

Aliphatic alcohols oxidation with Hydrogen Peroxide in water catalyzed by supported Phosphotungstic acid (PTA) on Silica coated MgAl₂O₄ nanoparticles as a recoverable catalyst

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Received 08 July 2018; revised 06 September 2018; accepted 09 September 2018; available online 16 September 2018

Abstract

In this paper, a novel catalyst (MgAl₂O₄@SiO₂-PTA) was proposed for the green oxidation of aliphatic alcohols. The resultant composite was characterized by different techniques, such as X-ray diffraction (XRD), SEM, FT-IR, EDX and Brunauer-Emmett-Teller (BET) surface area analysis. The prepared nanocomposite was used as a catalyst for oxidation of aliphatic alcohols with hydrogen peroxide in water at 90. Aliphatic alcohols were converted to aldehydes and ketones. Primary alcohols were converted to aldehydes but secondary alcohols were converted to ketones. Cyclohexanol is very active in this catalyst system but no product was detected in cyclohexanol oxidation without catalyst. It is noteworthy to highlight that the catalyst is environmentally friendly since it could be recovered by a simple filtration. The catalyst was reused for at least four successive times without any changes or loss of its high catalytic activity.

Keywords: Aliphatic Alcohols, Catalyst, MgAl₂O₄, Nanoparticles, Oxidation, Phosphotungstic Acid.

How to cite this article

Hajavazzadeh R, Kargar Razi M, Mahjoub AR. Aliphatic alcohols oxidation with Hydrogen Peroxide in water catalyzed by supported Phosphotungstic acid (PTA) on Silica coated MgAl₂O₄ nanoparticles as a recoverable catalyst. *Int. J. Nano Dimens.*, 2019; 10 (1): 69-77.

INTRODUCTION

The selective oxidation reaction of alcohols to aldehydes and ketones is a basic reaction in organic synthesis [1-2]. Most common inorganic compounds in order to oxidize alcohols are well known, such as KMnO₄, MnO₂ and K₂Cr₂O₇ [3], but these oxidants are toxic. Due to beneficial properties of hydrogen peroxide, significant progresses have been achieved for oxidation of aliphatic alcohols with hydrogen peroxide, catalyzed by nanocomposite. Hydrogen peroxide is an environmentally safe and interesting oxidant for different organic oxidation reactions [4-5].

Polyoxometalates (POM) are categorized as one of the most important catalysts in inorganic metal oxide cluster group. Heteropolyacid (HPAs) compounds of keggin have attracted many attentions, because of their applications, such as significant catalytic properties and high

activity [6-8]. The problem of HPAs is the low available surface area. Supporting compounds on nanoparticles is the best solution for improving their effective surface area and solubility in polar solvents. Mesoporous materials such as zeolites, silica, and titania have been used as supports for PTA [9-13]. Due to its chemical and physical stability, hydrophilic nature and being mesoporous, Silica (SiO₂) has attracted growing attentions in diverse applications [14-15]. Using Polyoxometalates dissolved in polar solvents composed of homogeneous catalysts provides convenience in use due to the ease of their recovery. A utilized method is immobilizing POM species on the surface of nanoparticles which can be isolated and recovered from the reaction system by a simple filtration. Similar research has been done in recent years [16-17].

Magnesium aluminate has attracted many

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attentions as catalyst support because of its structure stability and high melting point. Magnesium aluminate has a good resistance against chemical changes. Also it has high resistance at very high temperatures, has a very high melting point (2135) and low density (3.58 g/cm^3) [18]. Different methods for production of magnesium aluminate nanoparticles include sol-gel [19-20] co-precipitation [21] and self-combustion. These methods are mainly expensive in large scale production. In general, smaller particle size along with higher surface area is suitable for various catalytic applications [22].

In this research, a new composite was prepared by a simple method for oxidation of aliphatic alcohols to aldehydes and ketones with hydrogen peroxide as oxidant and water as solvent. This nanocomposite was proved to be useful for immobilization of PTA on silica coated magnesium aluminate nanoparticles. Primary alcohols were converted to aldehydes with high selectivity and conversion ratios. Cyclohexanol was converted to cyclohexanone with a high selectivity [23-27]. At the end of the reaction, the products were isolated from the aqueous phase by a simple filtration (see Fig. 1).

EXPERIMENTAL

Materials and methods

All chemicals were purchased from Sigma-Aldrich or Merck with analytical grade and used as received. $\text{H}_3\text{PW}_{12}\text{O}_{40}$ (PTA) was purchased from Sigma-Aldrich. Fourier transform infrared (FT-IR) spectra were obtained using FT BOMEM MB102 IR spectrophotometer. X-ray diffraction (XRD) patterns of the synthesized samples were determined with a Philips X-ray diffractometer (model PW1730). The SEM images were obtained by Hitachi Japan S4160. The Scanning Electron

Microscopy analysis was performed along with an Energy Dispersive Spectroscopy (EDX).

Synthesis of $\text{MgAl}_2\text{O}_4 @ \text{SiO}_2$ -PTA nanocomposite

MgAl_2O_4 was prepared using the method reported by Mostafa Y. Nassar [28]. Coating of MgAl_2O_4 nanoparticles with a layer of silica was performed by the following method. In this method, ethanol (1/5 ml) and H_2O (10 ml) were mixed and put in ultrasonic bath for 1 hour. After that, NH_3 (1/5 ml) was added to this mixture. Then, 2g of MgAl_2O_4 particles were dispersed in it and the mixture was vigorously stirred at 40°C for 10 minutes. Then, TEOS (0/53ml) was added and mixing was continued for 1 hour and the mixture was stirred overnight. The coated particles were separated by filtration and washed with ethanol several times and dried at 80°C in the oven. In this process, for synthesis of the nanocomposite, ethanol/water (80 : 20 ratio) solution was prepared and then 1.0 g of PTA was added and the solution was stirred at room temperature for 1 hour. After that, 1.0 g of $\text{MgAl}_2\text{O}_4 @ \text{SiO}_2$ was dispersed in it and the mixture was stirred for another 3 hours. The resulting precipitation was separated by filtration. At last, this nanocomposite was washed with ethanol and dried in an oven at 100°C for 2 hours. The typical preparation of composite ($\text{MgAl}_2\text{O}_4 @ \text{SiO}_2$ -PTA) is shown in Fig. 2.

Catalytic studies

A mixture of an alcohol (1mmol), catalyst (0.015 mmol), water (3 ml), and H_2O_2 (30% aq.) were stirred at 90 for the specified time. The reaction was characterized by TLC. CH_3Cl was added to dilute the reaction mixture and the organic layer was isolated by filtration. At the end of the reaction, the isolated solution was purified on a silica-gel plate to obtain pure product. After separation of

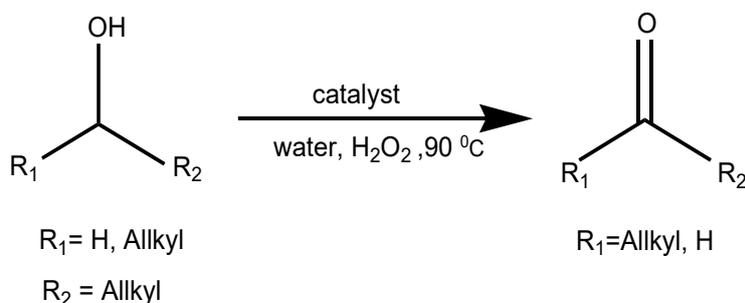


Fig. 1. Synthesis of aliphatic alcohols in presents of $\text{MgAl}_2\text{O}_4 @ \text{SiO}_2$ -PTA using H_2O_2 /water at 90.

product, recycled catalyst was reused for the next oxidation cycle with alcohols (1 mmol), H₂O₂ (30% aq) and water.

RESULTS AND DISCUSSION

Characterization of MgAl₂O₄@SiO₂-PTA composite FT-IR spectra

MgAl₂O₄@SiO₂-PTA was synthesized by a simple method. MgAl₂O₄ was prepared via

sol-gel combustion method as a support for nanocomposite. Then, it was coated by thin layer of silica. The FT-IR spectra of MgAl₂O₄ and MgAl₂O₄@SiO₂-PTA, is presented in Fig. 3. In the IR spectra, the MgAl₂O₄ sample display two characteristic at 555 cm⁻¹ and 700 cm⁻¹ consecration to the [AlO₆] groups, the lattice vibration of Mg-O stretching, and displaying the formation of MgAl₂O₄ spinel [29-30]. Two

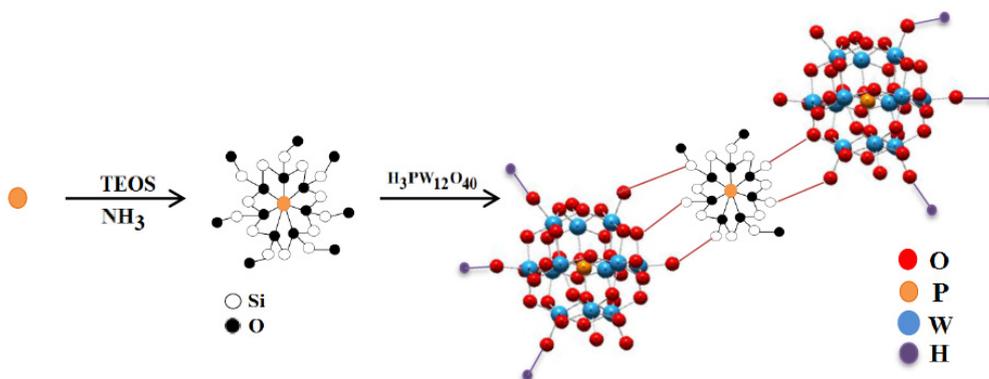


Fig. 2. Typical preparation procedure of the synthesis of MgAl₂O₄@SiO₂-PTA nanocomposite.

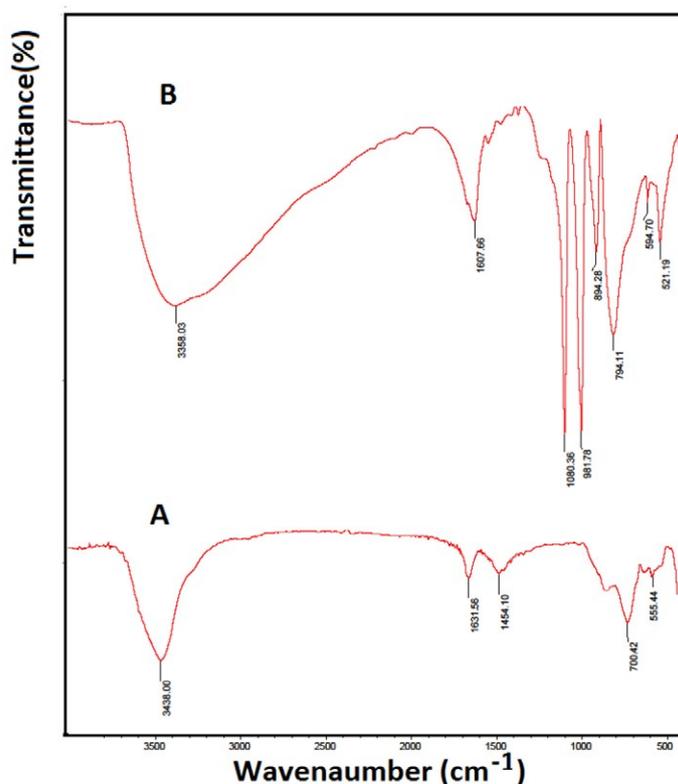


Fig. 3. FT-IR spectra of MgAl₂O₄ (A), MgAl₂O₄@SiO₂-PTA (B).

vibration bands at 3358 cm^{-1} and 1607 cm^{-1} appeared in the IR spectra of the products could be attributed to the stretching and bending vibrations of the molecular surface adsorbed water interacting with MgAl_2O_4 [31-34]. Two bands at 1080 cm^{-1} and 794 cm^{-1} were observed which are ascribed to the symmetrical and asymmetrical vibrations of the Si-O-Si bonds. Two other bands at 894 cm^{-1} and 981 cm^{-1} were attributed to the immobilized PTA [35].

X-ray diffraction

The XRD patterns of MgAl_2O_4 and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$, are displayed in Fig. 4. The peaks are compatible with pure MgAl_2O_4 phase (JCPDS card no. 98-007-5897), indicating the retention of spherical spinel structure of MgAl_2O_4 during the functionalization and coating process. The crystallite size of MgAl_2O_4 nanoparticles was determined about 40 nm using Debye-Scherrer formula (Fig. 4A). The XRD patterns of MgAl_2O_4 , after coating with silica and functionalization with PTA (Fig. 4B), are more or less the same as previous MgAl_2O_4 with the same spinel structure.

Comparison to XRD patterns of MgAl_2O_4 (A) and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ (B). (see Table 1).

Scanning Electron Microscopy (SEM)

The morphology of MgAl_2O_4 and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ were investigated by SEM are shown in Fig. 5. SEM images display that MgAl_2O_4 and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ particles are well dissolved and most of the fabricated nanoparticles have spherical structures (Fig. 5 A and B). As it is shown in the Fig. 3, the maximum of particles size is 31nanometer.

EDX Microscopy and Brunauer-Emmett-Teller (BET) surface area analysis

The EDX spectrum is shown in Fig. 6. The spectrum clearly reveals the presence of all the expected main elements (O, Si, P, Al, Mg, and W) including the three component composite. The surface area of $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ was also estimated by using the N_2 gas adsorption (BET) method and a value of $36.73\text{ m}^2\text{ g}^{-1}$ was found for this composite.

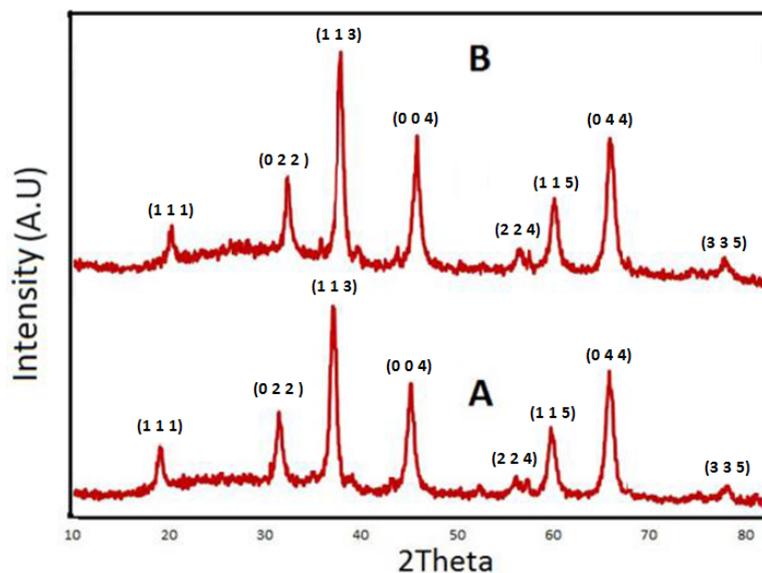


Fig. 4. XRD patterns of MgAl_2O_4 (A) and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ (B).

Table 1. Comparison to XRD patterns of MgAl_2O_4 (A) and $\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ (B).

2Theta peak	(1 1 1)	(0 2 2)	(1 1 3)	(0 0 4)	(2 2 4)	(1 1 5)	(0 4 4)	(3 3 5)
MgAl_2O_4 (A)	19	32	36	45	56	60	66	87
$\text{MgAl}_2\text{O}_4@\text{SiO}_2\text{-PTA}$ (B)	21	33	37	46	57	61	67	87

Aliphatic alcohols oxidation

As indicated in Table 2. The primary alcohols (amyl alcohol and ethanol) were converted to aldehydes after oxidation. The linear aliphatic alcohols (amyl

alcohol, ethanol and 2-propanol) were more difficult to oxidize than cyclohexanol. Consequently, 5/1 molar ratio H_2O_2 /alcohol and 6 hours reaction time was needed for oxidation of these alcohols (entries

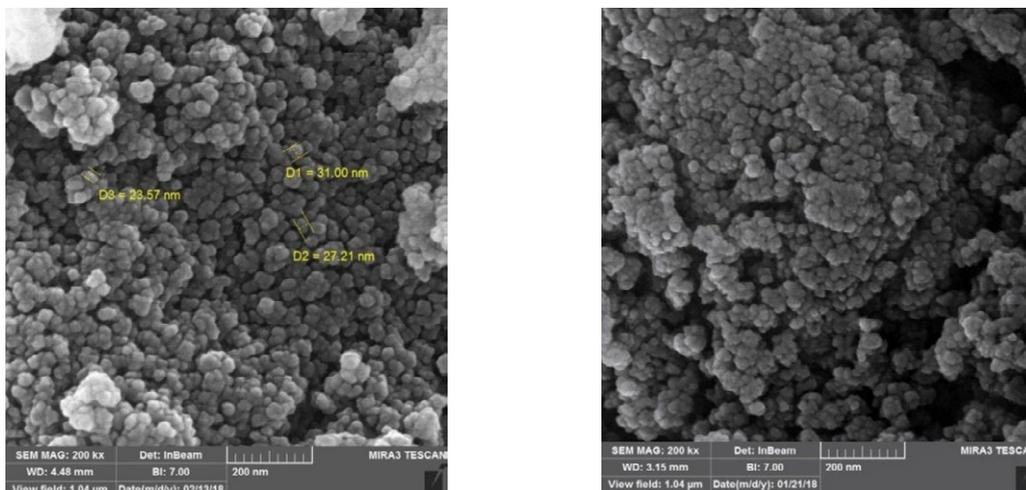
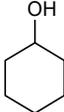
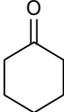
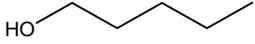
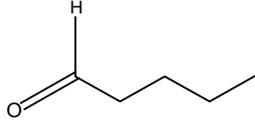
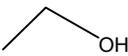
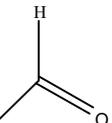
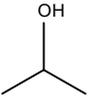
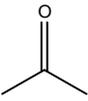
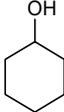
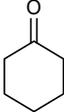


Fig. 5. SEM image of the obtained $MgAl_2O_4$ (A) and $MgAl_2O_4@SiO_2$ -PTA (B).

Table 2. Synthesis of diversified alcohols in the presence of $MgAl_2O_4@SiO_2$ -PTA.

Entry	Substrate	product	H_2O_2 / substrate molar ratio	Time (h)	yield (%) ^b
1			2/1	1/5	93
2			5/1	6	87
3			5/1	6	85
4			5/1	6	88
5 ^a			2/1	5	-

^a Alcohols (1mmol) water (3 ml), and H_2O_2 (30% aq) was stirred at 90°C without catalyst.

All reaction condition: alcohol (1mmol) catalyst (0.015 mmol), water (3 ml) and H_2O_2 (30% aq.) was stirred at 90°C.

^b Isolated yields.

2-4). About cyclohexanol (entry 1) the 2/1 molar ratio received of H_2O_2 /cyclohexanol was appropriate for this reaction (see Table 2).

The reaction of cyclohexanol, hydrogen peroxide and $MgAl_2O_4@SiO_2$ -PTA was chosen as a model for aliphatic alcohols oxidation reaction. In order to obtain the best results, different solvents such as water, acetonitrile, toluene, chloroform and solvent free condition were employed. The results are displayed in Table 3. The best results were obtained as soon as this reaction was terminated by H_2O (see Table 3).

Although cyclohexanol is very active in this system, the control experiment displayed that no product was detected in cyclohexanol oxidation without the catalyst. $MgAl_2O_4$, $MgAl_2O_4@SiO_2$, $MgAl_2O_4@SiO_2$ -PTA and $H_3PW_{12}O_{40}$ were used to evaluate the effectiveness of catalyst on this reaction. As shown in Table 4. $MgAl_2O_4@SiO_2$ -PTA displayed the best catalytic activity for oxidation of cyclohexanol (see Table 4).

The oxidation of cyclohexanol to cyclohexanone by $MgAl_2O_4@SiO_2$ -PTA with various molar ratio of H_2O_2 /cyclohexanol was studied in details and

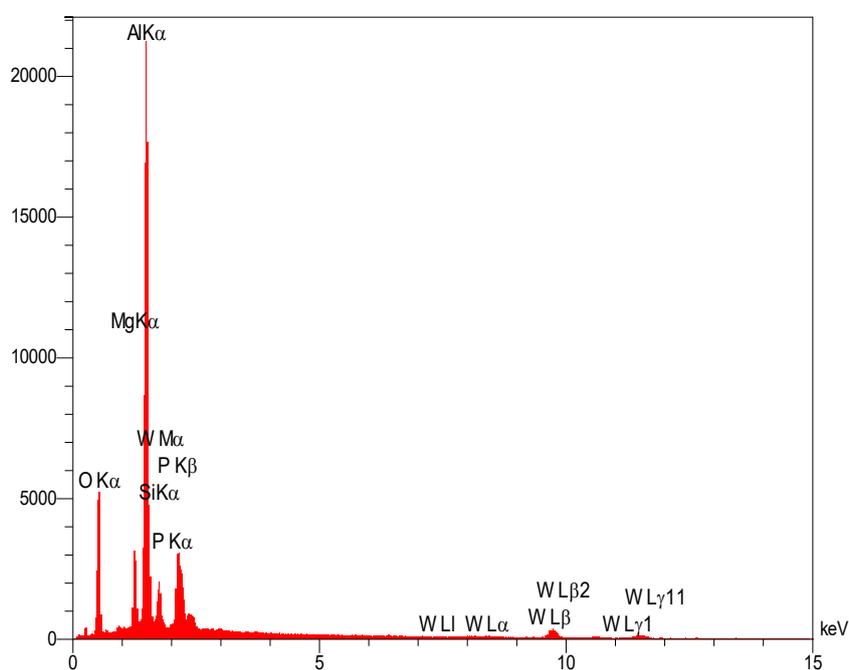


Fig. 6. EDX spectrum of $MgAl_2O_4@SiO_2$ -PTA nanocomposite.

Table 3. Effect of various solvents on the cyclohexanol oxidation.

Entry	Solvent	Time (h)	Yield (%)
1	Water	1.5	93
2	Acetonitrile	3	50
3	Chloroform	3	61
4	Solvent free	8	30
5	Toluene	5	62

All reaction conditions cyclohexanol (1mmol) catalyst (0.015 mmol), solvent (3 ml) and H_2O_2 (2 mmol) was stirred at $90^\circ C$.

Table 4. Effect of various catalysts on the cyclohexanol oxidation.

Entry	catalyst	Time (h)	Yield (%)
1	MgAl ₂ O ₄	5	-
2	MgAl ₂ O ₄ @SiO ₂	5	-
3	MgAl ₂ O ₄ @SiO ₂ -PTA	1.5	93
4	H ₃ PW ₁₂ O ₄₀	2.5	79

All reaction conditions: cyclohexanol (1mmol) catalyst (0.015 mmol), water (3 ml) and H₂O₂ (2 mmol) was stirred at 90°C.

Table 5. Effect of various molar ratios of H₂O₂/alcohol on the cyclohexanol oxidation.

Entry	H ₂ O ₂ /alcohol	Time (h)	Yield (%)
1	2/1	1.5	93
2	1/1	1.5	80
3	1/2	5	69
4	3/1	8	62
5	4/1	10	60

All reaction conditions cyclohexanol (1mmol) catalyst (0.015 mmol), water (3 ml) and H₂O₂ (30% aq) was stirred at 90°C.

results are listed in Table 5. When the amount of H₂O₂/ cyclohexanol was 2/1 (entry1), yield of product (cyclohexanone) was 93%, but while using equal ratio of H₂O₂/ cyclohexanol, the production yield decreased to 80 % at the same time. Increasing the ratio of H₂O₂/ cyclohexanol to 4/:1 resulted in a 60 % of decrease in the amount of cyclohexanone. The best molar ratio was 2 : 1 for H₂O₂/ cyclohexanol in this reaction. The amount of hydrogen peroxide in this reaction is very effective under these conditions. (see Table 5).

Recovering of the catalyst

The recovery process of MgAl₂O₄@SiO₂-PTA in this system has the same process as the optimized conditions. The catalyst was isolated from final product by a simple filtration. After that, it washed twice with water and ethanol. After drying the isolated catalyst at 100 for 2 hours, it was reused in a new reaction. The results are listed in Table 6. The recovered catalyst could be reused for four

Table 6. Reusability of MgAl₂O₄@SiO₂-PTA catalyst in the model reaction.

Entry	Time(h)	Yield (%)
fresh	1/5	93
1	1/5	92
2	1/5	90
3	1/5	89
4	1/5	88

All reaction conditions: Cyclohexanol (1mmol) catalyst (0.015 mmol), water (3 ml) and H₂O₂ (2 mmol) was stirred at 90°C.

times with no changes in activity (see Table 6).

CONCLUSIONS

In this study a novel nanocomposite as a recyclable catalyst was introduced for oxidation of aliphatic alcohols in water with hydrogen peroxide. The synthesized catalyst was analyzed by X-ray diffraction (XRD), FT-IR, SEM, EDX and Brunauer-Emmett-Teller (BET) surface area analysis techniques. Cyclohexanol was converted to cyclohexanone with a high yield by controlling the ratio of H₂O₂ to cyclohexanol. The reaction of this nanocomposite is environmentally friendly. Also, the catalyst is recyclable in aliphatic alcohols oxidation process. This catalyst could be recovered by simple filtration and reused for four times without any loss of activity.

ACKNOWLEDGMENT

The authors wish to acknowledge the support of this work by the Department of Chemistry, Tehran North Branch, Islamic Azad University, Tehran.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this review article.

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