

SYNTHESIS OF MIXED-METAL MIL(Ti-Fe) FROM VIETNAM ILMENITE ORE AND ITS APPLICATION FOR DEGRADATION OF DYE

Nguyen Thi Hoai Phuong^{1*}, Nguyen Ba Quan², Nguyen Thi Phuong¹,
Nguyen Ba Cuong², Tran Van Chinh¹

Abstract: In this work, the mixed-metal metal-organic frameworks MIL(Ti-Fe) were synthesized by the hydrothermal method. MIL(Ti-Fe) hybrid material was fabricated from ilmenite ore and 1,3,5-benzene tricarboxylic acid at a temperature of 130 °C for 24 hours. The prepared material was characterized by using scanning electron microscopy (SEM), X-ray diffraction (XRD), infrared spectroscopy (IR), and Brunauer-Emmett-Teller (BET) surface area. The obtained MIL(Ti-Fe) particles have a diameter of from 0.2-1.0 μm with a BET surface area of 85.482 $\text{m}^2 \text{g}^{-1}$. The influence of various vital parameters such as pH of the dye solution, initial dye concentration, adsorption time, and amount of the catalyst on the dye removal efficiency was investigated. The photocatalytic degradation rate of Rhodamine B was found to be 0.0074 min^{-1} at pH 7. The maximum removal of Rhodamine B was obtained at the catalyst dose of 1.0 g L^{-1} . Under simulated sunlight irradiation, the resultant mixed-metals MOFs showed high photodegradation toward Rhodamine with degradation efficiency of approximately 99.97% after 6 hours. Furthermore, the resultant materials also showed remarkable absorption behavior toward Rhodamine B with the adsorption capacity of 70 mg g^{-1} .

Keywords: MIL-125(Ti); Photocatalytic degradation; Rhodamine B; Ilmenite ore.

1. INTRODUCTION

The discharge of wastewater containing dye causes many environmental issues such as hampering sunlight, reduction of dissolved oxygen in water, breaking off the reoxygenation processes of the aquatic system, increasing toxicity, enlarging chemical oxygen demand index (COD), biochemical oxygen demand index (BOD), etc. [1]. Moreover, dyes can cause allergies, dermatitis, skin irritation, carcinogenic and mutagenic actions, acute and chronic toxicity to humans [2]. So, the dye-containing wastewater needs to be treated before discharge in order to protect the environment. Many processes for treating dye waste, including biological treatment, catalytic oxidation, filtration, sorption process, and combination treatments, have been proposed [3]. Adsorption has been demonstrated as a practical pathway to treat dye-containing wastewater because of its high treatment performance, cost-effectiveness, and simplicity in operation. The selection of appropriate adsorbents is vital for the effective removal of dye from the aqueous solution.

In recent years, metal-organic frameworks (MOFs), which are constructed from metal ions or clusters and organic ligands, have attracted great attention for their promising applications in many areas such as gas storage and separation [4], sensor [5], drug delivery [6], energy storage and conversion [7], catalysis [8], environmental pollution treatment [9], etc. Metal-organic frameworks were chosen to be a potential alternative because they possess an attractive semiconductor property. Different molecular functional components are integrated to bring out the incident light and even various photocatalytically driven chemically useful reactions [10]. The development of MOF as photocatalyst is from ultra-violet (UV) light-driven to visible-light-driven. Mixed-metal

MOFs are metal-organic frameworks that contain at least two different metal ions as nodes in their frameworks. These materials could be facilely prepared by either a one-pot synthesis with a synthesis mixture containing the different metals or a post-synthetic ion-exchange method [11]. Although the investigation of new MOF materials is still in the early stage, several promising applications from these materials have been reported, revealing higher performance than conventional mono-metallic MOFs. Significantly, these mixed-metal MOFs showed high photocatalytic activity compared to the single metal MOFs [12].

Iron-based metal-organic frameworks (MIL-Fe) are gradually developing into an independent branch in environmental remediation due to their economical, practical, and low toxic materials. Jing-Jing Du et al. [13] first used MIL-53(Fe) MOF in the year 2011 for the decolorization of methylene blue (MB) dye. The result showed that after 40 min of UV-vis light and visible light, MIL-53(Fe) degraded 3% of MB, which showed low photocatalytic activity. Lunhong Ai et al. [14] discussed the capability of MIL-53(Fe) for the activation of H₂O₂ in order to increase the efficiency of the photocatalytic degradation of Rhodamine B (RhB) dye under visible light irradiation. Guest et al. [15] synthesized MIL-100(Fe) for the photocatalytic degradation of methyl orange (MO) dye in water under both ultraviolet and solar light radiation. It was found that only 64% of 5 ppm MO was photo-catalytically degraded under UV light irradiation for 7 h. In contrast, solar light was able to degrade only 40% of 5 ppm of MO. Mahmoodi et al. [16] prepared MIL-100(Fe) to degrade Basic Blue 41 using a UV-C lamp as an irradiation source. It was found that the reaction followed the first-order kinetics model, and the catalyst was recovered and reused for three runs.

On the other hand, titanium is considered one of the most appealing metal nodes for constructing MOFs with high chemical stability and structural engineering. The high stability of Ti-based MOFs could also be obtained from Ti-oxo-carboxylate SBUs with strong Ti-O bonds [17]. Wang et al. [18] used UiO-66(Ti) nanocomposite as a photocatalyst to degrade MB dye under sunlight. The optimum degradation of MB was shown by UiO-66(1.25Ti) with an efficiency of 82.2%. Li et al. [19] synthesized a visible-light-driven photocatalyst TiO₂ encapsulated in salicylaldehyde NH₂-MIL-101(Cr). MB dye was photo-degraded using this photocatalyst under visible light irradiation, which was found that the degradation efficiency was as high as 86% in 60 min.

The combination of at least two metals in the MOFs framework could utilize the properties of these metals, which enable the higher performance of the resultant MOFs. A novel Ti-Fe mixed-metal organic framework was synthesized by Weiyi Ouyang and showed significant improvement in light absorption compared with MIL-125 (Ti). This material shows potential in the application as a photo-catalyst [20].

Ilmenite is one of the essential sources for titanium and titanium dioxide, which is used in paints, printing inks, fabrics, plastics, paper, sunscreen, food, and cosmetics. In Vietnam, titanium placers are discovered along the coast of the Middle, spreading across provinces from Thanh Hoa to Ba Ria - Vung Tau. Ilmenite consists of the following main components as TiO₂ (48.50-53.00%) and FeO (39.96-44.78%) [21]. The ore is a valuable source of two metal ions (titanium and iron) synthesizing MIL(Ti-Fe).

In this study, mixed-metal MOFs (MIL Ti-Fe) will be synthesized by a simple

hydrothermal approach from ilmenite ore. The simulated absorption and photocatalytic behaviors of the resultant MOFs toward Rhodamine B are investigated.

2. MATERIALS AND METHOD

2.1. Synthesis of MIL(Ti-Fe)

A mixture of 10 g milled ilmenite ore, and 70 g KHSO_4 was calcined at 600 °C for two hours. The calcinated mixture was dissolved in 100 ml of H_2SO_4 10 % solution, and removed insoluble compounds were to obtain a solution containing TiOSO_4 and FeSO_4 .

1,4-benzene dicarboxylic acid (BDC) as an organic linker was used to synthesize mixed-metal MOFs by hydrothermal method. 0.42 g of BDC were dissolved in 100 ml of a solution containing TiOSO_4 and FeSO_4 , loaded into a Teflon-lined steel autoclave, and heated under autogenous pressure at 130 °C for 24 hours. After that, the solution was centrifuged. The material was purified in boiling DMF, washed with ethanol/water mixture (ratio of 1/1), and dried at 80 °C for 4 hours.

2.2. Characterization

The powder X-Ray diffraction (XRD) patterns of the MIL(Ti-Fe) were recorded on an X'Pert Pro analyzer with CuK_α radiation X-ray source voltage of 40 kV and electron beam current of 100 mA with scanning angle 2θ from 5 to 90°. Scanning electron microscopy (SEM) was conducted using HITACHI S-4600 (Japan). N_2 adsorption-desorption isotherm (BET) analysis of MIL(Ti-Fe) was conducted on equipment TriStar II 3020 Version 3.02 at 77 K and using N_2 adsorbate. The functional groups of the samples were investigated with Fourier transform infrared spectroscopy (IR) (FT-IR TENSOR II, Bruker).

2.3. Adsorption and catalysis studies

The whole adsorption experiments were performed in the form of batch adsorption. The 1000 mg/L stock solution of Rhodamine B was obtained by dissolving 1 g of Rhodamine B powders into distilled water. The different concentrations of Rhodamine B solution used in adsorption experiments were prepared by diluting the stock solution. All adsorption experiments were performed at a constant temperature in the dark for 24 hours. The 20 ml solution of Rhodamine B (different concentrations), MIL(Ti-Fe) (the content of 1 mg/mL) was kept in a transparent glass tube. At certain time intervals, the suspensions were collected and centrifuged to remove the products. The concentrations of Rhodamine B were tested using a Drawell D8200 UV-Vis spectrophotometer. The band intensity for calibration was chosen at 552 nm. The adsorption capacity of adsorbents was calculated according to the following formula:

$$q_e = ((C_0 - C_e)V)/m \quad (1)$$

Where C_0 (mg/L) is the initial concentrations of Rhodamine B, C_e (mg/L) is the equilibrium concentrations, and (g) is the mass of adsorbents and V (L) is the volume of Rhodamine B solutions.

In photo-catalyst experiments, simulated sunlight irradiation was provided using Photo-catalytic Reaction Chamber 350 with a 350 W Xenon lamp. The content of material and Rhodamine B solution volume used the same previous one. The degradation performances were calculated according to the following formula:

$$H = ((C_0 - C_e) / C_0) \times 100 \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. Material characterizations

The XRD pattern studied the crystal structure of the material after removing solvent from pores. The XRD pattern of MIL(Ti-Fe) is presented in figure 1.

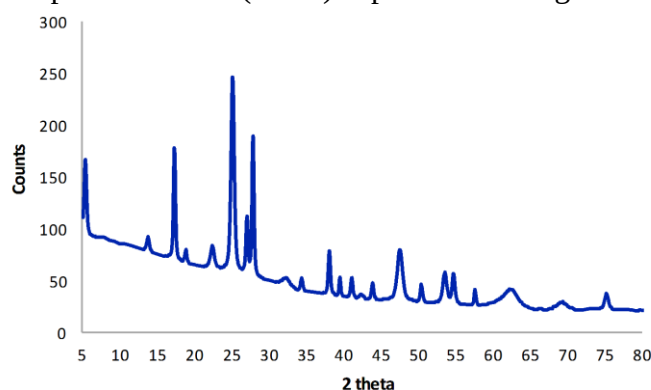


Figure 1. The XRD pattern of MIL(Ti-Fe).

To get insights into the crystallographic structure of the as-prepared materials, the XRD patterns of mixed-metal MOFs were compared with the single metal MOFs of Ti-BDC and Fe-BDC. As seen in fig. 1, the diffraction peaks of MIL-125(Ti) didn't appear at 2θ of 6.79, 9.83, 11.69, 15.06, 15.45, 16.63, 17.92, 19.07, 19.64 and 22.65° [22]. It was meant that no diffraction peaks of MIL-125(Ti) were observed in XRD patterns of MIL(Ti-Fe). Almost crystal plane of Fe-BDC at 9.27, 11.1, 16.3, 18.1, and 22.3° [23] also missed, and new peaks at 5.346, 17.275, 25.066, 26.986, and 27.792° appeared evidently. The material grew into different crystal structures when iron and titanium were used together in the synthesized process.

Table 1. The lattice parameters of MIL(Ti-Fe).

Lattice parameters, Å		$2\theta, ^\circ$	Hkl	FWHM (β)	Crystallite size (D), nm
a (Å)	c (Å)				
16.546	16.532	5.346	100	0,3936	211.023
		17.275		0,2952	284.282
		25.066		0,492	172.752
		26.986		0,2952	289.037
		27.792		0,2952	289.533
		Average crystalline size			249.325

Table 1 shows the lattice parameters and the average crystallite size of MIL(Ti-Fe), which were calculated from FWHM of XRD peaks at 5.346, 17.275, 25.066, 26.986 and 27.792°, 2θ position using Scherer formula given in the following equation:

$$D = \frac{0.94\lambda}{\beta \cos \theta}$$

where D is the average crystalline size, λ is a wavelength in Å, β is the FWHM in radian, and θ is diffraction angle in degree. The average crystallite size of MIL(Ti-Fe) was 249.325 nm.

Figure 2 showed the FT-IR spectra of MIL(Ti-Fe) in the range of 400-4000 cm^{-1} . It can be exhibited that a broad peak at 3360.97 cm^{-1} due to the -OH stretching mode respectively in the FT-IR spectra of MIL(Ti-Fe).

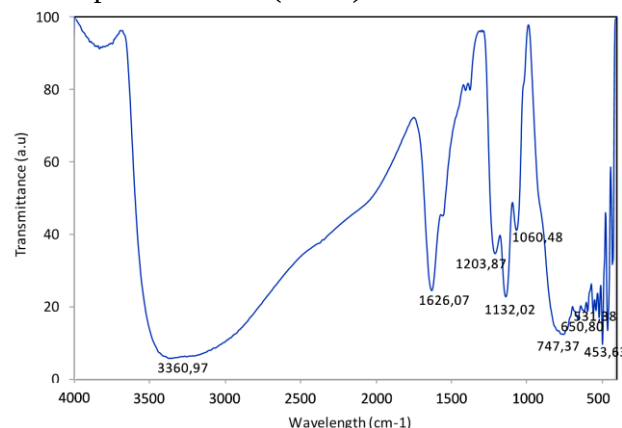


Figure 2. The FT-IR spectra of MIL(Ti-Fe).

Another peak related to adsorb water was observed at 1626.07 cm^{-1} , assigned to the bending band of the -OH group. The FTIR spectrum also shows the characteristic of the aromatic group by the stretching vibration of C=C and -C-C from the aromatic ring (triple peak at 1203.87, 1132.02, and 1060.48 cm^{-1}) [24]. The peak at 747.37 cm^{-1} corresponds to C-H bonding vibrations of the benzene rings. The presence of $\nu(\text{Fe-O})$ at 531.38 cm^{-1} , indicating the formation of a metal-oxo bond between the carboxylic group of terephthalic acid and the Fe(III) [25]. The region below that peak is characterized by the vibration stretching bands (centered at 650.80 cm^{-1}) of -Ti-O-Ti clusters and a peak at 453.63 cm^{-1} , corresponding to the bending vibration of these metal clusters [26]. Moreover, the peaks at the band from 400.0 to 800.0 cm^{-1} were also attributed to the Ti-O and Fe-O stretching modes, respectively, indicating the formation of a metal-oxo bond between the carboxylic group of BDC and iron/titanium ions in MIL(Ti-Fe) particles [24].

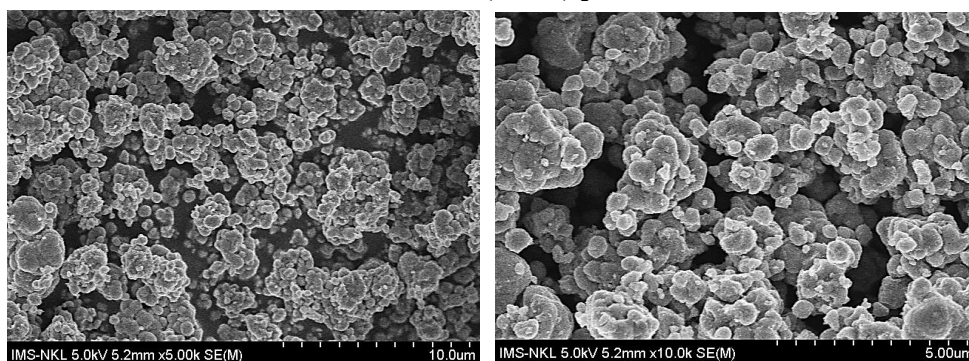


Figure 3. The SEM image of MIL(Ti-Fe).

The morphology of synthesized MIL(Ti-Fe) and its size were studied by SEM, as shown in fig. 3. The morphology of Ti was reported as thin disk-like shapes in the literature [27]. The introduction of Fe seems to have no relevant effect on the morphology of the resulting MOF. However, the appearance of Fe provoked significant size changes. In the case of the MIL(Ti-Fe) sample, disc-shaped particles were also obtained, although not so well-defined as MIL-125(Ti) [28] and with a multi-size (around 200 nm - 1.0 μm).

It seems that an amount of Fe prevents the formation of the MIL-125(Ti) crystalline structure. Probably other synthesis conditions, namely temperature or duration of the treatment, may lead to the formation of multi sizes of crystals.

The specific surface areas of the MIL(Ti-Fe) were measured by BET analysis, and the corresponding pore-size distribution curves were displayed. Accordingly, BET-specific surface areas results indicate that the MIL(Ti-Fe) represents a type-IV isotherm curve with a mesoporous structure. The particular surface area of MIL(Ti-Fe) is $85.482 \text{ m}^2\text{g}^{-1}$. In addition, its pore size values from 3.097 nm to 4.288 nm, and the pore volume is from $0.032 \text{ cm}^3\text{g}^{-1}$ to $0.056 \text{ cm}^3\text{g}^{-1}$. The pore size can indicate the formation of mesoporous materials.

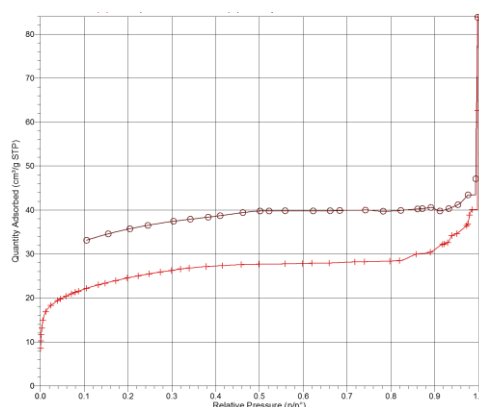


Figure 4. The linear isotherm plot of MIL(Ti-Fe).

3.2. Rhodamine B adsorption

The effect of different initial contact time was investigated, and the result was showed table 2. The adsorption data of MIL(Ti-Fe) were fitted well with a pseudo-second-order model on $R^2 = 0.9986$ (fig. 5). It suggested that the rate-limiting step in the adsorption process might be the chemisorption [29]. The adsorption of Rhodamine B onto the MIL(Ti-Fe) fitted well with Langmuir and Freundlich isotherm models (table 3), which confirms the surface adsorption sites on adsorbents were homogeneous distribution and the adsorption of Rhodamine B on the MIL(Ti-Fe) material might occurred in the monolayer model.

Table 2. The effect of different initial contact time on the adsorption capacity of MIL(Ti-Fe) for Rhodamine B.

t (min)	0	60	120	240	360
C_t (mg/L)	10	8.997	8.687	8.589	8.480
q_t (mg/g)	0	2.006	2.626	2.822	3.040
H (%)	0	10.03	13.13	14.11	15.20

Table 3. Langmuir and Freundlich isotherms parameters for Rhodamine B adsorption on MIL(Ti-Fe).

Isotherm models	Parameters	Value
Langmuir	$q_{\max, \text{exp}}$ (mg/g)	2.2083
	$q_{\max, \text{cal}}$ (mg/g)	2.7739
	K_L (L/mg)	0.167
	R^2	0.9963
Freundlich	K_F	0.515
	$[(\text{L/mg})^{1/n} \cdot \text{mg/g}]$	0.7321
	$1/n$	0.9986
	R^2	

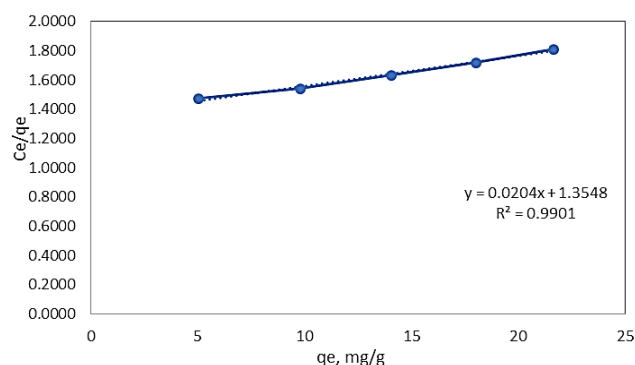


Figure 5. The maximum adsorption capacity of MIL(Ti-Fe) for Rhodamine B.

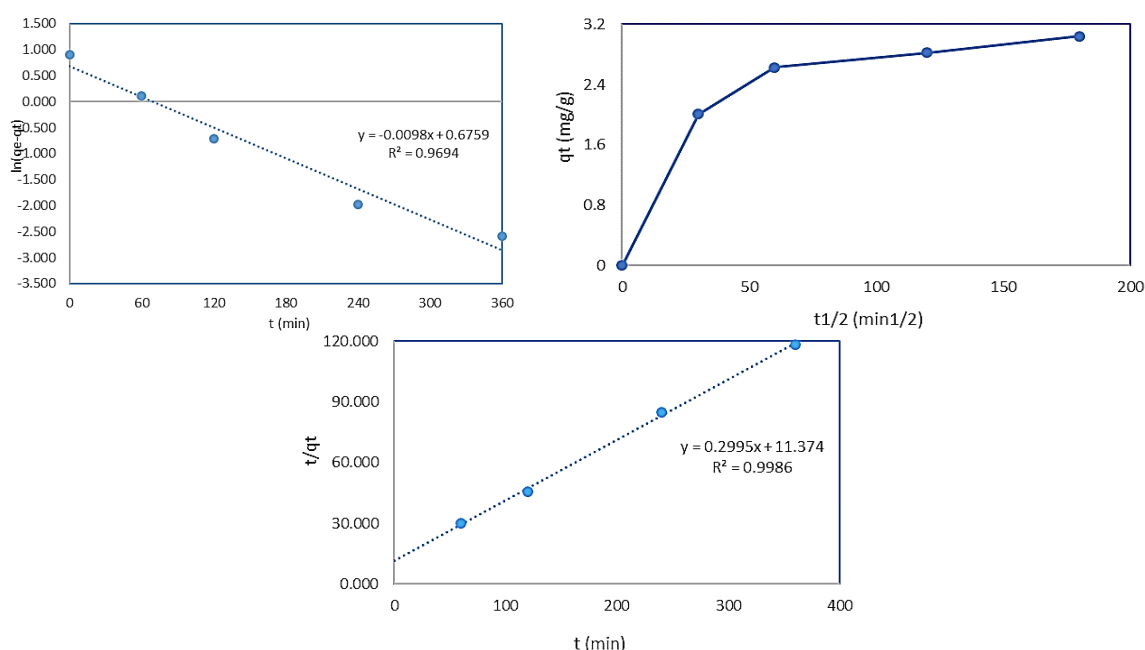


Figure 6. The pseudo-first-order model (a) pseudo-second-order model (b) and intra-particle diffusion model (c) for Rhodamine B adsorption.

The effect of different temperatures was assessed for adsorption experiments. With the increase of temperature, the adsorption rate of MIL(Ti-Fe) material increased obviously, but the temperature had a slight effect on the equilibrium adsorption capacity of MIL(Ti-Fe) sample. To better evaluated the effect of temperature, the thermodynamic parameters of enthalpy change (ΔH), Gibbs free energy (ΔG), and entropy change (ΔS) could be calculated according to the following equations [30]:

$$\Delta H = RT \cdot (\ln C_e - K_L) \quad (3)$$

$$\Delta G = -RT \cdot \ln K_a \quad (4)$$

$$\Delta S = (\Delta H - \Delta G)/T \quad (5)$$

$$K_a = 106K_L \quad (6)$$

In equations: R is the gas constant (8.314 J/mol.K); T (K) is thermodynamic temperature; K_a is the thermodynamic equilibrium constant; K_L (L/mg) is Langmuir equilibrium constant.

Table 4. The thermodynamic parameters of Rhodamine B adsorption on MIL(Ti-Fe) material.

T (K)	ΔG (kJ.mol ⁻¹)	ΔH (kJ.mol ⁻¹)	ΔS (kJ.mol ⁻¹ .K ⁻¹)
298	- 29.789	4.567	0.115
308	- 30.799	-	-
318	- 31.799	-	-
328	- 32.799	-	-
338	- 33.799	-	-

As shown in table 4, the ΔG values were negative, which illustrated that the Rhodamine B adsorption over MIL(Ti-Fe) sample was spontaneous and thermodynamically favorable. Furthermore, with the increase of temperature, the values of ΔG decreased, which confirmed that the adsorption process at higher temperature might promote Rhodamine B adsorption onto adsorbents. The Rhodamine B adsorption over MIL(Ti-Fe) material could be due to a physicochemical adsorption process [22]. Moreover, with the positive ΔH values, Rhodamine B adsorption is considered a typical endothermic process. The positive ΔS values demonstrated that increased randomness occurred at the solid-liquid interface. In meaning, the Rhodamine B adsorption process on MIL(Ti-Fe) was endothermic and spontaneous.

Table 5. The effect of dye concentration on dye removal by MIL(Ti-Fe).

C_0 , mgL ⁻¹	9,675	19,531	29,265	38,720	48,975
C_e , mgL ⁻¹	7,467	15,609	23,950	32,128	41,310
H, %	22,82	20,08	18,16	17,03	15,65

The adsorption performance is depended on its initial dye concentration [31]. Table 5 shows the effect of dye concentration on dye removal by MIL(Ti-Fe). Dye removal at different initial dye concentrations including 10, 20, 30, 40 and 50 mgL⁻¹ was 22.82, 20.08, 18.16, 17.03 and 15.65 % for Rhodamine B, respectively. The data presented that dye removal decreased with increasing dye concentration. It can be attributed that at fixed adsorbent dosage, the adsorption sites are constant. At a low initial concentration (10 mgL⁻¹), dye removal is intense and reaches equilibrium fast. At higher dye concentration, dye removal decreases due to saturation of adsorption active sites of adsorbent and dye aggregation.

3.3. Performance evaluation of Rhodamine B degradation

To evaluate the impact of various factors on the Rhodamine B degradation in aquatic media, the Langmuir-Hinshelwood models were employed [32]. The equations relating to the Langmuir-Hinshelwood models are classified as first-order estimated by the equation $\ln(C_0/C_t) = k_{app}t$, where C_0 is expressed as the initial concentration of Rhodamine B (mgL⁻¹), C_t is the residual concentration of Rhodamine B at time t (min), K_{app} is the apparent reaction rate constant. Considering that, the apparent kinetic rate constants and the corresponding correlation coefficients (R^2) of MIL(Ti-Fe) material under different variables are tabulated in table 6.

In the current study, the impact of change in the pH values on the degradation of Rhodamine B was evaluated (table 5). The effect of initial pH on the Rhodamine B degradation was assessed at various pHs of 3.0, 5.0, 7.0, 9.0, and 11.0. As shown in table

4, it can be seen that the degradation rate of Rhodamine B dramatically decreased with an increase or decrease in pH values out of 7.0. The photocatalytic degradation of Rhodamine B was evaluated by varying the content of MIL(Ti-Fe) at pH 7 under solar-driven light irradiation. As depicted in table 4, the degradation of Rhodamine B increases along with the increase of catalyst amounts from 0.5 to 1.5 g L⁻¹, and the maximum removal of Rhodamine B was obtained at 1.0 g L⁻¹. On the contrary, a further increase in the catalyst amounts of higher than 1.0 g L⁻¹ resulted in a reduction in removal efficiency. As can also be deduced in table 4, the degradation rate of Rhodamine B is also attributed to the escalation of photo-catalytic activity with increasing of the photo-catalyst dosage from 0.5 g L⁻¹ ($k = 0.0014$) to 1.0 g L⁻¹ ($k = 0.0074$). These observations are well consistent with the previous study in which an increase in the amounts of the catalyst resulted in the reduction of light penetration in the aqueous solution [33].

Table 6. Kinetics of photocatalytic degradation of Rhodamine B under different conditions.

Condition		K_{app} (min ⁻¹)	R^2
pH	3	0.0007	0.9954
	5	0.0010	0.9912
	7	0.0074	0.9980
	9	0.0006	0.9938
	11	0.0005	0.9641
Dosage (g L ⁻¹)	0.50	0.0014	0.9935
	0.75	0.0021	0.9993
	1.00	0.0074	0.9980
	1.25	0.0029	0.9826
	1.50	0.0026	0.9687

The effects of pH of the solution, initial Rhodamine B concentration, and catalyst dosage on the photocatalytic activity of the prepared photocatalysts were assessed by monitoring the degradation of Rhodamine B in aqueous media. The optimization results indicated that the MIL(Ti-Fe) exhibited good photocatalytic activity for the degradation of Rhodamine B compared with other catalysts. Additionally, the optimum values for pH and catalyst dosage were found to be 7 and 1.0 g L⁻¹, respectively.

4. CONCLUSIONS

In summary, mixed metal MIL(Ti-Fe) metal-organic framework as photocatalyst for the photo-degradation of Rhodamine B was successfully developed. The prepared mixed metal MIL(Ti-Fe) MOF is of particle shape with the size ranging from 0.2-1.0 μm and a BET surface area of 85.482 m² g⁻¹. The resultant MOFs show high photodegradation of the Rhodamine B under simulated light irradiation with the RhB degrading rate of 7.4×10^{-3} min⁻¹ at catalyst dose of 1.0 g L⁻¹ and pH of 7. The MIL(Ti-Fe) materials also reveals the remarkable adsorption capacity toward RhB with the maximal capacity of 70 mg g⁻¹. Due to outstanding characteristics of the joint MIL(Ti-Fe) photo-catalyst such as photo-catalytic activity, satisfactory stability, they could be potentially used as a good candidate for the degradation of organic pollutants in environmental waters.

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TÓM TẮT

TỔNG HỢP KHUNG HỮU CƠ-KIM LOẠI (Ti-Fe) TỪ QUẶNG ILMENITE VIỆT NAM VÀ ỨNG DỤNG TRONG XỬ LÝ NƯỚC

Trong bài báo này, khung hữu cơ kim loại hỗn hợp MIL(Ti-Fe) được tổng hợp bằng phương pháp thủy nhiệt. Vật liệu lai MIL(Ti-Fe) được chế tạo từ quặng ilmenit và axit 1,3,5-benzentricarboxylic ở 130 °C trong 24 giờ. Vật liệu chuẩn bị được đặc trưng bằng cách sử dụng kính hiển vi điện tử quét (SEM), nhiễu xạ tia X (XRD), quang phổ hồng ngoại (IR) và diện tích bề mặt Brunauer-Emmett-Teller (BET). Các hạt MIL(Ti-Fe) thu được có đường kính từ 0,2-1,0 μm với diện tích bề mặt BET là 85,482 $\text{m}^2 \text{g}^{-1}$. Để đánh giá hiệu quả phân hủy thuốc nhuộm, ảnh hưởng của các thông số chính khác nhau. pH của dung dịch thuốc nhuộm, nồng độ thuốc nhuộm ban đầu, thời gian hấp phụ và lượng chất xúc tác được khảo sát. Tốc độ phân hủy chất xúc tác quang của Rhodamine B được tìm thấy tối đa là 0,0074 phút^{-1} ở pH=7. Việc loại bỏ tối đa Rhodamine B thu được ở 1,0 g L^{-1} trong số lượng chất xúc tác. Dưới chiếu xạ ánh sáng mặt trời mô phỏng, kết quả MOFs hỗn hợp kim loại cho thấy khả năng phân hủy quang cao đối với Rhodamine với hiệu suất phân hủy xấp xỉ 99,97% sau 6 giờ. Hơn nữa, các vật liệu kết quả cũng cho thấy hành vi hấp thụ đáng kể đối với Rhodamine B với khả năng hấp phụ là 70 mg g^{-1} .

Từ khóa: MIL-125(Ti); Phân hủy xúc tác quang; Rhodamine B; Quặng ilmenite.

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Author affiliations:

¹ Institute of Chemistry and Materials, Academy of Military Science and Technology;

² Faculty of Chemico-Physical Engineering, Le Quy Don University.

*Corresponding author: hoaiphuong1978@gmail.com.