesis was scaled up to the one-gram scale under the identical optimised conditions, which gave excellent yield (94%) without any by-products or incomplete reaction. This scale-up also proved the efficiency of Fe(MIL-53) (1) MOF and present developed conditions for the industrial-scale production of xanthenes. According to the abovementioned substrate scope studies, they undoubtedly demonstrated that under the optimised conditions, the Fe(MIL-53) (1) MOF act as an efficient heterogeneous iron catalyst for the synthesis of a spectrum of xanthenes.

According to the screening and substrate scope studies, Fe(MIL-53) MOF (1) effectually catalysed the synthesis of a spectrum of xanthenes (4a–4t) with the minimum iron load under moderate conditions without the usage of any base, ligand or oxidant. However, to identify the role of iron present in the framework and prove its true inherent catalytic efficiency, the same xanthene synthesis was carried out using various other homogeneous iron sources under the present optimised reaction conditions, and the results are provided in Table 3. Initially, the iron source used for the synthesis of the Fe(MIL-53) MOF (1), iron nitrate (Table 3, entry 2), was employed as the catalyst. However, although the reaction proceeded under the optimised conditions, the yield was not impressive. A similar result was observed with other iron salts (entries 3–5, Table 3), and only poor product was produced, even after a longer reaction time (24 h). Furthermore, to understand the role of the framework metal in the synthesis of xanthene, other Lewis acid MOF catalysts were tested (Fig. 4).

Under the identical optimised reaction conditions, other transition metal-derived frameworks such as chromium [Cr(SO<sub>3</sub>H) MOF], nickel [Ni(HBTC)(BPY) MOF] and copper [Cu<sub>3</sub>(BTC)<sub>2</sub> MOF] were tested and compared in the present xanthene synthesis. However, although all the tested MOFs catalysed the formation of xanthene, the yield is not comparable to that of Fe(MIL-53) MOF. Among the screened MOFs, the copper-based MOF Cu<sub>3</sub>(BTC)<sub>2</sub> only gave a moderate yield (72%). Even another iron-MOF, Fe(BTC), gave only 80% of the product. This comparative study revealed the catalytic efficiency of the Fe(MIL-53) MOF (1) in the synthesis of xanthene. All the above-observed results from the control studies confirm that the  $\text{Fe}^{3+}$  present in the Fe(MIL-53) MOF (1) can efficiently catalyse the formation of xanthene derivatives. The observed results strongly evidenced that the unique characteristics of the Fe(MIL-53) MOF (1) such as high surface area, porous nature, and coordinatively unsaturated metal centre ligated by terephthalic acid are responsible for its high catalytic activity. Further, to prove its catalytic ability, another control experiment was performed using a 1 : 1 physical mixture of  $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ :



Table 2 Fe(MIL-53) (1) MOF-catalysed synthesis of xanthene derivatives<sup>a</sup>

Entry	Aldehyde	Xanthene	Yield <sup>b</sup> (%)
1	 2a	 4a	<sup>c</sup> 98%, 94% (Gram-scale synthesis)
2	 2b	 4b	89%
3	 2c	 4c	95%
4	 2d	 4d	97%
5	 2e	 4e	97%
6	 2f	 4f	94%
7	 2g	 4g	92%
8	 2h	 4h	95%



Table 2 (Contd.)

**Fe(MIL-53) (1)**  
(20 wt %)  
Ethanol, reflux, 2 h

**4a-t**  
(82-98%)

Entry	Aldehyde	Xanthone	Xanthene	Yield <sup>b</sup> (%)
9		<b>2i</b>		<b>4i</b> 89%
10		<b>2j</b>		<b>4j</b> 91%
11		<b>2k</b>		<b>4k</b> 90%
12		<b>2l</b>		<b>4l</b> 84%
13		<b>2m</b>		<b>4m</b> 87%
14		<b>2n</b>		<b>4n</b> 89%
15		<b>2o</b>		<b>4o</b> 82%
16		<b>2p</b>		<b>4p</b> 91%



Table 2 (Contd.)

Entry	Aldehyde	Xanthene	Yield <sup>b</sup> (%)
17			90%
18			92%
19			85%
20			93%

<sup>a</sup> Reaction conditions: aldehyde (0.71 mmol, 1.0 eq.), dimedone (1.42 mmol, 2.0 eq.), Fe(MIL-53) (20 wt%), ethanol (2.0 mL), reflux (80 °C), 2 h. <sup>b</sup> All are isolated yields. <sup>c</sup> Gram-scale synthesis.

terephthalic acid (precursors of Fe(MIL-53) MOF) as a catalyst in xanthene synthesis under the optimised conditions. The physical mixture also catalysed the reaction but only gave 17% yield. This catalytic performance of the physical mixture unambiguously confirms that the presence of the framework is responsible for the high catalytic efficiency in the synthesis of xanthene derivatives.

After successfully exploring the true catalytic efficiency of the present catalyst **1**, it was necessary to understand the stability of the heterogeneous catalyst under the screened reaction conditions, and thus hot filtration studies were carried out under the optimised conditions. During the heterogeneity test, the catalyst was removed from the reaction medium by simple filtration after 30 min under hot conditions.

Aliquots of the reaction mixture were subjected to HPLC analysis at 30 min. Extended intervals showed no further increase in the yield (Fig. 5). The hot filtration test strongly evidenced that the catalyst is highly stable and acts in a truly heterogeneous manner under the optimised reaction conditions without breaking or deforming the framework of Fe(MIL-

53) (**1**). The result obtained from the hot filtration studies was strongly endorsed by the inductively coupled plasma optical emission spectroscopy (ICP-OES) measurements of the filtrate from the reaction mixture in ethanol. The catalyst was filtered from the reaction medium after 30 min, and then the filtrate was subjected to ICP-OES analysis, where no proof of iron leaching was observed, manifesting the true heterogeneity of the Fe(MIL-53) MOF (**1**).

The reusability aspect determines the stability and sustainability of a heterogeneous catalyst. This is considered one of the indispensable parameters for a reliable heterogeneous catalytic system. Due to this, the catalyst was recovered by simple filtration at the end of the reaction, dried under vacuum at 120 °C for 2 h and reused. This procedure was repeated at the end of each cycle, and the recovered catalyst was reused up to 5 times without any remarkable loss in its activity (Fig. 6). In addition, the stability of the catalyst was confirmed by subjecting the recovered catalyst to analytical confirmations such as FTIR, powder XRD and SEM.



Table 3 Effect of different iron sources in xanthenone (4a) synthesis<sup>a</sup>


Entry	Iron source	Yield <sup>b</sup> (%)
1	—	—
2	Fe(NO <sub>3</sub> ) <sub>3</sub> · 9H <sub>2</sub> O	22 <sup>c</sup>
3	FeCl <sub>3</sub>	38 <sup>c</sup>
4	Fe <sub>3</sub> O <sub>4</sub>	29 <sup>c</sup>
5	Fe(III)acac	35 <sup>c</sup>
6	Fe(MIL-53)	98 <sup>d</sup>

<sup>a</sup> Reaction conditions: catalyst (0.71 mmol), benzaldehyde (0.71 mmol, 1.0 eq.), dimedone (1.42 mmol, 2.0 eq.), ethanol (2.0 mL), reflux.

<sup>b</sup> Isolated yield. <sup>c</sup> 24 h. <sup>d</sup> Catalyst (20 wt%).



Fig. 5 Hot filtration test for understanding the true heterogeneity of Fe(MIL-53) MOF (1).

The recovered catalyst was analysed by FTIR spectroscopy before the next catalytic cycle. The FTIR analysis of the reused catalyst showed that the vibrational bands are almost identical to the as-synthesised MOF without the appearance of any new peaks, even after reusing five times. In the FTIR spectrum of Fe-MIL-53 (1) (Fig. 7), the absence of strong vibrational bands in the range of 1760–1690 cm<sup>-1</sup> confirmed that the framework did not undergo any decomposition under the reaction conditions, and the carboxylate groups are still coordinated with the iron metal centre and exist as organic linkers coordinating with the secondary building units.

The observed stability results of the recovered catalyst from FTIR were further supported by the PXRD analysis. The powder XRD patterns of the recovered catalyst are identical to the fresh catalyst even after five consecutive reuses.

The presence of sharp diffraction patterns located nearly at  $2\theta = 12.68^\circ$  and  $25.44^\circ$  (Fig. 8) indicates that the reused MOF



Fig. 6 Reusability profile of Fe(MIL-53) MOF (1) for the catalytic synthesis of xanthenone (4a).



Fig. 4 Optimisation of different MOFs as catalysts for the synthesis of xanthenone (4a). <sup>a</sup>Reaction conditions: catalyst (20 wt%), benzaldehyde (0.71 mmol, 1.0 eq.), dimedone (1.42 mmol, 2.0 eq.), ethanol (2.0 mL), reflux. Reaction monitored by HPLC.





Fig. 7 FTIR spectra of fresh Fe(MIL-53) MOF (a) and reused Fe(MIL-53) MOF after the second run (b) and fifth run (c).



Fig. 8 Powder XRD patterns of fresh Fe(MIL-53) MOF (a) and reused Fe(MIL-53) MOF after the second run (b) and fifth run (c).

catalyst retained its crystalline nature, and the absence of any new peaks also confirmed this.

Further, the SEM analysis supports the observed stability of the reused catalyst in the PXRD analysis. The fresh Fe(MIL-53) MOF is highly crystalline in nature, with a rod-like shape and a porous and rough surface (Fig. 9). The SEM images of the reused catalyst appeared highly crystalline, and the same

morphology and rod-like shape were retained in the fifth reused catalyst. This strongly disclosed that the reaction conditions, solvent and the formed products did not affect the surface morphology of the catalyst, which was responsible for retaining the catalytic efficiency of the Fe(MIL-53) MOF (1) even after several reuses.

All the above-mentioned analytical, experimental and reusability studies of the Fe(MIL-53) (1) catalyst strongly evidenced the true heterogeneity and sustainable nature of the catalyst in heterocycle synthesis. Considering this fabulous efficiency of the Fe(MIL-53) MOF (1), it can be employed as a catalyst for the synthesis of xanthenes.

Further, a plausible mechanism (Scheme 1) has been proposed to understand the catalytic nature based on the literature reports.<sup>62–65</sup> The presence of a large surface area and high density of coordinatively unsaturated open Fe<sup>3+</sup> are highly responsible for the high catalytic efficiency of Fe(MIL-53) (1). The presence of a high density of open Fe<sup>3+</sup> in the secondary building unit and its inherent Lewis acidic nature initiate the catalytic cycle. The electron-rich oxygen on the carbonyl carbon of the benzaldehyde (2) coordinated with the Lewis acidic Fe<sup>3+</sup>, enhancing the nucleophilicity of the carbonyl carbon. The coordinated benzaldehyde (2) undergoes Knoevenagel condensation with a dimedone (3) molecule, followed by the elimination of a water molecule and an intermediate (I). After the formation of the Knoevenagel condensation intermediate, another molecule of dimedone attacks the condensed intermediate, resulting in the Michael addition product (III). Then, the intermediate (III) undergoes internal cyclisation to form (IV), which upon elimination of water, forms the desired product (4a) and the catalyst Fe(MIL-53) MOF (1) also gets regenerated and ready for another catalytic cycle.

Table 4 summarises several catalytic systems reported for the synthesis of xanthene derivatives. The peculiarity of Fe(MIL-53) MOF (1) is justified based on its selectivity in the synthesis of xanthenes over other existing systems, which is excellent in comparison with the other reported homogeneous and heterogeneous catalysts. The present Fe(MIL-53) MOF (1) exhibits enhanced catalytic activity regarding the catalyst load, reaction time, temperature and selectivity for this reaction. Furthermore, Fe(MIL-53) MOF (1) is highly stable, reusable, and feasible for the scaled-up synthesis of xanthenes.



Fig. 9 SEM images of fresh (1) (a) and reused Fe(MIL-53) MOF after fifth run (b–d).





Scheme 1 Plausible mechanism for the Fe(MIL-53) MOF (1)-catalysed synthesis of xanthene (4a).

Table 4 Comparison of catalytic potential of Fe(MIL-53) MOF (1) in the synthesis of xanthene derivatives<sup>a</sup>

Entry	Catalyst	Solvent	Catalyst load	Temp (°C)	Time	Yield (%)	Reusability	Ref.
1	FeCl <sub>3</sub> ·6H <sub>2</sub> O	[bmim][BF <sub>4</sub> ]	0.1 mmol	80	6 h	92	5	18
2	Fe <sub>3</sub> O <sub>4</sub> NPs	EtOH	0.1 mmol	rt	2.45 h	82	5	33 <sup>c</sup>
3	Indium triflate [In(CF <sub>3</sub> SO <sub>3</sub> ) <sub>3</sub> ]	Neat	0.02 mmol		1 h	95	5	17
4	<i>p</i> -Toluene sulfonic acid	Toluene	0.07 mmol	110	30 min	82	—	23 <sup>b</sup>
5	Nano-Fe <sub>3</sub> O <sub>4</sub> -TiO <sub>2</sub> -SO <sub>3</sub> H ( <i>n</i> -FTSA)	Neat	0.01 g	110	50 min	90	5	27
6	Fe <sub>3</sub> O <sub>4</sub> @NFC@NNSM-Mn(III)	EtOH	0.5 mol%	45	10 min	98	6	28 <sup>c</sup>
7	Fe <sub>3</sub> O <sub>4</sub> @SiO <sub>2</sub> @APTES@MPIB-Mn(II)	Neat	0.05 g	100	10 min	100	6	29
8	TMP-PECH-COOH polymer	Water	8 mg	50	10 min	97	6	30
9	CuCeO <sub>2</sub> NPs	Water	10 mol%	80	12 min	98	5	31
10	ZrO <sub>2</sub> NPs	Neat	20 mg	100	20 min	85	5	32
11	Cu(II) NPs	EtOH	0.2 g	Reflux	3.5 h	98	5	34
12	CuS quantum dots	Neat	6 mg	80	6 min	95	5	35
13	Amberlyst-15	CH <sub>3</sub> CN	200 mg	Reflux	5 h	92	3	36
14	NaHSO <sub>4</sub>	[bmim]BF <sub>4</sub>	0.2 mmol	100	1 h	93	5	20
15	Fe-MIL(53)	EtOH	20 wt%	80 (reflux)	2 h	98	5	This work

<sup>a</sup> NPs-nanoparticles, 1-*n*-butyl-3-methylimidazolium tetrafluoroborate-[bmim]BF<sub>4</sub>. <sup>b</sup> *N*-tosylhydrazone. <sup>c</sup> carboxylic acid.

### 3. Conclusions

In summary, a simple, facile, economical and efficient methodology for the synthesis of xanthenes was developed using an iron-based metal-organic framework Fe(MIL-53) (1) as a sustainable heterogeneous catalyst. The presence of coordinatively unsaturated Fe<sup>3+</sup> in the secondary building unit catalyses the present heterocyclic synthesis through its inherent Lewis acidic nature. This catalyst offers a straightforward

catalytic methodology to access a wide range of xanthene derivatives without any influence from the electronic nature of the substituents on aldehydes. The catalyst could be easily recovered by simple filtration and reused up to five times without any remarkable loss in its activity. The hot filtration test proved the stability and true heterogeneity of the catalyst. This Fe(MIL-53) MOF (1) replaces the homogeneous and non-reusable Lewis acid catalyst and acts as a solid-heterogeneous Lewis acid catalyst, replacing iron-salt-based catalysts. A





## Conflicts of interest

There are no conflicts to declare.

## Data availability

All the data from the research article are available in the SI. See DOI: <https://doi.org/10.1039/d5su00191a>.

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