

Sulfated Titania Nanoparticles: an Efficient Catalyst for the Synthesis of Polyhydroquinoline Derivatives through Hantzsch Multicomponent Reaction

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Abstract

Sulfated titania nanoparticles ($\text{SO}_4^{2-}/\text{TiO}_2$ NPs) were synthesized using titanium tetraisopropoxide (TTIP) by the sol-gel method. The structure and morphology of the prepared nanocatalyst was characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM) and Brunauer–Emmett–Teller (BET) methods as well as Fourier transform infrared (FT-IR) and energy dispersive X-ray (EDX) spectroscopy. The obtained nanoparticles were used as an efficient, reusable and environmentally friendly catalyst for the synthesis of polyhydroquinoline (PHQ) derivatives *via* a one-pot multicomponent reaction of various aldehydes, ammonium acetate and 1,3-dicarbonyl compounds under reflux conditions. The desired Hantzsch esters were obtained in good to excellent yields and short reaction times. The $\text{SO}_4^{2-}/\text{TiO}_2$ NPs could be recycled at least three times without significant loss of their catalytic activity.

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1. Introduction

The synthesis of Hantzsch esters including 1,4-dihydropyridine (DHP) and polyhydroquinolines (PHQ) derivatives, as one of the most important *N*-containing heterocyclic compounds, has attracted considerable interest due to their wide biological and pharmacological activity as vasodilator, bronchodilator, antitumor, antiatherosclerotic, antihyperglycemic, antidiabetic, geroprotective agents and HIV

protease inhibition [1-6]. Especially, PHQ derivatives have emerged as one of the most important class of drugs for the treatment of cardiovascular diseases [7]. Hence, due to the aforementioned advantages, there has been considerable interest for the synthesis of these compounds. Most common routes for the preparation of PHQs involve an unsymmetric Hantzsch reaction *via* the one-pot four component condensation of an aldehyde with a diketone (such as dimedone or 1,3-

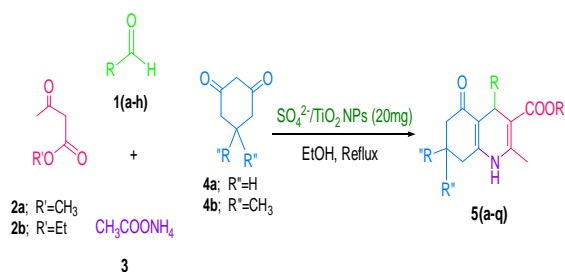
cyclohexanedione), a β -ketoester (such as methyl or ethyl acetoacetate) and ammonium acetate in the presence of a catalyst and solvent.

Literature survey shows that various catalysts mostly consisting of Bronsted or Lewis acids have been used for the Hantzsch reaction. Some of homogeneous catalytic systems include: Bu_4NHSO_4 , ceric ammonium nitrate (CAN), I_2 , tris(pentafluorophenyl) borane, boronic acids, BiCl_3 , Na- or Cs-Norit carbons, $\text{Sc}(\text{OTf})_3$, *p*-toluenesulfonic acid (PTSA), $\text{Cd}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, hafnium (IV) bis(perfluorooctanesulfonyl) imide complex $[\text{Hf}(\text{NPF}_2)_4]$ and $\text{Zn}[(\text{L})\text{proline}]_2$ can be mentioned [8-19]. On the other hand, ionic liquids, non-ionic surfactant Triton X-100, and enzymes such as fermenting Baker's yeast and *candida antarctica* lipase have been reported for Hantzsch reaction [20-23].

In spite of their merits, most of these methods encounter problems such use of hazardous or expensive catalysts or solvents, low yields, long reaction times, high temperatures, and complicated workup procedures. Furthermore, some of these catalysts are destroyed during the workup procedure and cannot be recovered or reused. Heterogeneous catalysts have advantageous over homogeneous catalysts as they can be easily recovered and can be reused, thereby making the process economically viable. Hence, recently some heterogeneous catalysts such as preyssler heteropolyacids, silica supported 12-tungstophosphoric acid, $[\text{TBA}]_2[\text{W}_6\text{O}_{19}]$, sulfonic acid supported γ - Fe_2O_3 or cellulose, polymers such as alginic acid, Ni nanoparticles, Zn- VCO_3 hydrotalcite and hydromagnesite developed for the synthesis of PHQs [24-33]. However, some of these methods have disadvantages such as the use of toxic organic solvents, high reaction

temperature and long reaction times. Therefore, improvement of the reaction conditions in terms of developing more efficient and reusable catalysts working under green conditions are still in high demand.

In the recent years, solid acids such as zeolites, metal oxides and sulfated metal oxides have been widely studied as efficient solid acid catalysts in different organic transformations [34-44]. This class of solid acid catalysts has excellent activity and in most cases can be simply recovered from the reaction mixture and reused. These features can lead to the better economical processes and less hazardous by-products [45]. Among them, $\text{SO}_4^{2-}/\text{TiO}_2$ NPs have various benefits such as stability, easy handling, and sustainability for commercial uses. $\text{SO}_4^{2-}/\text{TiO}_2$ contains both Bronsted and Lewis acid sites at the same time and represent an important family of materials that can be used as heterogeneous catalysts [46]. In this regard, $\text{SO}_4^{2-}/\text{TiO}_2$ NPs have been used as a suitable and efficient acid solid catalyst for many reactions such as esterification, oligomerization, alkylation, and Mannich reaction [47-50]. In continuation of our investigation on the use of $\text{SO}_4^{2-}/\text{TiO}_2$ NPs in organic reactions as well as multicomponent reactions (MCRs), we wish herein to report $\text{SO}_4^{2-}/\text{TiO}_2$ NPs, as facile and efficient heterogeneous catalyst, for the synthesis of PHQ derivatives *via* a one-pot, four-component Hantzsch condensation of methyl or ethyl acetoacetate, dimedone or 1,3-cyclohexanedione, various aldehydes and ammonium acetate in EtOH under refluxing conditions (Scheme 1).



Scheme 1. Synthesis of PHQs *via* condensation of various aldehydes (1), β -ketoester (2), ammonium acetate (3) and 1,3-diketone (4) in the presence of $\text{SO}_4^{2-}/\text{TiO}_2$ NPs

2. Experimental section

2.1. Materials and methods

All chemicals were purchased from Merck, Fluka and Sigma-Aldrich companies and were used without further purification. The crystalline phase of the nanoparticles were determined by X-ray diffraction (XRD) measurements using Cu α radiation ($\lambda=1.54 \text{ \AA}$) on a D Jeoljdx-8030 diffractometer. Scanning electron microscopy (SEM) image and energy dispersive X-ray (EDX) analysis were recorded by TESCAN (model VEGA-II) microscope. The specific surface area of the catalyst was obtained using Brunauer–Emmett–Teller (BET) technique with Belsorp mini II. The pore size and pore volume were determined by Barrett–Joyner–Halenda (BJH) method. Analytical thin layer chromatography (TLC) was carried out using Merck 0.2 mm silica gel 60 F-254 Al-plates. FTIR spectra of sulfated titania and PHQs were recorded in the range of $400\text{--}4000 \text{ cm}^{-1}$ by means of a Shimadzu FTIR-8400S spectrometer. Melting points were determined using an Electrothermal instrument. The ^1H NMR spectra of PHQs were recorded in CDCl_3 using Bruker Avance spectrometers (250 MHz). All yields refer to the isolated products.

2.2. General procedure for the synthesis of sulfated TiO_2 NPs

TiO_2 NPs were prepared by sol-gel method. 13.5 mL of titanium tetraisopropoxide (TTIP) in isopropanol (100 mL) was stirred for 60 min. Then, to this solution, a mixture of distilled water (20 mL) and isopropanol (100 mL) were added with constant stirring. Afterwards, isopropanol was eliminated using of a vacuum-rotary evaporator and pH solution was adjusted to 1.5 using HNO_3 solution (1 mol/L). To obtain a stable sol, the solution was stirred under reflux conditions at $70 \text{ }^\circ\text{C}$ for 24 h to afford a stable sol. The obtained sol was dried in an oven at $70 \text{ }^\circ\text{C}$ for 24 h. 1 g of TiO_2 powder were sulfated with an aqueous ammonium sulfate solution which contained 20 wt% sulfate ions with respect to Ti, via impregnation technique. The mixture was dispersed under ultrasonic waves at room temperature for 10 h. The solids were decanted and dried at $70 \text{ }^\circ\text{C}$ for 24 h. Then, the sulfated TiO_2 powders were calcined at $400 \text{ }^\circ\text{C}$ for 3 h to afford sulfated titania.

2.3. General procedure for the synthesis of PHQ derivatives (5) catalyzed by sulfated titania NPs

A mixture of aldehyde (1 mmol), methyl or ethyl acetoacetate (1 mmol), dimedone or 1,3-cyclohexanedione (1 mmol) and ammonium acetate (2 mmol) and sulfated titania (20 mg) in 2 mL absolute EtOH was refluxed at $80 \text{ }^\circ\text{C}$ for the time indicated in Tables 4 in a round bottomed flask equipped with a magnetic bar. The progress of the reaction was monitored by TLC. After completion of the reaction it was diluted with 2 mL of absolute EtOH and filtered. Then, distilled water was added dropwise with continuous stirring to the filtrate to provide crystals of PHQs. The separated crystals were filtered off, washed with cold aqueous EtOH

(50% v/v, 2 mL) and dried at 60 °C in an oven for 1 h. The pure products weighted and yields were obtained through calculation. All products were characterized by comparison of their melting point; FTIR and ¹H NMR data with those were reported in the literature [30, 37].

3. Results and discussion

3.1. Characterization of the catalyst

The XRD pattern of the TiO₂ and SO₄²⁻/TiO₂ calcined at 400 °C for 3 h are shown in Fig. 1. The results are in accordance with pure anatase crystalline phase of TiO₂. No new phases were found as a result of TiO₂ reaction with ammonium sulfate. Furthermore, no characteristic peaks of rutile or brookite phases were detected in the samples. The average crystallite size (*D*) of the synthesized nanoparticles was estimated using the Debye–Scherrer equation (1):

$$D = 0.9\lambda / \beta \cos\theta \quad (1)$$

Where λ is the wavelength of Cu K α radiation, β is the width at half maximum intensity and θ is the Bragg's angle. The average crystallite size of the TiO₂ and SO₄²⁻/TiO₂ was estimated to be 26 and 8 nm for TiO₂ and SO₄²⁻/TiO₂, respectively. In comparison with TiO₂, the average crystalline size of SO₄²⁻/TiO₂ decreases because sulfate ions interact with TiO₂ to hinder the agglomeration of the particles.

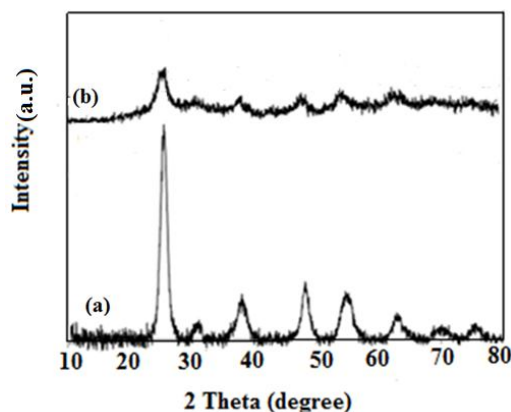


Fig. 1. XRD patterns of (a) TiO₂ and (b) SO₄²⁻/TiO₂.

The SEM image of SO₄²⁻/TiO₂ shows that the particles are distributed in spherical morphology (Fig. 2). Furthermore, to confirm the presence of sulfate, the EDS analysis for the product has done. The results of EDX analysis show that the SO₄²⁻/TiO₂ NPs contains 12.09 wt. % S (Table 1).

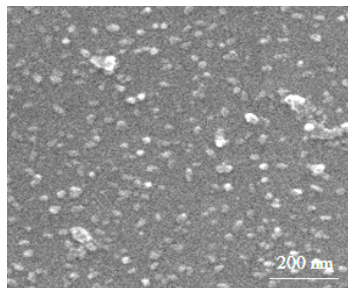


Fig. 2. SEM image of SO₄²⁻/TiO₂.

Table 1. Result of EDX analysis.

Catalyst	Element	Wt%	At%
SO ₄ ²⁻ /TiO ₂	S	12.09	17.05
	Ti	87.91	82.95

The functional groups and chemical bonds of the sulfated titania were evaluated by FTIR. The FTIR spectra for TiO₂ and SO₄²⁻/TiO₂ nanocatalysts were shown in Fig. 3. For SO₄²⁻/TiO₂, bands in the region between 980-1300 cm⁻¹ are corresponded to the vibrational modes of the bidentate sulfate ions. On the other hand, two bands are observed around 1620 and 3380 cm⁻¹, which are assigned to the bending and stretching vibrations modes of the OH groups of adsorbed water molecules on the surface of the solid as well as terminal OH, respectively. The peak around 480 cm⁻¹ is attributed to Ti–O vibrations.

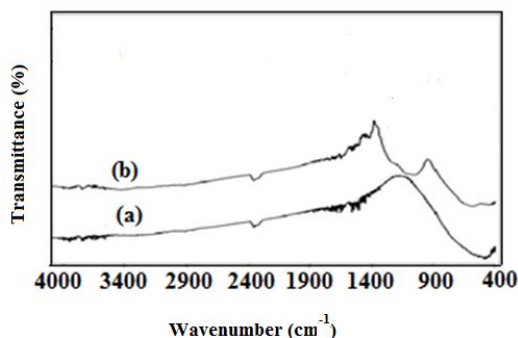


Fig. 3. FTIR spectra of (a) TiO_2 and (b) $\text{SO}_4^{2-}/\text{TiO}_2$.

The BET surface area, pore size and pore volume values for $\text{SO}_4^{2-}/\text{TiO}_2$ catalyst are shown in Table 2. As shown in Table 2, the surface area of $\text{SO}_4^{2-}/\text{TiO}_2$ is 98 g/m^2 . The pore size and pore volume of the catalyst were determined according to Barrett-Joyner-Halenda (BJH) method. On the other hand, the N_2 adsorption-desorption plot of $\text{SO}_4^{2-}/\text{TiO}_2$ catalyst, exhibited IUPAC type IV isotherm with hysteresis loop, which is characteristic of materials having uniform pore size distribution with mesoporous structure (Fig. 4). Mesoporous $\text{SO}_4^{2-}/\text{TiO}_2$ has an average pore size of 4.4 nm and pore volume equal to $0.11 \text{ cm}^3/\text{g}$.

Table 2. Physicochemical properties of the $\text{SO}_4^{2-}/\text{TiO}_2$

Catalyst	S_{BET} (m^2/g)	V_{pore} (cm^3/g)	d_{pore} (\AA)
$\text{SO}_4^{2-}/\text{TiO}_2$	98	0.11	44

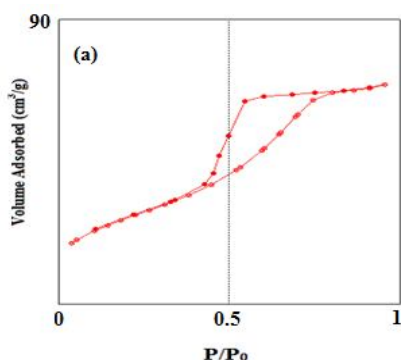


Fig. 4. N_2 adsorption-desorption isotherm of $\text{SO}_4^{2-}/\text{TiO}_2$.

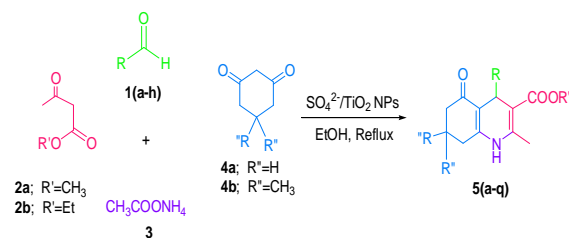
3.2. Catalytic activity

To investigate the catalytic activity of sulfated titania, initially, the one pot four-component reaction of the 4-chlorobenzaldehyde (1 mmol), ethyl acetoacetate (1 mmol), dimedone (1 mmol) and ammonium acetate (2 mmol) was examined under various conditions as a model reaction. The results have been summarized in Table 3. Preliminary experiments indicated that low yield of the corresponding PHQ **5b** is obtained in the absence of any catalyst under reflux conditions in EtOH after 5 h (entry 1). Interestingly, the yield of the desired product **5b** significantly is improved in shorter reaction times in the presence of catalytic amounts of sulfated titania under reflux conditions in EtOH (entries 6-8). As shown, 20 mg catalyst loading gave the best results among all. Further increasing of the catalyst loading up to 40 mg did not lead to significant improvements in the model reaction yield (entry 8). The model reaction was also studied in other solvents such as H_2O , CH_3CN using sulfated titania loading of 20 mg (entries 3, 4). Surprisingly, higher yield of the desired product **5b** in shorter reaction time was obtained in EtOH compared to other studied solvents under similar catalyst loading and reflux conditions (entry 5). Also, the effect of temperature on the reaction time as well as yield of product **5b** was studied (entries 5, 6). The obtained results demonstrated higher yields can be obtained in shorter reaction times under reflux conditions in EtOH. Furthermore, an experiment was run using TiO_2 powder under optimal conditions that results in the lower yield of the desired product **5b** (entry 9). Therefore, sulfated titania loading of 20 mg in EtOH under reflux conditions were selected as optimized reaction conditions (entry 5).

Encouraged by the obtained results, the scope of this reaction was investigated under optimized conditions and the results

have been summarized in Table 4. Therefore, sulfated titania was developed to a broad range of aromatic aldehydes bearing electron-donating or electron-withdrawing substituents (1a–h) for the synthesis of the desired PHQs 5 (Scheme 1). As shown in Table 4, all the aromatic aldehydes irrespective of the nature and position of the substituents in the aromatic ring reacted efficiently to afford the corresponding PHQs (5a–5q) in good to excellent yields in relatively short reaction times. Furthermore, heterocyclic aldehydes gave satisfactory yields of desired products (5g–5h, 5l). In the next stage, the effect of the other components of this reaction on the yield of the PHQs was also investigated using methyl acetoacetate (2a) instead of ethyl acetoacetate (2b) and 1,3-cyclohexanedione (4a) instead of dimedone (4b). In all of the cases, the desired PHQs were obtained in good to excellent yields.

Table 4. Four-component synthesis of different PHQs (5a–p) via condensation of various aldehydes (1a–h), 1,3-diketone (2a or 2b), β -ketoester (4a or 4b) and ammoniumacetate (3) in the presence of $\text{SO}_4^{2-}/\text{TiO}_2$ NPs under refluxing conditions in EtOH^a



Entry	Aldehyde	1,3-diketone / β -ketoester	P ^b	Time (min) / Yield ^c (%)
1	2-Chlorobenzaldehyde	2b / 4b	5a	120/
	1a			65
2	4-Chlorobenzaldehyde	2b / 4b	5b	90/
	1b			83
3	4-Bromobenzaldehyde	2b / 4b	5c	120/
	1c			87
4	Methylbenzaldehyde	2b / 4b	5d	75/
	1d			87
5	4-Methoxybenzaldehyde	2b / 4b	5e	60/
	1e			93
6	4-Hydroxybenzaldehyde	2b / 4b	5f	75/
	1f			91
7	Thiophen-2-carbaldehyde	2b / 4b	5g	60/
	1g			96
8	Furfural	2b / 4b	5h	120/
	1h			80
9	4-Chlorobenzaldehyde	2a / 4b	5i	75/
	1b			95
10	4-Methylbenzaldehyde	2a / 4b	5j	60/
	1d			96
11	4-Methoxybenzaldehyde	2a / 4b	5k	75/
	1e			94
12	Thiophen-2-carbaldehyde	2a / 4b	5l	90/
	1g			83
13	4-Chlorobenzaldehyde	2a / 4a	5m	60/
	1b			91

14	4-Methylbenzaldehyde 1d	2a / 4a	5n	120/ 83
15	4-Methoxybenzaldehyde 1e	2a / 4a	5o	120/ 73
16	4-Chlorobenzaldehyde 1b	2b / 4a	5p	75/ 94
17	4-Methylbenzaldehyde 1d	2b / 4a	5q	90/ 82
14	4-Methylbenzaldehyde 1d	2a / 4a	5n	120/ 83
15	4-Methoxybenzaldehyde 1e	2a / 4a	5o	120/ 73
16	4-Chlorobenzaldehyde 1b	2b / 4a	5p	75/ 94
17	4-Methylbenzaldehyde 1d	2b / 4a	5q	90/ 82

^a Reaction conditions: Aromatic aldehydes (1 mmol), 1,3-diketone (1 mmol), β -ketoester (1 mmol), and ammonium acetate (2 mmol), $\text{SO}_4^{2-}/\text{TiO}_2$ NPs (20 mg) and EtOH (2 mL).

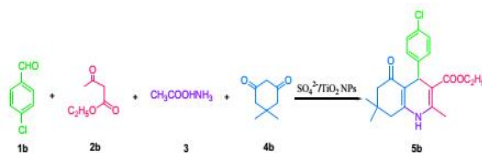
^b Product

^c The yields refer to the isolated product

The merit and superiority of the $\text{SO}_4^{2-}/\text{TiO}_2$ NPs in the preparation of PHQs in comparison with various catalysts can be seen by comparing the obtained results with the reported results in the literature (Table 5). As shown in Table 5, some catalysts such as I2, HY-Zeolite, [TBA]2[W6O19], and nano- γ - Fe_2O_3 - SO_3H required higher catalyst loading over $\text{SO}_4^{2-}/\text{TiO}_2$ NPs. Furthermore, in contrast to I2, HY-Zeolite, nano- γ - Fe_2O_3 - SO_3H catalysts, the desired product 5e is obtained in excellent yield in a shorter reaction time.

To examine the recyclability of the catalyst, after completion of the reaction for the synthesis of PHQ 5e, the sulfated titania cat-

Table 3. Optimization conditions for the synthesis of PHQs.^a



Entry	Catalyst loading (mol %)	Solvent	Temp. (°C)	Time(min) /Yield ^b (%)
1	-	EtOH	Reflux	300/10
2	-	H ₂ O	Reflux	180/25
3	$\text{SO}_4^{2-}/\text{TiO}_2$ (20)	H ₂ O	Reflux	105/65
4	$\text{SO}_4^{2-}/\text{TiO}_2$ (20)	CH ₃ CN	Reflux	105/60
5	$\text{SO}_4^{2-}/\text{TiO}_2$ (20)	EtOH	Reflux	90/83
6	$\text{SO}_4^{2-}/\text{TiO}_2$ (20)	EtOH	r.t.	90/50
7	$\text{SO}_4^{2-}/\text{TiO}_2$ (10)	EtOH	Reflux	120/68
8	$\text{SO}_4^{2-}/\text{TiO}_2$ (40)	EtOH	Reflux	90/88
9	TiO ₂ (20)	EtOH	Reflux	90/65

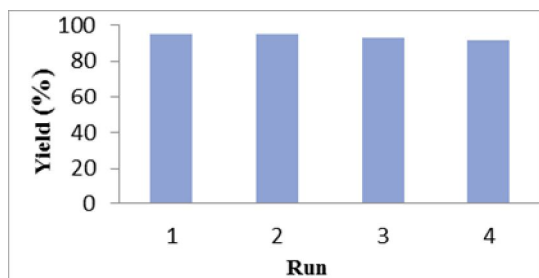
^a Reaction conditions: 4-chlorobenzaldehyde (1 mmol), dimedone (1 mmol), ethyl acetoacetate (1 mmol), and ammonium acetate (2 mmol).

^b The yields refer to the isolated product.

alyst was recovered by simple filtration and washed with acetone prior to drying, then it was dried in air at 100 °C (Fig. 5). The results in Fig. 5 demonstrated that recycled catalyst can be used three consecutive runs without significant loss of its catalytic activity. However, the slight reduction of catalytic activity of the $\text{SO}_4^{2-}/\text{TiO}_2$ NPs after recycling is probably due to the blockage of active sites on the catalyst surface.

Table 5. Comparison of results for the synthesis of PHQ **5e** via Hantzsch reaction using other catalysts.

Entry	Catalyst/Conditions	Catalyst loading (mg)	Time (min) /Yield (%)	Ref
1	I ₂ /EtOH, r.t.	76	120/93	10
2	HY-Zeolite/CH ₃ CN, r.t.	100	120/90	55
3	[TBA] ₂ [W ₆ O ₁₉]/110°C	132	20/82	26
4	nano- γ -Fe ₂ O ₃ -SO ₃ H/60°C	31	90/93	41
5	SO ₄ ²⁻ /TiO ₂ NPs/EtOH, reflux	20	60/93	Thi s wor k

**Fig. 5.** Reusability of SO₄²⁻/TiO₂ NPs for the synthesis of PHQ **5e** via Hantzsch reaction.

4. Conclusions

The sulfated titania as catalyst showed high efficiency for the synthesis of PHQ derivatives using various aldehydes, dimedone or 1,3-cyclohexanedione, methyl or ethyl acetoacetate, ammonium acetate in EtOH under reflux conditions. Furthermore, the catalyst could be recovered and reused three times with no significant decrease in its catalytic activity. Therefore, advantages of this protocol are: Easy synthesis of the catalyst, low catalyst loading, environmentally friendly, short reaction times, good to excellent yields, heterogeneous conditions, easily works up procedure and reusability.

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