

Catalytic Effects of Some Keggin-Type Heteropoly Acids and Polyoxometalates on Selective Nitration of Phenols

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Catalytic amounts of heteropoly acids and polyoxometalates promoted mononitration of phenolic compounds using iron(III) nitrate nonahydrate and bismuth(III) nitrate pentahydrate in dichloromethane at room temperature. Tungstophosphoric acid cesium salt, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$, in a heterogeneous phase, exhibited significant rate enhancement of reactions as well as *ortho* selectivity without over-nitration and oxidation byproducts.

Keywords: Heteropoly acid, Polyoxometalate, Nitration, Phenol, Iron(III) nitrate, Bismuth(III) nitrate

INTRODUCTION

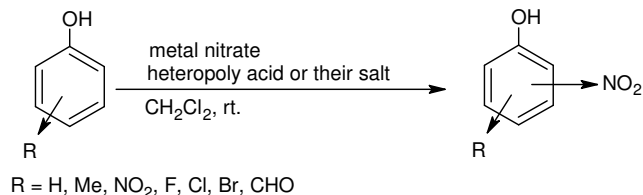
The reactions catalyzed by heteropoly acids (HPAs) and polyoxometalates (POMs) in both heterogeneous and homogeneous systems have been reviewed by various authors [1]. HPAs have several advantages as catalysts, which make them economically and environmentally attractive. They have a very strong Brønsted acidity, approaching the super-acid region. They have significantly higher catalytic activity than that of strong mineral or organic acids, such as H_2SO_4 , HCl, HNO_3 , TsOH, TfOH, MeSO_3H , and conventional catalysts, such as alumina, silica gel, zeolites, clay, and acidic Amberlyst-15 [2]. This makes it possible to carry out the catalytic processes at lower temperatures and catalyst concentrations.

On the other hand, nitration of aromatic substrates is an important process [3] and nitro aromatic compounds are widely used for the synthesis of dyes, pharmaceuticals, perfumes, plastics and explosives. Nitration of phenols is an important industrial process and today pollution free processes

are important environmental concerns. Earlier industrial processes involve the use of corrosive nitric acid/sulfuric acid mixtures (liquid phase), which are responsible for the generation of large amounts of hazardous wastes [3,4]. Other associated problems are over-nitration, oxidation byproducts and poor selectivity. These problems have encouraged the search for other methods, especially alternating catalytic amounts of various solid acids with stoichiometric amounts of corrosive Brønsted acids and various nitrates or nitrites with nitric acid. Some of these methods include AcONO_2 [5], TfONO_2 [6], NaNO_3/HCl with catalytic amounts of $\text{La}(\text{NO}_3)_3$ [7], trichloroisocyanoric acid/ $\text{NaNO}_2/\text{wet SiO}_2$ [8], $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ [9], $\text{Bi}(\text{NO}_3)_3/\text{montmorillonite KSF}$ [10], $\text{NaNO}_3/\text{wet SiO}_2$ [11], $\text{NaNO}_2/\text{silica sulfuric acid}$ [12], $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ [13], $\text{Cu}(\text{NO}_3)_2/\text{clay}$ [14], $\text{Fe}(\text{NO}_3)_3/\text{clay}$ [15], $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}/\text{ionic liquid}$ [16], $\text{VO}(\text{NO}_3)_3$ [17], some other metal nitrate/clay combinations activated by acetic anhydride [18], and more recently, ultrasound promoted nitration in ionic liquid with ferric nitrate and clayfen with good *para* selectivity [19], calcium nitrate/microwave [20], zirconyl nitrate [21] and PTSA/ $\text{Ni}(\text{NO}_3)_3$ [22].

In this paper, we wish to report the mononitration of

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Scheme 1

phenols using iron(III) nitrate nonahydrate and bismuth(III) nitrate pentahydrate in dichloromethane at room temperature promoted with catalytic amounts of heteropoly acids and polyoxometalates. Nitration was directed to both *ortho* and *para* positions of the phenols used in this study. We found that tungstophosphoric acid cesium salt, Cs_{2.5}H_{0.5}PW₁₂O₄₀ exhibits significant enhancement in reaction rates as well as *ortho* selectivity without over-nitration and oxidative byproducts (Scheme 1).

EXPERIMENTAL

Chemicals were purchased from Fluka and Merck

Chemical Companies without further purification. All of the heteropoly acids and polyoxometalates, with the exception of H₃PMo₁₀V₂O₄₀·xH₂O, were preheated at 120 °C under reduced pressure, *ca.* 10 mmHg, in a vacuum oven for 24 h before use. The products were analyzed using a Shimadzu model 8A gas chromatograph, with a 10% SE-30 packed column, FID detector, and high purity nitrogen as the carrier gas. The retention time of phenol was taken as the internal reference. All reactions were performed at room temperature.

General Procedure for Mononitration of Phenol with Metal Nitrates

Catalyst (0.1 mmol) and metal nitrate (0.4-0.5 mmol) were ground together and placed in a 10 ml round-bottom flask containing CH₂Cl₂ (2.5-5.0 ml) and stirred for 10 min. Phenol (1 mmol, 0.094 g) was then added and the reaction mixture was stirred at rt. until the phenol was consumed completely (Tables 1-3). The conversion and yield percentages of the products were determined by GC. Products were identified by their retention times and by co-injection with authentic samples.

Table 1. Effect of H₃PW₁₂O₄₀ on the Mononitration of Phenol by Fe(NO₃)₃·9H₂O

Entry	Catalyst	Time (h)	Conv. (%)	Product (%) ^a				Selectivity <i>ortho/para</i>
				<i>ortho</i>	<i>para</i>	<i>meta</i>	x ^b	
1	None ^c	0.25	0.0	-	-	-	-	-
		0.5	38.5	70.5	27.5	1.5	-	2.54
		1	46.1	68.5	30.5	1.0	-	2.25
		2	58.2	68.0	31.5	0.5	-	2.16
		45	97.4	57.5	41.5	0.5	0.5	1.38
2	H ₃ PW ₁₂ O ₄₀ ^d	0.25	39.3	75.0	25.0	-	-	3.00
		0.5	48.5	68.8	31.2	-	-	2.21
		1	59.2	66.2	33.8	-	-	1.96
		2	69.5	57.5	42.5	-	-	1.67
		45	96.0	56.3	43.7	-	-	1.29
3	H ₃ PW ₁₂ O ₄₀ ^e	0.25	53.6	69.8	30.2	-	-	2.31
		2	95.0	53.0	45.3	-	1.7	1.17

^aProducts were identified by their retention times in addition to co-injection with authentic samples. Retention time of phenol was taken as the internal reference. ^bx = any product addition to mononitration products consisted of polynitrophenols and oxidative byproducts. Reaction conditions: ^cphenol (1 mmol), Fe(NO₃)₃·9H₂O (0.4 mmol), rt. CH₂Cl₂ (5 ml). ^dphenol (1 mmol), Fe(NO₃)₃·9H₂O (0.4 mmol), H₃PW₁₂O₄₀ (0.1 mmol), rt. CH₂Cl₂ (5 ml). ^ephenol (1 mmol), Fe(NO₃)₃·9H₂O (0.5 mmol), H₃PW₁₂O₄₀ (0.1 mmol), rt. CH₂Cl₂ (2.5 ml).

Catalytic Effects of Some Keggin-Type Heteropoly Acids

Table 2. Effect of other Keggin-type Heteropoly Acids and polyoxometalates^a on the Mononitration of Phenol by Fe(NO₃)₃·9H₂O

Entry	Catalyst	Time (h)	Conv. (%)	Product (%) ^b				Selectivity <i>ortho/para</i>
				<i>ortho</i>	<i>para</i>	<i>meta</i>	x ^c	
1	H ₃ PMo ₁₂ O ₄₀	1	64.4	53.4	46.6	-	-	1.15
		2	70.5	48.9	51.1	-	-	0.96
2	H ₃ PMo ₁₀ V ₂ O ₄₀ ·xH ₂ O	1	70.0	47.8	44.4	-	6.8	1.08
		2	77.0	47.0	50.0	-	3.0	0.94
3	H ₄ SiW ₁₂ O ₄₀	2	95.0	47.2	43.2	-	9.6	1.09
4	AlPW ₁₂ O ₄₀	2	56.2	56.4	43.6	-	-	1.29
5	(NH ₄) ₂ HPW ₁₂ O ₄₀	2	66.2	66.0	34.0	-	-	1.29
6	Cs _{2.5} H _{0.5} PW ₁₂ O ₄₀	0.25	37.0	79.4	20.6	-	-	3.85
		1	59.6	71.9	28.3	-	-	2.26
		2	68.5	65.2	34.8	-	-	1.87
		45	97.8	62.2	37.8	-	-	1.65
7	Cs _{2.5} H _{0.5} PW ₁₂ O ₄₀ ^d	1	75.0	68.9	31.1	-	-	2.22
		2	100	69.0	31.0	-	-	2.22

^aConditions: phenol (1 mmol), Fe(NO₃)₃·9H₂O (0.4 mmol), catalyst (0.1 mmol), rt. CH₂Cl₂ (5 ml). ^bProducts were identified by their retention times in addition to co-injection with authentic samples. Retention time of phenol was taken as the internal reference. ^cx = any product addition to mononitration products consisted of polynitrophenols and oxidative byproducts. ^dConditions: phenol (1 mmol), Fe(NO₃)₃·9H₂O (0.5 mmol), catalyst (0.1 mmol), rt. CH₂Cl₂ (2.5 ml).

Table 3. Effect of H₃PW₁₂O₄₀ and Cs_{2.5}H_{0.5}PW₁₂O₄₀^a on the Mononitration of Phenol by Bi(NO₃)₃·5H₂O

Entry	Catalyst	Time (h)	Conv. (%)	Product (%) ^b				Selectivity <i>ortho/para</i>
				<i>ortho</i>	<i>para</i>	<i>meta</i>	x ^c	
1	None	0.25	67.0	67.1	29.7	-	-	2.26
		1	73.0	64.6	32.8	-	-	1.97
		4	76.0	58.6	33.9	-	6.4	1.73
2	H ₃ PW ₁₂ O ₄₀	0.25	78.7	54.3	44.3	-	-	1.23
		1	96.1	51.3	48.1	-	-	1.07
		2	98.7	50.8	44.3	-	4.9	1.15
3	Cs _{2.5} H _{0.5} PW ₁₂ O ₄₀	0.25	71.6	55.0	34.1	-	7.9	1.62
		1	74.0	54.2	38.4	-	7.3	1.41
		2	76.0	53.7	37.5	-	7.6	1.43
4	H ₃ PW ₁₂ O ₄₀ ·nH ₂ O	0.25	93.0	41.4	49.2	-	8.4	0.84
		2	97.8	52.3	45.0	-	2.7	1.16

^aConditions: phenol (1 mmol), Bi(NO₃)₃·5H₂O (0.4 mmol), catalyst (0.1 mmol), rt. CH₂Cl₂ (5 ml). ^bProducts were identified by their retention times in addition to co-injection with authentic samples. Retention time of phenol was taken as the internal reference. ^cx = any product addition to mononitration products consisted of polynitrophenols and oxidative byproducts.

General Procedure for Mononitration of Phenol Derivatives with Iron(III) Nitrate Nonahydrate

Catalyst (0.1 mmol) and iron(III) nitrate nonahydrate (0.5 mmol) were ground together and placed in a 10 ml round-bottom flask containing CH₂Cl₂ (2.5 ml) and stirred for 10 min. Phenols (1 mmol) were then added and the reaction mixture was stirred at rt. for the appropriate time as indicated in Table 4. After the completion of the reaction (as determined by TLC), the reaction mixture was filtered through a short pad and the filtrate was washed with water and extracted with ethyl acetate. Evaporation of ethyl acetate afforded crude product, which was subjected to silica gel column chromatography using EtOAc-hexane (1:9) as the eluent.

RESULTS AND DISCUSSION

Earlier works reported by Firouzabadi *et al.* have demonstrated that iron(III) nitrate nonahydrate and bismuth(III) nitrate pentahydrate are activated well with

tungstophosphoric acid as a catalyst [2f]. Therefore, in this study, phenol was treated with iron(III) nitrate nonahydrate in the presence of catalytic amounts of tungstophosphoric acid at room temperature. At first, the mononitration of phenol was examined carefully and the progress of the reaction was monitored by GC at 0.25, 0.5, 1 and 2 h time intervals. As indicated in Table 1, in the absence of the catalyst, no reaction had taken place after 15 min and as the reaction time extended to 2 h, only 58.5% of the phenol was converted to mononitrated products with a distribution of 68% 2-nitrophenol, 31.5% 4-nitrophenol and 0.5% 3-nitrophenol (Table 1, entry 1). When the reaction was carried out in the presence of tungstophosphoric acid under similar reaction conditions, the conversion percentage was enhanced after 15 min, and 39.3% of the phenol was transformed, with a distribution of 75% 2-nitro and 25% 4-nitrophenol, suggesting the influence of the catalyst on the conversion rate and selectivity (Table 1, entry 2). The reaction was somewhat selective, since over-nitration, oxidation, and the formation of 3-nitro products were not

Table 4. Nitration of Phenols Using Iron(III) Nitrate Nonahydrate Activated by Cs_{2.5}H_{0.5}PW₁₂O₁₄ (A) and H₃PW₁₂O₄₀ (B) in CH₂Cl₂^a

Entry	Phenol	Product ^b	Catalyst	Time (h)	Isolated yield (%)
1	<i>p</i> -cresol	4-methyl-2-nitrophenol	A	3	96
			B	3	94
2	4-fluorophenol	4-fluoro -2-nitrophenol	A	2	97
			B	2	95
3	4-bromophenol	4-bromo-2-nitrophenol	A	6	98
			B	6.30	97
4	2-bromophenol	2-bromo-4-nitrophenol	A	7.30	68:30
		2-bromo-6-nitrophenol	B	8.30	60:36
5	2-chlorophenol	2-chloro-4-nitrophenol	A	8	66:31
		2-chloro-6-nitrophenol	B	8	58:39
6	salicylaldehyde	4-nitrosalicylaldehyde	A	8	84
			B	8	72
7	4-nitrophenol	2,4-dinitrophenol	A	10	83
			B	10	76
8	2-nitrophenol	2,4-dinitrophenol	A	10	0
			B	10	0

^aConditions: phenols (1 mmol), Fe(NO₃)₃·9H₂O (0.5 mmol), catalyst (0.1 mmol), rt. CH₂Cl₂ (2.5 ml). ^bDistribution of products was determined by GC.

observed.

Although after 2 h only 69.5% conversion was accomplished, we found that the volume of the solvent plays an important role in the rate enhancement and conversion yield. By decreasing the volume of CH_2Cl_2 to 2.5 ml and using 0.5 mmol of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, after 2 h, a 95% conversion of phenol to mononitrated compounds were obtained, with a ratio of *ortho/para* isomers of 1.17 (Table 1, entry 3).

In order to increase the ratio of *ortho/para* isomers, we have studied the catalytic activities of some other Keggin-type heteropoly acids and polyoxometalates under similar reaction conditions (Table 2). Among the catalysts studied, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ and $(\text{NH}_4)_2\text{HPW}_{12}\text{O}_{40}$ were found to be the catalysts of choice and a higher ratio of production of 2-nitrophenol was detected. We then studied the catalytic activity and selectivity of $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ by decreasing the volume of the solvent to 2.5 ml and increasing the amounts of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ to 0.5 mmol. After 2 h, a quantitative conversion was observed with an *ortho/para* ratio of 69/31 (Table 2, entry 7).

Mononitration of phenol was also performed in other solvents, such as *n*-hexane, carbon tetrachloride, chloroform, tetrahydrofuran, acetone and acetonitrile, and under solvent-free conditions. In nonpolar solvents, such as *n*-hexane and carbon tetrachloride, and in solvent-free conditions, the reaction proceeded rapidly resulting in unidentified resinous tarry materials from the oxidation of phenol. In polar solvents, such as acetone and acetonitrile, the reaction did not proceed smoothly. Among these solvents, we found that dichloromethane and chloroform were the appropriate media for the mononitration of phenol.

We also studied nitration of phenol by bismuth(III) nitrate pentahydrate as the nitrating agent catalyzed by $\text{H}_3\text{PW}_{12}\text{O}_{40}$ or $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ under the above mentioned optimized reaction conditions. As shown in Table 3, in the presence of bismuth(III) nitrate, reactions also proceeded well, however, $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ as a nitrating agent afforded better ratios of *ortho/para* isomers (Table 3).

The above-mentioned results demonstrated that iron(III) nitrate nonahydrate activated with tungstophosphoric acid cesium salt, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$, is an efficient nitrating agent for the mononitration of phenols under heterogeneous reaction conditions. Therefore, some phenols with various *ortho* and

para substituents were studied. The results in Table 4 show that most phenols were converted to the corresponding mononitro compounds in good to excellent yields. Phenols with electron donating groups, such as *p*-cresol, afforded the corresponding *o*-nitrophenol as the exclusive product in excellent isolated yield (Table 4, entry 1). 4-Fluorophenol gave 4-fluoro-2-nitrophenol with 95% isolated yield (Table 4, entry 2). Phenols, such as 2-chlorophenol, 2-bromophenol, and 4-bromophenol were converted to the corresponding mononitrated products in good yields with selectivity (Table 4, entries 3, 4 and 5). It is surprising to note that 4-nitrophenol was nitrated to 2,4-dinitrophenol in 83% yield, while 2-nitrophenol was quite unreactive under similar reaction conditions (Table 4, entries 7 and 8). We have also used tungstophosphoric acid as a catalyst for the above reactions as summarized in Table 4.

In all the reactions we have presented in this article, we suggest that the nitration of phenol proceeds *via* the nitronium ion mechanism, in which the nitronium ion is generated by the interaction of NO_3^- with the Bronsted acid sites of the catalysts.

CONCLUSIONS

We have presented a simple method for mononitration of phenols using iron(III) nitrate or bismuth(III) nitrate pentahydrate as the nitrating agent in conjunction with a catalytic amount of tungstophosphoric acid cesium salt, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ or $\text{H}_3\text{PW}_{12}\text{O}_{40}$, in dichloromethane at room temperature. Iron(III) nitrate catalyzed by $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ is a suitable nitrating system for the mononitration of phenols with high selectivity and efficiency.

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