Iranian Journal of Analytical Chemistry
Volume 12, Spring 1, March 2025 (123-133) Original Research Article
مجله ایرانی شیمی تجزیه
دوره ۱۲، شماره ۱، فروردین ۱۴۰۴ (۱۳۳-۱۲۳)

Efficient Oxidative Desulfurization of Thiophenic Model Compounds and Real Gas Condensate over a Phosphotungstic Acid–Hexamine–Cobalt Hybrid Catalyst

Mehdi Taghdiri[a,b,*], Mohammad Golzari[a]

[a]Department of Chemistry, Payame Noor University, 19395-3697 Tehran, Iran

[b]Research Center of Environmental Chemistry, Payame Noor University, Ardakan, Yazd, Iran

[*]Corresponding author: Tel: +98 35 32220012, Fax: +98 35 32228110, taghdiri@pnu.ac.ir, mehditaghdiri@yahoo.com

Received: 11 November 2025 **Accepted:** 3 January 2026
DOI: 10.30473/IJAC.2026.76456.1331

Abstract
A novel hybrid catalyst based on phosphotungstic acid–hexamine–cobalt (PTA–HMT–Co) was synthesized and evaluated for the oxidative desulfurization (ODS) of thiophenic compounds. The Taguchi L_9 orthogonal design was employed to optimize key reaction parameters including temperature, reaction time, catalyst dosage, and oxidant-to-sulfur ratio. The optimized conditions achieved 99.84% desulfurization efficiency for model oil containing benzothiophene and 92.94% for real gas condensate samples. The catalyst exhibited strong oxidative activity, thermal stability, and recyclability for at least six cycles. The high catalytic performance is mainly attributed to the Keggin-type phosphotungstic acid framework, while cobalt incorporation contributes to structural stabilization and catalyst durability rather than acting as a primary active site. This study demonstrates the potential of PTA–HMT–Co as a green and efficient catalyst for deep desulfurization under mild conditions.

Keywords
Oxidative desulfurization, Hybrid catalyst, Phosphotungstic acid-hexamine-cobalt, Taguchi optimization, Dibenzothiophene, Real gas condensate.

1. INTRODUCTION

Sulfur compounds present in petroleum-derived fuels contribute to severe environmental pollution, including acid rain and particulate matter formation. Conventional hydrodesulfurization (HDS) is energy-intensive and inefficient for refractory sulfur compounds such as dibenzothiophene (DBT) [1]. Therefore, oxidative desulfurization (ODS) has emerged as an attractive complementary process operating under mild conditions and without hydrogen consumption [2-5]. Polyoxometalates (POMs) have shown promise as efficient oxidative catalysts owing to their tunable acidity and redox properties. These versatile compounds have found extensive application in extractive and catalytic oxidative desulfurization (ECODS) systems. Nevertheless, despite their remarkable catalytic activity, the major challenge associated with POMs lies in their pronounced solubility in polar media, which hampers their recovery and reuse from the reaction mixture [6]. Consequently, the design and fabrication of robust heterogeneous POM-based catalysts are of great importance. In this context, organic–inorganic POM hybrid materials have recently emerged as promising alternatives for enhancing the efficiency and recyclability of catalysts employed in ECODS processes [7-12].

In this work, a novel Phosphotungstic Acid–Hexamine–Cobalt hybrid (PTA–HMT–Co) catalyst was synthesized and applied in ODS of model and real sulfur-containing fuels. The Taguchi L_9 orthogonal array method was used for optimization of reaction parameters to maximize

* Corresponding author:

M. Taghdiri; E-mail: mehditaghdiri@yahoo.com

sulfur removal efficiency. In recent years, various ionic liquid–polyoxometalate (IL–POM) salts have been investigated as efficient catalysts for the ECODS process [13–15]. Although these systems demonstrate excellent catalytic performance, their large-scale application is limited by the relatively high cost of ionic liquids. Therefore, developing cost-effective and easily accessible organic components to replace ionic liquids in POM-based ECODS systems remains highly desirable. In this context, hexamethylenetetramine (HMT) offers several advantages, including low cost, commercial availability and strong coordination ability with both metal centers and heteropolyacid anions. In the present study, hexamethylenetetramine (HMT), commonly known as hexamine, was employed as an organic component to construct a polyoxometalate-based hybrid catalyst. HMT $(CH_2)_6N_4$) is a easily synthesized non-aromatic heterocyclic amine derived from ammonia and formaldehyde [16,17]. The incorporation of cobalt ions into the PTA–HMT hybrid structure was primarily intended to enhance the structural integrity and physicochemical stability of the catalyst. Hydrogen peroxide was selected as the oxidizing agent due to its high atom economy and environmentally benign nature, yielding only water as a byproduct. Furthermore, this study reports the ECODS performance of the synthesized catalyst toward the removal of organosulfur compounds from real gas condensate samples.

2. EXPERIMENTAL

2.1. Chemicals and reagents

All chemicals were of analytical grade and used as received. Benzothiophene (BT), dibenzothiophene (DBT), n-octane, n-hexane, acetonitrile, and 35% hydrogen peroxide (H_2O_2), Phosphotungstic acid ($H_3PW_{12}O_{40}$) and cobalt nitrate were obtained from Merck. The hexamine powder (99.5 %) was from Sina Chemical Industries Co. (Shiraz, Iran). Real gas condensate samples were supplied by Ilam refinery (Iran).

2.2. Catalyst preparation

The Phosphotungstic Acid–Hexamine–Cobalt (PTA–HMT–Co) hybrid catalyst was synthesized via a controlled precipitation route. In a typical procedure, 5 mL of an ethanolic solution of hexamethylenetetramine (2.0 wt%) was added gradually to 5 mL of an aqueous cobalt nitrate hexahydrate solution (4.0 wt%) under continuous stirring at room temperature. After achieving complete mixing, 5 mL of a 13.0 wt% ethanolic solution of phosphotungstic acid was introduced dropwise into the reaction mixture. Upon addition, a suspension was immediately formed, indicating the generation of the hybrid complex. The precipitate was then separated by centrifugation, repeatedly washed with deionized water to remove unreacted residues, and subsequently dried in an oven at 100 °C. The obtained pale pink solid was ground gently to yield a fine powder catalyst, denoted as PTA–HMT–Co.

2.3. Oxidative desulfurization procedure of model fuel

Model fuel solutions were prepared by dissolving dibenzothiophene (DBT) in n-hexane to obtain a sulfur concentration of approximately 600 ppmw. In a typical ODS experiment, 5 mL of the model fuel was introduced into a round-bottom flask containing a predetermined amount of catalyst, followed by the addition of 35 wt% hydrogen peroxide as the oxidizing agent. The reaction mixture was stirred magnetically at 500 rpm and maintained at the desired temperature for a specific reaction time. Upon completion, the mixture was allowed to cool to ambient temperature, and 5 mL of acetonitrile was added to extract the oxidized sulfur species.

Phase separation between the organic (hexane) and extractant (acetonitrile) layers occurred spontaneously. The upper organic layer, representing the treated model fuel, was analyzed using gas chromatography (Bruker 4200 GC) equipped with a flame ionization detector (FID) and an OPTIMA-5 capillary column (30 m × 0.32 mm × 0.25 μm film thickness). Analytical parameters were as follows: split ratio of 30:1, injector temperature of 280 °C, detector temperature of 340 °C, and injection volume of 2.0 μL. The GC oven was initially held at 150 °C for 3 min, ramped to 240 °C at 13 °C min^{-1}, and then increased to 300 °C at 20 °C min^{-1}, holding for 20 min. High-purity helium was used as the carrier gas at a constant flow rate of 30 mL min^{-1}. A second model fuel containing benzothiophene (BT) was similarly prepared by dissolving the compound in n-octane to achieve the same sulfur content (600 ppmw), following identical experimental procedures. Different solvents were used for DBT and BT model fuels to ensure complete solubility and stable sulfur concentration during the experiments. Direct quantitative comparison between the two sulfur compounds was not intended, as the objective was to evaluate their relative oxidative reactivity under comparable conditions.

2.4. Oxidative desulfurization procedure of real sample

The oxidative desulfurization of real Ilam gas condensate (sulfur content: 2606 ppm, density: 0.715 g mL□¹, sample volume: 50 mL) was carried out under the same experimental conditions used for the model fuel, with slight modifications.

DOI: 10.30473/IJAC.2026.76456.1331

Specifically, 0.2 g of the synthesized PTA–HMT–Co catalyst and 4.5 mL of 35 wt% hydrogen peroxide were employed as the catalytic and oxidizing agents, respectively. Following the oxidation step, the reaction mixture was allowed to cool to room temperature, and the oxidized sulfur compounds were extracted using acetonitrile at a 1:1 volume ratio with the oil phase.

After complete phase separation, the treated oil layer was collected for sulfur analysis. The sulfur concentrations in the condensate before and after oxidation were determined by X-ray fluorescence spectroscopy (Tanaka Scientific Sulfur Meter, model RX-360SH) in accordance with the ASTM D4294 standard method.

2.5. Taguchi method

To evaluate the influence of different operational variables on the ECODS performance and to determine the optimal reaction conditions, a systematic experimental design methodology was employed. The effects of key parameters-including catalyst loading, hydrogen peroxide dosage, reaction time, and temperature-were studied at three distinct levels using an orthogonal array design (OA_9). The detailed experimental matrix and corresponding factor levels are presented in Table 1. The selected ranges of reaction parameters were determined based on preliminary experiments, literature precedents, and practical considerations such as catalyst stability, oxidant decomposition, and operational safety. It should be noted that the Taguchi L_9 orthogonal array was employed as a screening and optimization tool to reduce the number of experimental runs. This approach does not account for interaction effects between variables; however, it provides a reliable estimation of the relative significance of individual parameters in the ECODS process.

3. RESULTS AND DISCUSSION

3.1. Characterizations of catalyst

The synthesized hybrid material had been thoroughly examined in our previous study using a combination of analytical and spectroscopic techniques, including elemental (CHN) analysis, Fourier-transform infrared spectroscopy (FTIR), powder X-ray diffraction (XRD), and thermogravimetric (TG) measurements [18]. The FTIR spectra (Figure 1) and XRD patterns (Figure 2) confirmed that both the HMT and PTA frameworks were successfully preserved within the solid hybrid structure. Furthermore, the thermal behavior observed in TG analysis was consistent with the composition determined from elemental data, corresponding to the molecular formulation $Co_4[C_6H_{12}N_4]_9[PW_{12}O_{40}][HPW_{12}O_{40}]_{0.5}[NH_4PW_{12}O_{40}](NO_3)_2.16H_2O.5C_2H_5OH$.

Table 1. Taguchi OA_9 design employed to optimize reaction variables in the oxidative desulfurization of model fuel over PTA–HMT–Co catalyst

Experiment No	Catalyst dosage (mg)	Hydrogen peroxide dosage (μL)	Temperature (°C)	Time (h)	Desulfurization (%)
1	15	85	30	1	88.90
2	15	170	45	2	96.68
3	15	250	60	3	99.47
4	33	85	45	3	89.12
5	33	170	60	1	99.84
6	33	250	30	2	99.18
7	50	85	60	2	89.40
8	50	170	30	3	99.07
9	50	250	45	1	99.64

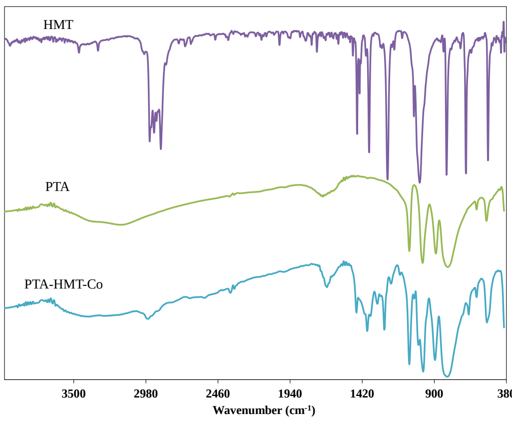

Figure 1. IR spectra of hexamine, phosphotungstic acid, and phosphotungstic acid- hexamine-cobalt hybrid.

3.2. Optimizing the ECODS Reaction Parameters for Model Fuel

To determine the optimal conditions for the oxidative desulfurization of model fuel using the PTA–HMT–Co hybrid catalyst, the Taguchi statistical design methodology was employed. This fractional factorial approach significantly minimizes the number of experimental trials required while maintaining reliable optimization accuracy [19]. In this study, the effects of key

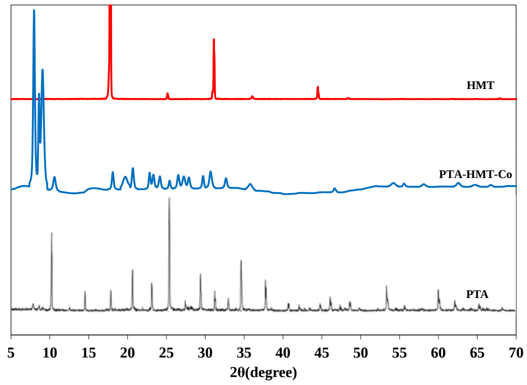

Figure 2. X-ray diffraction patterns of hexamine, phosphotungstic acid, and phosphotungstic acid-hexamine-cobalt hybrid.

operating factors-namely catalyst dosage, hydrogen peroxide amount, reaction temperature, and reaction time-on the ECODS efficiency of dibenzothiophene (DBT) were systematically evaluated.

The experimental matrix and corresponding factor levels are summarized in Table 1, while the desulfurization efficiencies obtained in each run are listed in the final column. The average response of each factor across its three levels revealed that variations in reaction conditions strongly influenced sulfur removal efficiency. The relative significance of each parameter was statistically determined through analysis of variance (ANOVA), and the results are summarized in Table 2. Based on ANOVA calculations at a 95% confidence interval, the descending order of influence among the studied variables was: hydrogen peroxide dosage > catalyst loading > temperature ≈ reaction time.

The average DBT conversion corresponding to each factor level is depicted in Figure 5. The catalyst loading was varied at 15, 33, and 50 mg, with 33 mg yielding the highest desulfurization performance (Figure 3a). Similarly, among the hydrogen peroxide dosages of 85, 170, and 250 µL, the maximum conversion was achieved at 250 µL (Figure 3b). Reaction temperature also exhibited a positive effect, with 60 °C identified as the optimal value (Figure 3c). In contrast, reaction time exerted only a marginal influence on sulfur removal, with negligible variations observed at longer reaction periods (Figure 3d).

Overall, hydrogen peroxide dosage was the most dominant factor influencing DBT oxidation, consistent with the fact that phosphotungstic acid

Table 2. Statistical analysis of variance (ANOVA) results for the effect of operational parameters on the ECODS efficiency of DBT model fuel

Factors	DOF (f)	Sum of Squares (S)	Variance (V)	Percent (%)
Catalyst dosage	2	82426.41	1.05	1.05
Hydrogen peroxide dosage	2	194.87	97.44	97.18
Temperature	2	1.78	0.89	0.89
Time	2	1.78	0.89	0.89

(PTA) and its encapsulated analogues are inactive in the absence of H_2O_2 [20].

Although the ANOVA results indicate that hydrogen peroxide dosage has the highest contribution to sulfur removal, the blank experiments shown in Figure 4 reveal that hydrogen peroxide alone is not capable of achieving effective oxidative desulfurization. The sulfur removal obtained in the absence of both catalyst and hydrogen peroxide is very close to that achieved in the presence of hydrogen peroxide without catalyst. This minor difference suggests that sulfur removal under these conditions mainly arises from the extractive effect of the solvent rather than oxidative conversion of sulfur compounds. In the absence of the catalyst, hydrogen peroxide is not efficiently activated to generate reactive oxidizing species. Therefore, the high contribution of H_2O_2 in the ANOVA analysis reflects its critical role as an oxidant only when used in combination with the PTA–HMT–Co catalyst.

The Taguchi method predicted nearly complete desulfurization at 33 mg catalyst, 250 µL of 35 wt% H_2O_2, 1 h reaction time, and 60 °C. These optimal parameters closely matched those of experimental run 5 (Table 1), except for hydrogen peroxide dosage. This observation is reasonable, as further increasing the hydrogen peroxide dosage from 170 to 250 µL produced only a marginal improvement in desulfurization efficiency (Figure 3b). The molecular nature of sulfur compounds in fuel significantly affects their reactivity during

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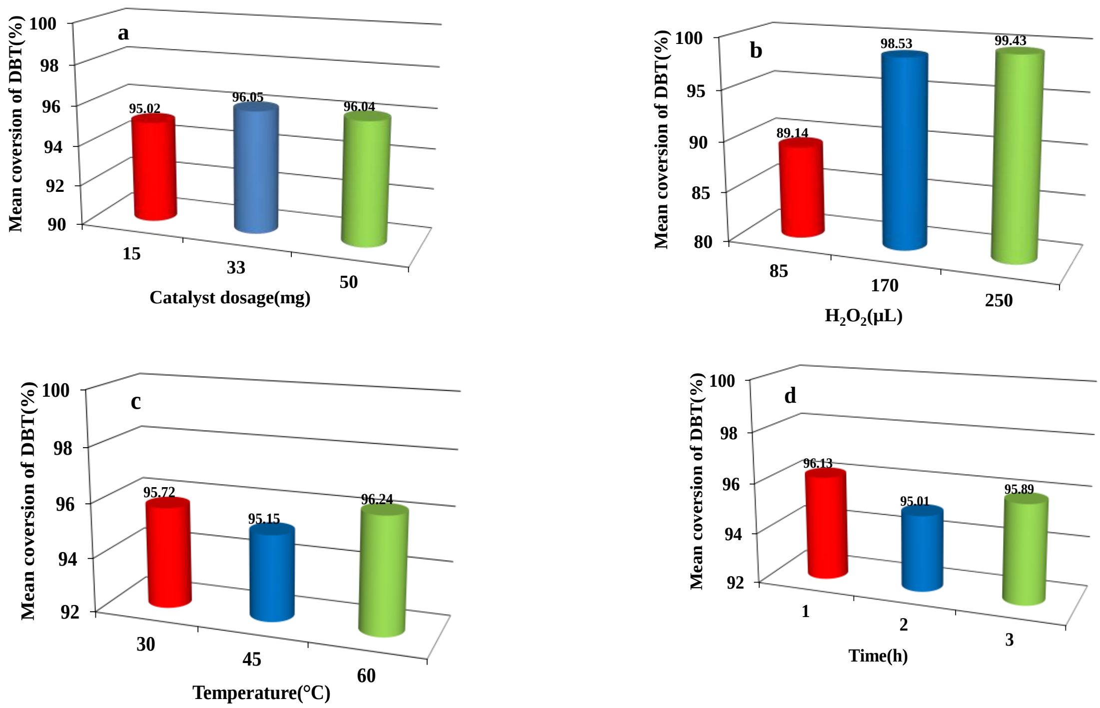

Figure 3. Influence of key process parameters on the oxidative desulfurization efficiency of DBT model fuel using the PTA–HMT–Co catalyst: (a) catalyst dosage, (b) H_2O_2 volume, (c) temperature, and (d) reaction time**.**

oxidative desulfurization. Therefore, to further assess the catalytic performance of the PTA–HMT–Co hybrid, the oxidation of benzothiophene (BT) was also examined under similar optimized conditions. The conversion of BT reached 80.23%, indicating lower reactivity compared to DBT. The lower oxidation efficiency of benzothiophene compared to dibenzothiophene can be attributed to its lower sulfur electron density, reduced π-electron delocalization and weaker interaction with peroxo species, which reduces its susceptibility toward oxidative transformation [21].

To benchmark the catalytic efficiency of the PTA–HMT–Co hybrid against previously reported PTA-based organic hybrid catalysts, a comparison of the main results is presented in Table 3. It is evident that the developed system achieves deep desulfurization of DBT under mild conditions comparable to or better than other reported hybrids. The major advantage of this catalyst lies in its economic and environmentally friendly synthesis route, as neither ionic liquids are required in catalyst preparation nor during the ECODS process, reducing overall cost and environmental burden. To evaluate the influence of cobalt incorporation on catalytic performance, the oxidative desulfurization activity of the PTA–HMT–Co hybrid was compared with that of the parent PTA–HMT catalyst (our pervious work) under identical operating conditions [22].

Both catalysts exhibited high oxidative efficiency toward dibenzothiophene (DBT) conversion, achieving nearly complete sulfur removal within similar reaction times. The introduction of cobalt into the hybrid framework did not significantly alter the overall desulfurization capacity, indicating that the main catalytic sites responsible for the ODS reaction are predominantly associated with the phosphotungstate and hexamine components. In the presence of Co^{2+} ions, the enhancement in sulfur removal efficiency was marginal. This suggests that cobalt acts primarily as a structural promoter rather than as an essential active center in the oxidation process. From a

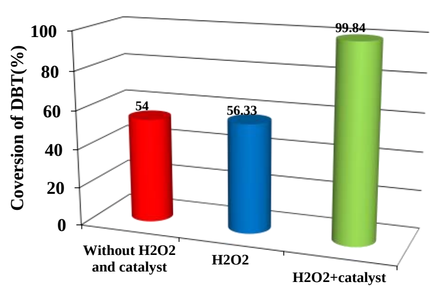

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Figure 4. Sulfur removal efficiency for DBT model fuel under extractive–oxidative conditions without catalyst and in the presence of PTA–HMT–Co catalyst. Reaction conditions: catalyst dosage 33 mg, H_2O_2 dosage 170 µL, time 1 h, temperature 60 °C.

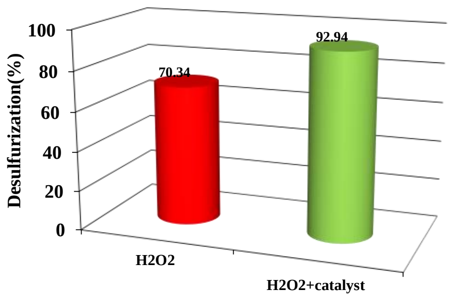


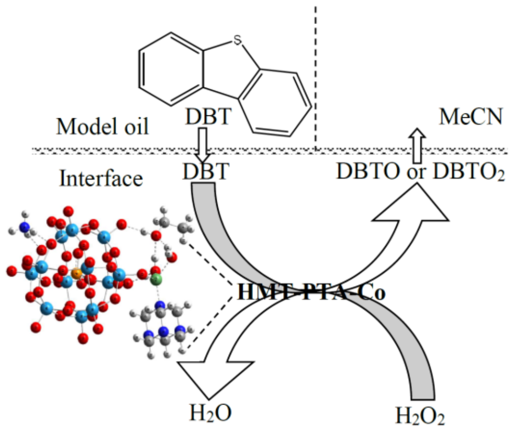
Figure 5. Sulfur removal efficiency for Ilam gas condensate under extractive–oxidative conditions without catalyst and in the presence of PTA–HMT–Co catalyst. Reaction conditions: catalyst dosage 200 mg, H_2O_2 dosage 5.9 mL, time 3 h, temperature 60 °C for 50 mL real sample.

practical perspective, this observation is important, as it confirms that the catalytic efficiency of the system is governed by the PTA–HMT architecture, while cobalt incorporation mainly contributes to maintaining consistent performance under repetitive oxidative conditions. Therefore, both PTA–HMT and PTA–HMT–Co hybrids can be considered efficient and comparable catalysts for oxidative desulfurization applications, with only minor differences in performance.

for the oxidation of sulfur-containing organic molecules. During the reaction, the peroxo species oxidize dibenzothiophene (DBT) sequentially to dibenzothiophene sulfoxide (DBTO) and subsequently to dibenzothiophene sulfone ($DBTO_2$). Following this transformation, the active peroxo complex is reduced, while the reduced catalyst species is readily reoxidized by hydrogen peroxide, thereby regenerating the active sites. Through this redox cycle, the catalyst continuously facilitates the conversion of organosulfur compounds and is restored to its original form after completion of the desulfurization process. The cobalt species are proposed to facilitate redox cycling and stabilize intermediate peroxo species, while the fundamental oxidation pathway follows the well-established phosphotungstate–H_2O_2 mechanism.

3.4. Proposed Mechanism of the Oxidative Desulfurization Process

The plausible reaction pathway for the oxidative desulfurization catalyzed by the PTA–HMT–Co hybrid is illustrated in Scheme 1. It is generally accepted that the phosphotungstate anion within the hybrid framework interacts with hydrogen peroxide to generate active peroxo species [1]. These oxygen-rich intermediates are responsible



Scheme 1. Proposed mechanism for oxidation desulfurization

Table 3. Benchmarking the desulfurization efficiency of the synthesized PTA–HMT–Co hybrid against previously reported polyoxometalate–organic hybrid catalysts

Catalysts	oxidant	extractant	T (°C)	t (h)	S (ppm)	O/S molar ratio	Conversion of DBT, BT (%)	Ref.
$[C_5H_5NH]_3PTA$	H_2O_2	IL	40	1.5	1000	6:1	99.8, 90	[1]
$[(C_4H_9)_4N]_3PTA$	H_2O_2	IL	40	1.5	1000	6:1	99.8, -	[1]
$[C_4H_6N_2H]_3PTA\cdot 3C_4H_6N_2$	H_2O_2	IL	40	1	1000	6:1	99.7, -	[1]
$(DDA)_3PTA$	H_2O_2	butanone/butanol	50	0.67	175	36:1	100, -	[11]
$[PSPy]_3PTA$	H_2O_2	IL	30	1	500	8:1	100, 69.9	[13]
$[Bmim]_3PTA$	H_2O_2	IL	30	1	500	8:1	97, 80	[14]
$[PhPyBs]_3PTA$	H_2O_2	Diethyl ether	70	6	100	24:1	75, -	[21]
$(n\text{-}Bu_4N)_3PTA$	H_2O_2/acetic acid	acetonitrile	60	2.5	640	20:1	52, -	[23]
$[MIMBS]_3PTA$	H_2O_2	acetonitrile	60	1.5	1000	12:1	99.9, -	[24]
$[C_2(MIM)_2]PTA$	H_2O_2	acetonitrile	50	1	85	6:1	98.0, -	[25]
$[C_1ImBs]_3PTA$	H_2O_2	acetonitrile	60	1	1000	6:1	99.0, -	[26]
$[C_3SO_3Hnhm]_3PTA$	H_2O_2	acetonitrile	50	1.75	1000	15:1	99.4, -	[27]
PTA-HMT	H_2O_2	acetonitrile	60	1	910	20.7:1	99.9, 70.3	[22]
PTA-HMT-Co	H_2O_2	acetonitrile	60	1	600	30.5:1	99.8, 80.2	This work

Note: DDA: dodecyl trimethyl ammonium, PSPy: (3-sulfonic acid) propylpyridine, Bmim: 1-butyl-3-methyl imidazolium, PhPyBs: 1-(4-sulfonic acid) 4-phenyl-pyridinium, MIMBS:1-(4-sulfonic acid) methylimidazolium, IL: ionic liquid, MIM: 1-methylimidazole.

DOI: 10.30473/IJAC.2026.76456.1331

3.5. Reusability and Stability of the Hybrid Catalyst

Catalyst recyclability is a crucial parameter in evaluating the practical and economic viability of heterogeneous catalytic systems. Therefore, the reusability of the PTA–HMT–Co hybrid catalyst was examined under identical oxidative desulfurization conditions. The results, summarized in Figure 6, illustrate the catalyst performance over multiple consecutive reaction cycles. Even after six reuse cycles, DBT conversion remained as high as 91.4%, indicating excellent stability and retention of catalytic activity. The slight reduction in efficiency observed after several runs is likely attributed to minor catalyst loss during the recovery and washing steps rather than structural degradation of the active sites. Although post-reuse characterization techniques such as FTIR or XRD were not conducted in the present study, the consistent catalytic performance observed over several consecutive reuse cycles indicates that the hybrid catalyst largely maintains its structural integrity under the applied reaction conditions. Moreover, in our previous catalytic studies [18] on structurally similar polyoxometalate-based hybrid catalysts, post-reuse characterization confirmed negligible structural changes after repeated use. Based on these prior findings and the stable recyclability results obtained here, additional post-reaction characterization was not considered essential within the scope of the current work. Although metal leaching was not directly quantified, the high catalytic stability observed over multiple cycles suggests strong ionic interactions between cobalt species and the hybrid framework, which effectively suppress metal loss during operation.

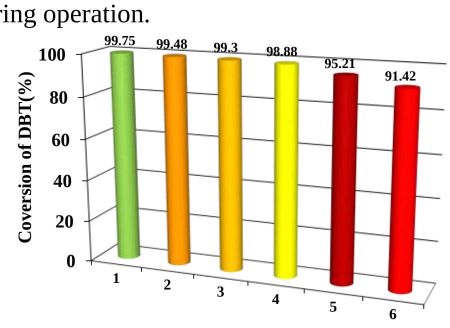


Figure 6. Reusability performance of the PTA–HMT–Co hybrid catalyst in consecutive oxidative desulfurization cycles.

4. Conclusions

In conclusion, the synthesized phosphotungstic acid–hexamine–cobalt hybrid catalyst demonstrated excellent performance for the extractive–oxidative desulfurization (ECODS) of model fuels using hydrogen peroxide as the oxidant and acetonitrile as the extraction solvent. Although acetonitrile is not an ideal extractant for industrial applications, it was employed as a benchmark solvent in this study. Future work will focus on replacing acetonitrile with greener extractants or ionic liquids. Among the investigated variables, the influence of reaction parameters followed the order: H_2O_2 dosage > catalyst amount > temperature ≈ reaction time. Under the optimized conditions, the sulfur concentration in the DBT model fuel was efficiently reduced from 600 ppmw to approximately 1 ppmw. While relatively high O/S ratios were employed to achieve deep desulfurization, the results demonstrate that efficient sulfur removal can be obtained under milder conditions, which is promising for future process optimization and scale-up. The catalyst exhibited remarkable reusability and retained high activity after multiple reaction cycles, confirming its structural stability during operation. Furthermore, the HMT–PTA–Co hybrid showed high catalytic efficiency in the oxidative desulfurization of real gas condensate under mild conditions, highlighting its potential as a robust and environmentally benign catalyst for practical fuel purification applications. The results indicate that cobalt does not act as the primary active center for sulfur oxidation; instead, it serves as a secondary redox promoter and structural stabilizer. The dominant catalytic activity originates from the phosphotungstate species, while Co^{2+} ions facilitate electron transfer and enhance the durability of the hybrid framework during repeated catalytic cycles. These findings highlight that both PTA–HMT and PTA–HMT–Co systems are viable and efficient catalysts for ECODS applications, with cobalt incorporation offering structural advantages rather than fundamentally altering catalytic activity.

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گوگرد زدایی اکسایشی ترکیبات تیوفنیک و میعانات گازی

مهدی تقدیری[۱و۲*]، محمد گلزاری[۱]

۱- بخش شیمی، دانشگاه پیام نور، تهران، ایران
۲- مرکز تحقیقات شیمی محیطی، دانشگاه پیام نور، اردکان، یزد
* E-mail: taghdiri@pnu.ac.ir, mehditaghdiri@yahoo.com

تاریخ دریافت: ۲۰ آبان ۱۴۰۴ **تاریخ پذیرش:**۱۳ دی ماه ۱۴۰۴

چکیدهدر این پژوهش، یک کاتالیست هیبریدی جدید بر پایه فسفوتنگستیک اسید–هگزامین–کبالت (PTA–HMT–Co) سنتز شد و برای گوگردزدایی اکسیداسیونی (ODS) ترکیبات تیوفنی مورد ارزیابی قرار گرفت. برای بهینه‌سازی پارامترهای کلیدی واکنش شامل دما، زمان واکنش، مقدار کاتالیست و نسبت اکسیدکننده به گوگرد، از طراحی متعامد تاگوچی L9 استفاده شد. شرایط بهینه منجر به دستیابی به بازده گوگردزدایی۹۹/۸۴٪ برای روغن مدل حاوی بنزوتیوفن و ۹۲/۹۴٪ برای نمونه‌های واقعی میعانات گازی شد. کاتالیست سنتزشده فعالیت اکسیداسیونی بالا، پایداری حرارتی مناسب و قابلیت بازیافت حداقل تا شش چرخه متوالی را از خود نشان داد. عملکرد بالای کاتالیستی عمدتاً به چارچوب کگین‌نوع فسفوتنگستیک اسید نسبت داده می‌شود، در حالی که حضور کبالت بیشتر در تثبیت ساختار و افزایش دوام کاتالیست نقش دارد و به‌عنوان مرکز فعال اصلی عمل نمی‌کند. نتایج این مطالعه پتانسیل بالای PTA–HMT–Co را به‌عنوان یک کاتالیست سبز و کارآمد برای گوگردزدایی عمیق در شرایط ملایم نشان می‌دهد.

کلید واژه ها

گوگردزدایی اکسایشی، کاتالیست هیبریدی، فسفوتنگستیک اسید–هگزامین–کبالت، بهینه‌سازی تاگوچی، دی‌بنزوتیوفن، میعانات گازی

DOI: 10.30473/IJAC.2026.76456.1331