Direct oxidation of benzene to phenol catalyzed by a vanadium-substituted heteropolymolybdic acid catalyst

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Abstract: The direct synthesis of phenol by hydroxylation of benzene with hydrogen peroxide over a vanadium substituted heteropolymolybdic acid catalyst was investigated at 70 °C. Hydrogen peroxide was used as the oxidant while 36 wt.% acetic acid was employed as the solvent. After 100 minutes, the selectivity for phenol was 93 % and the yield of phenol was 10.1 %. The catalyst was characterized by elemental analysis, thermogravimetry, infrared spectroscopy, UV-Vis spectroscopy, X-ray diffraction, and 31P-NMR and 51V-NMR techniques. The experimental conditions, such as reaction temperature, the amount of hydrogen peroxide and catalyst, were investigated. The as-prepared phenol could be separated by column chromatography and was characterized by infrared and mass spectrometry.

Keywords: vanadium substituted, heteropolymolybdic acid, hydroxylation of benzene, phenol.

INTRODUCTION

Phenol, one of the valuable intermediates for the synthesis of agrochemicals, petrochemicals, and plastics1–3 is mainly manufactured by the cumene process. However, this process consists of three steps, and has many disadvantages. For example, the one-pass yield of phenol remains at only 5 %, accompanied by a large energy consumption, especially in the distillation process for separating the products and reactants.4 Hence, finding a one-step process for the production of phenol by the direct oxidation of benzene, which is one of the most challenging tasks in oxidation catalysis, has attracted a lot of attention in recent years.4–8

Normally, the direct hydroxylation of benzene to phenol is performed both in the liquid and gas phase. To avoid deep oxidation, an oxygen species of mild reactivity seems to be necessary. One of the routes is the oxidation of benzene with N2O over ZSM-5 at 573–673 K.9–11 Other methods include catalytic hydroxylation of benzene with hydrogen peroxide. These reactions have been carried out in acetone, methanol or
acetonitrile using vanadium- or titanium-containing heterogeneous catalyst, such as Ti/MCM-41,12 TS-1,13 and VOx/MCM-4114 supported VOx catalysts.15 Recently, iron and chromium containing phosphotungstate salts were reported to be efficient catalysts for the hydroxylation of benzene.16,17 Various other catalytic systems involving a vanadium-exchanged heteropolyacid18 or palladium acetate were also reported to be catalytic precursors for the hydroxylation of benzene.19 However, the yield of benzene hydroxylation to phenol reported in the literature was relatively low and the as-prepared phenol was not separated. This motivated the present investigation of the reaction, in which the catalyst and reaction conditions were optimized to improve the yield and selectivity of phenol.

Heteropolyacids (HPAs) are transition metal oxygen anion clusters which exhibit a wide range of molecular sizes, compositions and architectures.20 Among them, the Keggin-type HPAs21 have been widely used as catalysts for oxidation reactions.22,23 One of the great advantages of HPAs is that their catalytic properties can be tuned by changing the identity of charge-compensating counter-cations, heteroatoms and framework metal atoms.24

In the present work, a vanadium-substituted heteropolymeric acid was synthesized. Its catalytic behavior was tested in the hydroxylation of benzene with hydrogen peroxide as the oxidant and 36 wt.% acetic acid as the solvent. Optimum reaction conditions for the hydroxylation of benzene to phenol were investigated and are discussed.

EXPERIMENTAL

Catalyst preparation

The purchased chemicals (analytical grade) were used without further purification. Na2MoO4·2H2O, Na2HPO4·12H2O, V2O5, Na2CO3, H3PMo12O40, silica gel H, and cation exchange resin (001×7) 732 were purchased from the Shanghai Chemical Co. Ltd., and diethyl ether, H2SO4, hydrogen peroxide, 36 wt.% acetic acid from the Chengdu Chemical Co., Ltd.

The vanadium substituted heteropolymeric acid was synthesized according to a previous method,25 which was modified to obtain a high yield of the heteropolyacid. The experimental details were as follows: 18.0 g of Na2HPO4·12H2O was dissolved in 250 mL distilled water and 4.6 g of V2O5 was dissolved in 100 mL of 2 mol·L−1 Na2CO3 solution. These solutions were mixed and heated to boiling. After thirty minutes of boiling 133.0 g Na2MoO4·2H2O dissolved in 400 mL distilled water was added to the above-mentioned mixture and the temperature was maintained at 90 ºC for 30 min. Then 1:1 H2SO4 was added dropwise under stirring to the solution until a pH of 2 was attained. The stirring was continued until the mixture was at room temperature, and then 150 mL diethyl ether was added to the mixture. After thoroughly shaking, 1:1 H2SO4 was added until three layers appeared in the solution. The middle oil-like red material (heteropolyacid–ether compound) was collected and the ether was removed. Some distilled water was then added and the product placed in a vacuum desiccator. The resulting fine orange powder was characterized and used for the hydroxylation of benzene.

Apparatus and instrumentation

Elemental analyses of the HPA sample were performed by ICP-atomic emission spectroscopy, IRIS Advantage ER/S.
Thermogravimetric (TG) and differential thermal analyses (DTA) curves were acquired using a thermoanalysis instrument (EXSTAR-6000, TG/TDA6300) under a nitrogen atmosphere at a heating rate of 10 °C/min.

Infrared spectra (IR) of the heteropolyacids were recorded on a FT-IR-8400 spectrometer at room temperature using the KBr pellet technique.

The electronic spectra of the catalysts in acetic acid were recorded at room temperature on a TU-1901 UV-Vis spectrometer.

Powder X-ray diffraction experiments were carried out on a DX-1000 diffraction instrument using CuKα radiation at a wavelength of 0.154060 nm. A scan rate of 0.03 °C/s with a step size of 0.0300 ° was used for data collection.

31P-NMR and 51V-NMR were recorded on an AVANCE 300 spectrometer. The 31P-NMR spectra were directly measured in D2O and the 51V-NMR spectra, referenced to an external standard of VOCl3, were measured by a substitution method.

**Catalytic tests**

The oxidation of benzene in the liquid-phase was performed in a three-necked 150 mL round-bottom flask (placed in a water bath) at 70 °C. Typically, 0.3 mmol catalyst and 2 mL of benzene were added to 25 mL of acetic acid (36 wt.%) as solvent. Five milliliters of H2O2 (30 wt.%) were added dropwise over 30 min by titration through one neck of the flask. A magnetic stirrer was provided to stir (600 rpm) the reaction mixture. After all the H2O2 had been added, the reaction mixture was stirred for a further 70 min at 70 °C. The oxidation reaction was monitored at various time intervals by GC analysis (GC-960 equipped with a hydrogen flame detector and a capillary column). Then, the resulting samples were analyzed by GC. o-Cresol was used as an internal standard to quantify the phenol formed.

The self-decomposition of H2O2 in the presence of the catalysts was measured by the amount of O2 released under the reaction conditions in controlled experiments. Another controlled experiment was carried out using NaVO3 as the catalyst for the hydroxylation of benzene under the same reaction conditions.

The yield of phenol was calculated as mmol phenol / mmol initial benzene. The selectivity of phenol was calculated as mmol phenol / (mmol phenol + mmol HQ + mmol BQ). The self-decomposition of H2O2 was calculated from the volume of oxygen released in controlled experiment. The conversion of H2O2 was calculated as the consumption of H2O2 (including self-decomposition) / the amount of H2O2 added. The selectivity of the H2O2 was calculated as mmol of H2O2 for phenol formation / mmol total H2O2 consumed.

The products were also separated by column chromatography using silica gel H as the stationary phase and dichloromethane containing 5 % ethyl acetate as the mobile phase. Further, IR (FT-IR-8400) and MS (Finnigan MAT 4510) were used for the characterization of the formed phenol.

**RESULTS AND DISCUSSION**

*Catalyst sample (desired to prepare H4PMo11VO40·xH2O) characterization*

The infrared spectrum of the sample over the range of 700–1100 cm⁻¹ showed absorption bands at 1051 cm⁻¹, 961 cm⁻¹, 864 cm⁻¹ and 786 cm⁻¹, corresponding to the four typical skeletal vibrations of the Keggin oxoanion.²⁶ These peaks could be attributed to v(P–O), v(Mo–O), v(Mo–O₇–Mo), v(Mo–O₈–Mo) (O₇: corner-sharing oxygen, O₈: edge-sharing oxygen), respectively. The UV-Vis spectrum of the sample in acetic acid displayed absorption bands at 251 nm and 308 nm, which are probably associated with the vanadium in the heteropoly cage.²⁵ It has been suggested²⁷ that these absorption bands should be ascribed to the charge transfer band of octahedrally
coordinated $\text{Mo}^{6+}$. The Keggin nature of the heteropolyacids was also confirmed by X-ray diffraction, which exhibited typical peaks at $2\theta$: 8.3, 9.0, 27.8 and 29.1°. Evidently, the obtained sample belonged to the set of Keggin-type heteropolyacids. TG/DTA analysis of the sample showed a weight loss of 11.7% below 150°C, corresponding to the release of hydrated water, which gives a $\chi$ value of about 13. ICP analysis indicated that the composition of sample was $P$, 1.51; $\text{Mo}$, 50.06; $V$, 2.82, that is, the found atomic ratio of $P$/Mo/$V$ was: 1.00/10.72/1.14. If the sample were pure $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$, the composition should be $P$, 1.54; $\text{Mo}$, 52.38; $V$, 2.53. Thus, the $V$ content found in sample was higher than that required for $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$. The $^{31}\text{P}$-NMR ($\text{D}_2\text{O}$, at room temperature) gave two peaks, one at –3.87 ppm (major peak) and the other at –3.54 ppm (minor peak), indicating the existence of two types of $P$, as shown in Fig. 1. Correspondingly, the $^{51}\text{V}$-NMR ($\text{D}_2\text{O}$, at room temperature) also gave two peaks, one at –533.76 ppm (major peak) and the other at –540.25 ppm (minor peak). These facts indicate the presence of $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ (major) and $\text{H}_5\text{PMo}_{10}\text{V}_2\text{O}_{40}$ (minor), which is consistent with the literature. The above information implies that the sample obtained was a mixture composed of $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ (major) and $\text{H}_5\text{PMo}_{10}\text{V}_2\text{O}_{40}$ (minor).

**Catalytic properties**

*Separation and characterization of product.* The as-prepared phenol was separated by column chromatography on silica gel H, as the stationary phase, using dichloromethane containing 5% ethyl acetate as the mobile phase. The prominent IR
bands of the as-prepared phenol appeared at 3402.4 cm\(^{-1}\), 1596.0 cm\(^{-1}\), 1434.0 cm\(^{-1}\), 1230.0 cm\(^{-1}\), 754.0 cm\(^{-1}\) and 690.0 cm\(^{-1}\), which is consistent with the characteristic spectra of phenol\(^{31}\). The 94 (M\(^+\)) peak in the MS measurement also confirms this feature. Hence, the IR spectrum and mass spectrometry measurements confirm that the product obtained was really phenol.

**Effect of vanadium atoms in the heteropolyacid.** The above prepared vanadium-substituted heteropolyacid sample and a controlled sample of molybdophosphoric heteropolyacid (H\(_3\)PMo\(_{12}\)O\(_{40}\)) were used as catalysts for benzene hydroxylation. The results are shown in Table I. The presence of vanadium atoms in the heteropolyacid is essential for performing the oxidation of benzene to phenol. Only a trace amount of phenol was observed when HPA without vanadium substitution was used as the catalyst. Simultaneously, another controlled experiment was carried out using NaVO\(_3\) as the catalyst for benzene hydroxylation under the same reaction conditions. The results are also shown in Table I. It was found that NaVO\(_3\) also acts as a catalyst for the titled reaction, but the yield of phenol only reached 5.59 %, which is just about a half and about 4.52 % less than that obtained using the vanadium-substituted heteropolyacid sample as catalyst. These data reveal that different vanadium species, including those formed in NaVO\(_3\) and the HPA, are all responsible for the hydroxylation of benzene and that the vanadium species existing in the HPA are quite effective. It is suggested that the catalysis by HPAs for the hydroxylation of benzene is due to the cooperative action of the molybdenum framework with one vanadium (V) center\(^{29}\). This cooperative effect is present in HPAs; thus, the activity of the HPA sample was higher than that of NaVO\(_3\) for the hydroxylation of benzene to phenol. This implies that the structure of the HPA is important.

**Effect of the amount of the catalyst.** The yield of phenol versus the amount of catalyst is shown in Fig. 2, from which it can be seen that the yield of phenol increased with increasing amount of catalyst. However, rate of the increase of the yield

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**Fig. 2.** Effect of the amount of catalyst on the yield of phenol. Experimental conditions: 2 mL of benzene, 25 mL of acetic acid (36 wt.%) and 5 mL of H\(_2\)O\(_2\) (30 wt.%); reaction time 100 min at 70 °C.

**Fig. 3.** Effect of temperature on the yield of phenol. Experimental conditions: 0.3 mmol catalyst, 2 mL of benzene, 25 mL of acetic acid (36 wt.%) and 5 mL of H\(_2\)O\(_2\) (30 wt.%); reaction time 100 min.
tailed off when the amount of the catalyst exceeded 0.3 mmol. Remias et al.\textsuperscript{32} studied the effect of the amount of vanadium loading on the activity for benzene hydroxylation; an optimum critical vanadium loading was observed and was interpreted by the assumption that the catalytically active species was monomeric vanadium species. It was proposed that higher vanadium loading favored the existence of vanadium in the form of the inactive \(\mu\)-oxo dimer. The results obtained in the present work are consistent with the literature; that is, excessive vanadium does not result in a significant increase in the yield of phenol. The HPA structure may provide a structure favorable for the reaction.

\textit{Effect of temperature.} To investigate the effect of temperature on the yield of phenol, the temperature was varied from 20 °C to 90 °C, with the other parameters being kept constant. The results are shown in Fig. 3, from which it can be seen that the yield of phenol increased with increasing temperature. The yield of phenol decreased slightly when reaction temperature exceeded 70 °C. The reason for this decrease may lie in the fact that the higher temperatures favored volatilization, the deep oxidation of benzene and the self-decomposition of H\(_2\)O\(_2\).

\textit{Effect of the amount of H\(_2\)O\(_2\).} The effect of the amount of H\(_2\)O\(_2\) on the yield of phenol is presented in Fig. 4. No phenol was obtained without H\(_2\)O\(_2\), while the yield of phenol increased with increasing amount of H\(_2\)O\(_2\) and reached a maximum at 5 mL (48.5 mmol) H\(_2\)O\(_2\); this corresponds to a molar ratio of H\(_2\)O\(_2\) to benzene of about 2.1. A slight decrease in the yield of phenol was observed when the amount of H\(_2\)O\(_2\) was further increased. This may result from the further oxidation of the formed phenol. The GC-MS (HP-689015973 GC/MS) results show that the reaction also produces small amounts of hydroquinone and benzoquinone and trace amounts of hexanoic acid and 2,5-furandione, besides the main product. The stoichiometric ratio of H\(_2\)O\(_2\) to benzene for the hydroxylation reaction is 1:1, while the results show that the amount of H\(_2\)O\(_2\) required for a favorable yield of phenol

![Fig. 4. Effect of amount of H\(_2\)O\(_2\) on the yield of phenol. Experimental conditions: 0.3 mmol catalyst, 2 mL of benzene, 5 mL of acetic acid (36 wt.%); reaction time 100 min at 70 °C.](image)

![Fig. 5. Effect of the amount of acetic acid on the yield of phenol. Experimental conditions: 0.3 mmol catalyst, 2 mL of benzene and 5 mL of H\(_2\)O\(_2\) (30 wt.%); reaction time 100 min at 70 °C.](image)
was about two times the stoichiometric amount. In fact, in the present reaction system, the catalyzed benzene oxidation is accompanied by self-decomposition of the hydrogen peroxide. As shown in Table I, the amount of H$_2$O$_2$ consumed by self-decomposition is much more than that consumed in the hydroxylation reaction. This may be why more than the stoichiometric amount of H$_2$O$_2$ is required.

**TABLE I. Catalytic performance of different catalysts in the oxidation of benzene**

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Phenol mmol</th>
<th>HQ mmol</th>
<th>BQ mmol</th>
<th>Yield$^a$ %</th>
<th>Selec.$^b$ %</th>
<th>Self-decom.$^c$ mmol</th>
<th>Conv.$^d$ %</th>
<th>Selec.$^e$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>No catalyst</td>
<td>trace</td>
<td></td>
<td></td>
<td>16.4</td>
<td>33.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$<em>3$PMo$</em>{12}$O$_{40}$</td>
<td>trace</td>
<td></td>
<td></td>
<td>28.2</td>
<td>58.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$<em>3$PMo$</em>{11}$VO$_{40}$</td>
<td>2.28</td>
<td>0.05</td>
<td>0.13</td>
<td>10.11</td>
<td>92.7</td>
<td>26.8</td>
<td>61.0</td>
<td>7.7</td>
</tr>
<tr>
<td>NaVO$_3$</td>
<td>1.26</td>
<td>0.04</td>
<td>0.18</td>
<td>5.59</td>
<td>85.1</td>
<td>29.3</td>
<td>64.3</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Experimental conditions: 0.3 mmol catalyst, 2 ml (22.56 mmol) of benzene, 5 ml (48.5 mmol) of H$_2$O$_2$ and 25 ml of acetic acid (36 wt.%); reaction time 100 min at 70 ºC. HQ = hydroquinone, BQ = benzoquinone. $^a$Yield = Yield of phenol: calculated as mmol phenol / mmol initial benzene. $^b$Selec. = Selectivity of phenol: calculated as mmol phenol / (mmol phenol + mmol HQ + mmol BQ). $^c$Self-decom. = Self-decomposition of H$_2$O$_2$: calculated as the volume of oxygen released during the reaction. $^d$Conv. = Conversion of H$_2$O$_2$: calculated as the consumption of H$_2$O$_2$ (including self-decomposition) / initial amount of H$_2$O$_2$. $^e$Selec. = Selectivity of H$_2$O$_2$: calculated as mmol consumption of H$_2$O$_2$ for phenol formation / mmol consumption of H$_2$O$_2$.

Thus, the excess H$_2$O$_2$ may be consumed in the deep oxidation of benzene and in its self-decomposition. The selectivity of the H$_2$O$_2$ was quite low; thus, enhancement of the effective deployment of the H$_2$O$_2$ in the present reaction system offers a further challenge.

**Effect of the amount of acetic acid.** The influence of the amount of acetic acid on the yield of phenol is shown in Fig. 5, from which it is obvious that the yield of phenol increased with increasing amount of acetic acid. The yield of phenol was the highest when 25 mL of 36 wt.% acetic acid was used. This is due to the fact that the amount of benzene dissolved increases with increasing amount of acetic acid. Two milliliters of benzene was completely dissolved when 25 mL of 36 wt. % acetic acid was used.

**Effect of reaction time.** The effect of the reaction time on the yield of phenol is shown in Fig. 6, from which it can be observed that the yield of phenol reached a maximum value of 10.1 % at a reaction time of 100 min, after which the yield remains nearly constant. This indicated that the optimized reaction conditions are more favorable than the reported ones,$^{13,33}$ because even though much longer reaction times were employed, the yields of phenol were less.

**Stability of the catalyst.** After reaction, the catalysts were recovered by column chromatography on silica gel H using dichloromethane containing 5 % ethyl
acetate as the mobile phase. The yield of phenol was 8.6 % when recovered catalyst was reused for benzene hydroxylation under the same conditions, that is, the yield of phenol over recovered catalyst was lower than over the corresponding fresh catalyst. The slight decrease in activity for the recovered catalyst may be attributed to the loss of catalyst during the recovery of the catalyst.

The recovered catalyst was characterized by FT-IR, as well as $^{31}$P and $^{51}$V NMR spectroscopy and the results are shown in Table II and Fig. 1 (b), respectively. The FT-IR data show that the four typical skeletal vibrations of the Keggin oxoanion remained. Figure 1 shows that the $^{31}$P and $^{51}$V NMR spectra of the catalyst before and after use in the reaction are different. The recovered catalyst gave only one $^{31}$P NMR signal at –3.90 ppm. The $^{51}$V NMR of the recovered catalyst retained its complexity, however, the strongest $^{51}$V signal of the recovered catalyst is at –533.68 ppm. These data suggest that the Keggin structure of $\text{H}_4\text{PMo}_{11}\text{VO}_{40}$ remained after the catalyst had been used in the reaction. The $^{51}$V NMR spectrum of the recovered catalyst also showed a peak at –536.84 ppm suggesting the existence of cationic VO$_2^+$ species, which must have been generated by the decomposition of $\text{H}_5\text{PMo}_{10}\text{V}_2\text{O}_{40}$.29,34 The $^{51}$VNMR spectrum also showed a peak at –536.84 ppm suggesting the existence of cationic VO$_2^+$ species, which must have been generated by the decomposition of $\text{H}_5\text{PMo}_{10}\text{V}_2\text{O}_{40}$.29,34,35

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>The data of IR / cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh catalyst</td>
<td>1051 961 864 786</td>
</tr>
<tr>
<td>Recovered catalyst</td>
<td>1056 962 868 782</td>
</tr>
<tr>
<td>Recovered I*</td>
<td>1055 962 867 783</td>
</tr>
</tbody>
</table>

The recovery of the catalyst was performed by column chromatography; recovered I*: The VO$_2^+$ in the recovered catalyst was removed by the cation exchange resin (001 × 7) 732.

The cationic VO$_2^+$ species in the recovered catalyst was removed by the cation exchange resin (001 × 7) 732. The yield of phenol was 7.5 % while the remaining catalyst (marked as recovered I*) was reused for benzene hydroxylation under the same conditions. The yield of phenol was lowered again. The recovered I* was also characterized by FT-IR, as well as $^{31}$P and $^{51}$V NMR spectroscopy and the re-
results are shown in Table II and Fig. 1 (c), respectively. The recovered I* gives only one $^{31}$P signal at −3.90 ppm and only one $^{51}$V signal at −534.0 ppm, the $^{51}$V signal at −536.84 ppm having disappeared, indicating the existence of only one HPA species. According to the NMR spectra of $^{31}$P and $^{51}$V, the remaining species is H$_4$PMo$_{11}$VO$_{40}$.$^{29,34}$ The FT-IR spectrum of the recovered I* again confirms the Keggin structure of H$_4$PMo$_{11}$VO$_{40}$. These data imply that H$_4$PMo$_{11}$VO$_{40}$ is a stable and reusable catalyst for the hydroxylation of benzene to phenol. The slight decrease in activity of the recovered I* may be attributed to the removal of the cationic VO$_2^+$ species.

**CONCLUSION**

An investigation of the one-step liquid-phase hydroxylation of benzene to phenol by hydrogen peroxide on a vanadium-substituted heteropolyacid catalyst has been described. Satisfactory results were obtained with a selectivity of 93 % and a yield of 10.1 % to phenol, respectively. The effects of various parameters on the yield of phenol have been discussed. The vanadium substituted heteropolyacid H$_4$PMo$_{11}$VO$_{40}$ exhibits good activity and stability for the hydroxylation of benzene to phenol.

**ИЗВОД**

ДИРЕКТНА ОКСИДАЦИЈА БЕНЗЕНА У ФЕНОЛ КАТАЛИЗОВАНА ХЕТЕРОПОЛИ МОЛИБДЕНСКОМ КИСЕЛИНОМ СА ВАНАДИЈУМОМ КАО СУПСТИТУЕНТОМ

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Испитивана је директна катализована синтеза фенола на 70 °C хидроксиловањем бензена водоник-пероксидом на хетерополи молибденској киселини са ванадијумом као супститутентом. Као оксидационо средство коришћен је водоник-пероксид, док је раствараћа била 36 % сирћетна киселина. После 100 минута селективност за фенол била је 93 % док је пренос фенола био 10,1 %. Катализатор је карактерисан елементалном анализом, термогравиметријском анализом, инфрацрвеној и UV-Vis спектроскопијом, рендгенском дифракцијом и $^{31}$P-NMR и $^{51}$V-NMR техникама. Проучени су утицаје реакције температуре, количине водоник-пероксида и количине катализатора. Добијен фенол се може одвојити хроматографијом на колони, а карактерисан је инфраспреченом и масеном спектроскопијом.

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