

Short communication

$H_{3+x}PMo_{12-x}V_xO_{40}$ (heteropolyacids)-catalyzed regioselective nitration of phenol to *o*-nitrophenol in heterogeneous system

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Abstract

Mononitration of phenol was examined, using nitric acid in the presence of heteropolyacids $H_{3+x}PMo_{12-x}V_xO_{40}$ ($x=1-3$) in different solvents. In all cases heteropolyacid with $x=3$ gave the highest yield by using carbon tetrachloride as solvent. The effects of various parameters such as concentration of phenol, solvent, temperature and time of reaction have been studied.

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1. Introduction

Nitration of aromatic compounds is widely used in organic syntheses and in industrial applications [1]. The most important nitro aromatic compounds in environmental chemistry are nitro-PAHs and nitrophenols [2].

The nitration of phenol is a fundamental processes, because nitrophenols are important intermediates for the manufacture of drugs and pharmaceuticals. Among these compounds *ortho*-nitrophenol (*o*-nitrophenol) is an important starting material used in multiple step synthesis of valuable compounds [3]. A variety of nitrating agents have been employed in nitration of phenols but usually these nitration reactions are not selective. Impregnated alumina and silica with N_2O_4 [4], $NaNO_3$ in a two phase system (water–ether) in the presence of catalytic amount of $La(NO_3)_3$ [5], an ionic complex of N_2O_4 with 18-crown-6 [6], ceric ammonium nitrate in the presence of $NaHCO_3$ [7], metal nitrates [8], nitronium tetrafluoroborate [9], zirconyl nitrate [10], have been used as nitrating agents for phenols.

Meanwhile zeolites-based solid acid catalysts [11], iron loaded sulfated titania catalyst [12], claycop (copper(II) nitrate

supported on K10-Montmorillonite) [13], ionic liquids [14], and TBAB as transfer catalyst [15] have been used as catalyst for regioselective nitration of phenols.

Considering these reactions and with the cause of environmental concerns, there is still a good scope for research towards finding green and eco-friendly catalysts for regioselective nitration of phenols.

Heteropolyanions are polymeric oxoanions formed by the condensation of more than two different mononuclear oxoanions [16]. The use of heteropolyacids, HPAs, as catalyst for fine organic synthesis processes is developing and synthesis of antioxidants, medicinal preparations, vitamins and biologically active substances has been reported by using them [17]. In addition, these catalysts are very important for industries related with fine chemicals as flavors, pharmaceutical and food industries [18]. Among the numerous heteropolyacids, heteropolymolybdates and tungstates related to the Keggin structure have received much attention [19,20].

Recently, we have investigated various catalytic performances of heteropolyacids in different reactions [21]. In seeking to develop new synthetic methods for organic compounds by using heteropolyacids, in the present work, the performance and applicability of three kinds of vanadium(V)-substituted polyoxomolybdates such as $H_4PMo_{11}VO_{40}$, $H_5PMo_{10}V_2O_{40}$, and $H_6PMo_9V_3O_{40}$ has been studied for regioselective nitration of

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phenol under mild experimental conditions. We have found that $H_6PMo_9V_3O_{40}$ in carbon tetrachloride as solvent afforded the regioselective *o*-nitrophenol in excellent yield.

2. Results and discussion

Nitration of phenol with nitric acid in different solvents was explored using vanadium(V)-substituted polyoxomolybdates, $H_{3+x}PMo_{12-x}V_xO_{40}$ ($x = 1-3$). Heteropolyacids with $x = 1-3$ catalyze the nitration of phenol leading to *o*-nitrophenol as major product depending on the solvent of the reaction. In a systematic study and aimed work, in the presence of all of the catalysts, the reaction has been examined with different solvents and then in the solvent of choice. The effects of the reaction temperature have also been studied. At the next stage, in the best solvent and temperature the effects of the reaction time have been studied. Finally in optimum conditions the effects of the concentration of phenol has been checked.

2.1. Effect of the solvent

The nitration of phenol at reflux temperature was carried out using various common solvents such as CCl_4 , CH_2Cl_2 and $CHCl_3$. The results are shown in Table 1. With using all of the catalysts the highest yield of *o*-nitrophenol was obtained with CCl_4 as solvent. In addition, the time required for completion of the reaction was found to be less in CCl_4 . GC analysis showed by using dichloromethane and chloroform as a solvent, the selectivity for *o*-nitrophenol is lower and a mixture of 2-nitro- and 2,4-dinitrophenol are obtained. The highest yield of 100% and selectivity 100% for *o*-nitrophenol in carbon tetrachloride indicates the influence of the solvent on the yield of reaction.

Because of large negative charge of polyoxoanions, all of the HOMOs and LUMOs of them have very high energy levels. These highly charged heteropolyanions do not exist in the gas phase and that the external field generated by the solvent is crucial to stabilize them. With regard to the heteropolyanions which are reducible easily and is required in catalytic reactions, the energy of the LUMO must be sufficiently low to accept the electrons in catalytic reactions. The solvent molecules can place these molecular orbitals at the appropriate level. As shown in Table 1, the solvent effects change in parallel to the charges of

the anions. The greater negative charge lead to the greater solvent effects and finally the higher yields. It is suggested that the solvent effects are dominated by the interactions of the polarized polyanions with the solvent, to place the molecular orbitals at the appropriate level and or to lower the activation energy. Apparently this effect is higher for CCl_4 .

2.2. Effect of the catalyst

The heteropolyacids of the series $H_{3+x}PMo_{12-x}V_xO_{40}$ ($x = 1-3$) showed good to excellent catalytic behaviors in the nitration of phenol in CCl_4 , CH_2Cl_2 and $CHCl_3$. The results are shown in Table 1. $H_6PMo_9V_3O_{40}$ catalyzes efficiently the formation of *o*-nitrophenol giving a total yield of 100% in CCl_4 . The yield with this catalyst was found to be decreased from 100% to 85% when the solvent was changed from CCl_4 to $CHCl_3$ (entries 7–9). In addition, $H_4PMo_{11}VO_{40}$ and $H_5PMo_{10}V_2O_{40}$ gave a total yield 93% and 96% in CCl_4 , respectively (entries 1 and 4). In another word, the activities of the $H_{3+x}PMo_{12-x}V_xO_{40}$ ($x = 1-3$) catalysts in the nitration of phenol in CCl_4 were found to decrease in the following order: $H_6PMo_9V_3O_{40} > H_5PMo_{10}V_2O_{40} > H_4PMo_{11}VO_{40}$. Many properties of the heteropoly compounds in solution depend on the concentration, the reaction time, the reaction temperature, the solvent type, the structure of catalyst, the pH value of the solution, and other factors.

The Keggin anion have an assembly of 12 corner-shared octahedral MoO_6 from trimetallic groups $[Mo_3O_{13}]$ around a heteroatom tetrahedron PO_4 [22]. The introduction of vanadium(V) into the Keggin framework of $[PMo_{12}O_{40}]^{3-}$ is beneficial for catalysis reactions [23]. Usually positional isomers are possible and coexist when two or more vanadium atoms are incorporated into the Keggin structure (for example 5 and 13 isomers for $x = 2$ and 3, respectively) [24]. Studies on these isomers in catalytic reactions indicate that different isomers cause to show different reactivities [25].

With respect to the catalytic performances for these catalysts and the overall effects of all isomers, for synthesizing of them, we cannot control the reaction conditions to synthesis of positional vanadium-substituted isomers separately, revealing the relationship between the structures of $H_{3+x}PMo_{12-x}V_xO_{40}$ ($x = 1-3$) and hence study of their catalytic activity, is difficult.

However, because the metal substitution may modify the energy and composition of the LUMO and redox properties, for mentioned heteropolyacids with different charges, the energy and composition of the LUMOs have significant effects on the catalytic activity [26]. Substitution of vanadium ions into the molybdenum framework stabilize the LUMOs because these orbitals derive, in part from vanadium d-orbitals which have been assumed to be more stable than those of molybdenum and tungsten [27].

The abundance of different isomers may also play an important role in catalytic performance. In addition, different positional Mo atom(s) substituted by the V atom(s) in $[PMo_{12}O_{40}]^{3-}$ may create different vanadium chemical environments, thus causing these catalysts to exhibit varying catalytic performances.

Table 1
Catalytic nitration of phenol in the presence of different solvents

Solvent	Catalyst	Temperature (°C)	Time (h)	Yield (%) ^a
CCl_4	$H_4[PMo_{11}VO_{40}]$	Reflux	5	93
CH_2Cl_2	$H_4[PMo_{11}VO_{40}]$	Reflux	5.5	82
$CHCl_3$	$H_4[PMo_{11}VO_{40}]$	Reflux	6	50
CCl_4	$H_5[PMo_{10}V_2O_{40}]$	Reflux	2.5	96
CH_2Cl_2	$H_5[PMo_{10}V_2O_{40}]$	Reflux	3	58
$CHCl_3$	$H_5[PMo_{10}V_2O_{40}]$	Reflux	4	41
CCl_4	$H_6[PMo_9V_3O_{40}]$	Reflux	1.5	100
CH_2Cl_2	$H_6[PMo_9V_3O_{40}]$	Reflux	1.5	87
$CHCl_3$	$H_6[PMo_9V_3O_{40}]$	Reflux	2	85

^a Yields analyzed by GC.

Table 2
Catalytic nitration of phenol in CCl₄ under different temperatures

Entry	HPA	Temperature (°C)	Yield (%) ^a
1	H ₄ [PMo ₁₁ VO ₄₀] ^b	25	24
2	H ₄ [PMo ₁₁ VO ₄₀] ^b	30	36
3	H ₄ [PMo ₁₁ VO ₄₀] ^b	40	55
4	H ₄ [PMo ₁₁ VO ₄₀] ^b	55	67
5	H ₄ [PMo ₁₁ VO ₄₀] ^b	78	93
6	H ₅ [PMo ₁₀ V ₂ O ₄₀] ^c	25	13.8
7	H ₅ [PMo ₁₀ V ₂ O ₄₀] ^c	30	31
8	H ₅ [PMo ₁₀ V ₂ O ₄₀] ^c	40	55
9	H ₅ [PMo ₁₀ V ₂ O ₄₀] ^c	55	71
10	H ₅ [PMo ₁₀ V ₂ O ₄₀] ^c	78	96
11	H ₆ [PMo ₉ V ₃ O ₄₀] ^d	25	27
12	H ₆ [PMo ₉ V ₃ O ₄₀] ^d	30	45
13	H ₆ [PMo ₉ V ₃ O ₄₀] ^d	40	63
14	H ₆ [PMo ₉ V ₃ O ₄₀] ^d	55	77.5
15	H ₆ [PMo ₉ V ₃ O ₄₀] ^d	78	100

^a Yields analyzed by GC.

^b Reaction time = 5 h.

^c Reaction time = 2.5 h.

^d Reaction time = 1.5 h.

Besides of energy and composition of the LUMO and abundance of different isomers, the presence of both Bronsted acidity and vanadium in the structure of mentioned heteropolyacids, is responsible for catalytic activity. The greater protons number may lower, the activation energy barrier and the greater vanadium atoms may provide many sites for catalytic reaction.

2.3. Effect of the reaction temperature

The temperature effect on the nitration of phenol in the solvent of choice (CCl₄) was also carefully investigated. The reaction was carried out in the presence of H_{3+x}PMo_{12-x}V_xO₄₀ (x = 1–3) and the temperature varied from room temperature (25 °C) to 78 °C. The results are shown in Table 2. The GC analysis have shown that the yield of *o*-nitrophenol decreases while the yield of 2,4-dinitrophenol increases. As can be seen in Table 2 the highest yield is obtained at 78 °C, and in the presence of H₆PMo₉V₃O₄₀. Generally the yields are lower when the reactions are carried out at temperatures lower than reflux temperature. We believe that increasing in the temperature for accelerating the reaction is apparently favorable.

2.4. Effect of the reaction time

The nitration of phenol was followed in different time by considering CCl₄ as solvent, in the presence of H_{3+x}PMo_{12-x}V_xO₄₀ (x = 1–3) at 78 °C (optimum conditions). The reaction study (Table 3) showed clearly a different time for completion of reaction. The reaction for formation of *o*-nitrophenol is slower with H₄PMo₁₁VO₄₀ compared to H₆PMo₉V₃O₄₀. The results indicate that there is an increase in the amount of product, while increasing the reaction time in the presence of all catalysts.

However, the maximum total yield of *o*-nitrophenol and selectivity of 100% were obtained between 1.5 h and 5 h. *o*-Nitrophenol can be obtained at the lowest time (1.5 h) in the presence of H₆PMo₉V₃O₄₀. This product can be obtained with max-

Table 3
Catalytic nitration of phenol in refluxing CCl₄ under different times

Entry	HPA	Time (h)	Yield (%) ^a
1	H ₄ [PMo ₁₁ VO ₄₀]	0.5	50
2	H ₄ [PMo ₁₁ VO ₄₀]	2	65
3	H ₄ [PMo ₁₁ VO ₄₀]	3	73
4	H ₄ [PMo ₁₁ VO ₄₀]	4	87
5	H ₄ [PMo ₁₁ VO ₄₀]	5	93
6	H ₅ [PMo ₁₀ V ₂ O ₄₀]	0.5	30
7	H ₅ [PMo ₁₀ V ₂ O ₄₀]	1	42
8	H ₅ [PMo ₁₀ V ₂ O ₄₀]	1.5	68
9	H ₅ [PMo ₁₀ V ₂ O ₄₀]	2	79
10	H ₅ [PMo ₁₀ V ₂ O ₄₀]	2.5	96
11	H ₆ [PMo ₉ V ₃ O ₄₀]	0.3	68
12	H ₆ [PMo ₉ V ₃ O ₄₀]	0.6	82
13	H ₆ [PMo ₉ V ₃ O ₄₀]	1	88
14	H ₆ [PMo ₉ V ₃ O ₄₀]	1.3	92
15	H ₆ [PMo ₉ V ₃ O ₄₀]	1.5	100

^a Yields analyzed by GC.

Table 4
Catalytic nitration of phenol in refluxing CCl₄ under different moles of the substrate

Entry	Mole numbers	Time (min)	Yield (%)
1	1 × 10 ⁻³	90	100
2	5 × 10 ⁻⁴	60	100
3	2.5 × 10 ⁻⁴	30	100

imum of yield at 5 h and 2.5 h in the presence of H₄PMo₁₁VO₄₀ and H₅PMo₁₀V₂O₄₀, respectively. These results indicate that the reaction time play an important role for completion of reaction.

2.5. Effect of the substrate concentration

In optimum conditions, we found that changing the moles of the substrate will lead to yield *o*-nitrophenol as like as before but the time of reaction will decrease significantly. The results of nitration under different mole numbers of phenol with carbon tetrachloride as the best solvent and H₆Mo₉V₃O₄₀ as the best catalyst are presented in Table 4. We found by changing the moles of the substrate 2,4-dinitrophenol did not produce.

2.6. Reusability of the catalyst

The catalyst was recovered after the reaction and reused as a catalyst in the nitration reactions. Several times recoveries had only slightly decreased the catalytic activity, pointing to the stability and retention capability of this useful polyanion.

At the end of the reaction, the catalyst was filtered, washed with diethyl ether, dried at 130 °C for 1 h, and reused in another reaction. The recycled catalyst was used for three reactions without observation of appreciable lost in its catalytic activities.

3. Conclusion

Recyclable, eco-friendly, easily prepared and inexpensive vanadium(V)-substituted polyoxomolybdates have been used as

a catalyst for regioselective nitration of phenol. Important features of this protocol are high regioselectivity, simplicity and versatility of process engineering, decreasing reactor and plant corrosion problems and environmentally safe disposal. The catalyst can be easily recovered, regenerated and reused without loss of structure and appreciable activity, thus providing economic and environmentally friendly method for nitration reaction.

4. Experimental

4.1. Chemicals and apparatus

All compounds were purchased from Merck Company and all of the catalysts were prepared according to the literatures [28–30].

All products were known and their physical and spectroscopic data were compared with those of authentic samples. Melting points were measured using Barnstead Electro thermal. IR spectra were recorded on Bruker 4000–400 cm^{-1} . Yields are based on GC/mass analysis using Agilent 6890 GC system Hp-5 capillary 30 m \times 530 μm \times 1.5 μm nominal.

4.2. General procedure

In each reaction, to a magnetically stirring mixture of solvent (3 mL) and phenol (1 mmol) at room temperature, nitric acid (1 mmol) and the catalyst (0.02 g) were added. The mixture was then refluxed for appropriate time. The progress of the reaction was monitored by TLC using petroleum ether:ethyl acetate as eluent. After completion of the reaction, the catalyst was filtered. The mixture was then washed with saturated sodium hydrogen carbonate (10 mL) and the product extracted into dichloromethane (2 \times 5 mL). The combined organic extracts were washed with distilled water (10 mL), dried over anhydrous MgSO_4 and the solvent was removed by evaporation to afford the nitrated compound. Yields determined by GC-Mass.

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