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Selective oxidation of phenol and anisole derivatives to quinones with hydrogen peroxide and polymer-supported methylrhenium trioxide systems

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Abstract—A convenient and efficient application of heterogeneous poly(4-vinylpyridine)/methyl rhenium trioxide (PVP/MTO) systems for the selective oxidation of substituted phenol and anisole derivatives to benzoquinones is described. Environment friendly, easily available, and low cost H_2O_2 was used as the oxygen atom donor. All catalysts were stable systems for at least five recycling experiments. In the oxidation of some natural phenols such as cardanol derivatives higher conversion and yields of benzoquinones were observed with respect to MTO in homogeneous phase suggesting a support-mediated molecular recognition process based on hydrogen-bonding interactions. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Natural products having a benzoquinone structure show biologically important properties such as cardiovascular, antitumour, antibacterial, antigerminative and antiprotozoan activities.[1] Furthermore, benzoquinones are important fine-chemicals in industry and are useful dienophiles in chemical transformations.[2] Benzoquinones are usually prepared by direct oxidation of phenol and methoxy benzene derivatives. The most commonly employed stoichiometric oxidants for these syntheses are Fremy's salt,[3] Weitz's salt (BAHA),[4] ceric ammonium nitrate (CAN),[5] *ortho*-chloranil (tetrachlorobenzo-1,2-quinone),[6] chromium(VI) salts,[7] hypervalent iodine(III),[8] *N*-bromosuccinimide (NBS),[9] and silver(I) oxide–HNO_3 system.[10] However, the different reagents used show varying degree of success as well as limitations due to low reproducibility,[11] the possibility of explosion,[12] high reaction temperatures,[13] and strongly basic or acidic conditions that may be incompatible with substituents on the aromatic ring.[14] To avoid these problems, catalytic systems including heteropolyacids,[15] ruthenium derivatives,[16] metalloporphyrins,[17] transition metal compounds,[18] supported vanadium,[19] cobalt,[20] and copper[21] salts, and titanium and chromium silicalites[22] have been used. Most of these systems perform in homogeneous phase reactions, and the process may be improved by using stable heterogeneous catalysts which usually have advantages with respect to their homogeneous counterparts. In the past few years methylrhenium trioxide (CH_3ReO_3, MTO)[23] has been shown to possess interesting catalytic properties in oxidation reactions with environment friendly hydrogen peroxide (H_2O_2) as an oxygen atom donor.[24] Among them, the oxidation of phenol and methoxybenzene derivatives has been studied. Methoxy-substituted benzenes are oxidized with the MTO/H_2O_2 system in acetic acid to yield the corresponding alkoxy-substituted *para*-benzoquinones,[25] some of which show important biological activities.[26] In a similar way, the oxidation of *para*-unsubstituted alkylphenols, characterized by small alkyl side-chains, afforded 1,4-benzoquinones in acceptable yields.[27] Noteworthy, a fine-tuned substituent effect on the regioselectivity of the oxidation (*ortho*-benzoquinones versus *para*-benzoquinones) was observed in the case of natural phenols, such as cardanol derivatives, depending on the steric hindrance and position of the alkyl substituents on the aromatic ring.[28] Recently, we have described the preparation of novel heterogeneous rhenium compounds of general formula $(\text{polymer})_f/(\text{MTO})_g$ (the f/g quotient expresses the ratio by weight of the two components) by heterogenation of MTO on poly(4-vinylpyridine) and polystyrene as low cost and easily available polymeric supports.[29] These novel MTO compounds were efficient and selective heterogeneous catalysts for the epoxidation of olefins even in the case of sensitive epoxides. Poly(4-vinylpyridine)/MTO systems were prepared starting from poly(4-vinylpyridine) 25% cross-linked (with divinylbenzene) (PVP-25%), and poly(4-vinylpyridine-*N*-oxide) 2% cross-linked (PVPN-2%), as supports. Poly(4-vinylpyridine) 2% cross-linked (PVP-2%)[30] was also used as a

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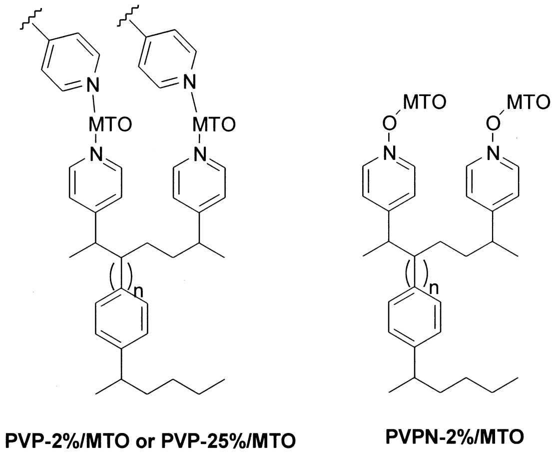


Figure 1.

Table 1. Poly(4-vinylpyridine)/MTO catalysed oxidation of phenols **1**–**4**

entry	Catalyst	Substrate	Conversion (%)	Product (s)	Yield(s)[a] (%)
1	MTO[b]	**1**	53	**5**	58
2	MTO	**1**	73	**5**	86
3	PVP-2%/MTO	**1**	79	**5**	83
4	PVP-25%/MTO	**1**	58	**5**	92
5	PVPN-2%/MTO	**1**	71	**5**	79
6	PVP-2%/MTO	**2**	69	**6**	85
7	PVP-25%/MTO	**2**	48	**6**	73
8	PVPN-2%/MTO	**2**	65	**6**	81
9	PVP-2%/MTO	**3**	83	**7**	>98
10	PVP-2%/MTO	**4**	23	**8**(**9**)	37(11)

Under otherwise specified all the reactions were performed in ethanol (5 mL) at 45°C, with H_2O_2 (35% aqueous solution), using a value of the catalyst loading factor of 1.0.

[a] Refers to isolated materials. Yields normalized to 100% conversion.

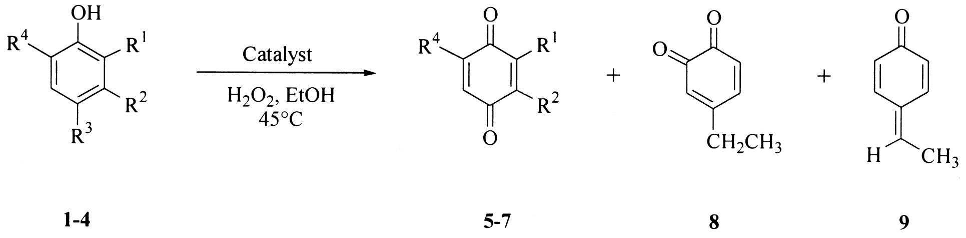
[b] Reaction performed at room temperature.

reference system. Microencapsulated polystyrene/MTO compounds were obtained by the use of polystyrene 2% cross-linked (with divinylbenzene) (PS-2%) or a mixture of PS-2% and PVP-2% (optimal ratio 5:1). All new MTO compounds were characterized by FT-IR, scanning electron microscopy (SEM), and wide-angle X-ray diffraction (WAXS). The reticulation grade of the polymer was found to be an important factor for the catalysts based on poly(4-vinylpyridine), either for the morphology of the surface of particles or for the reaction selectivity. The WAXS analysis showed that in these systems the rhenium atom is bonded to two nitrogen atoms of two pyridinyl moieties (probably on different polymeric chains) in a octahedral-like structure. The structure of PVP-2%/MTO, PVP-25%/MTO, and PVPN-2%/MTO catalysts is represented in the schematic drawing in Fig. 1.

We report here that these polymer-supported MTO systems may be used for the efficient and selective oxidation of natural phenol and anisole derivatives to the corresponding benzoquinones with H_2O_2 (35% water solution) as environment friendly primary oxidant. Even if silica-supported MTO complex of γ-(2,2′-dipiridyl) aminopropylpolysiloxane,[31] and a NaY zeolite/MTO super cage system[32] have been used for the epoxidation of olefins, to the best of our knowledge this is the first report in the literature dealing with the use of MTO heterogeneous compounds for the synthesis of quinone derivatives.

2. Results and discussion

Initially, the oxidation of phenol derivatives with poly(4-vinylpyridine)/MTO systems were investigated using 3-methyl phenol **1**, 2,6-dimethyl phenol **2**, 2,3,6-trimethyl phenol **3**, and 4-ethyl phenol **4** as simple representative model compounds. As a general procedure, the phenol (1 mmol) to be oxidized was added to a suspension of the catalyst (PVP-2%/MTO, PVP-25%/MTO, and PVPN-2%/MTO) using a value of the loading factor of 1.0 (that is mmol of MTO for 1 g of support) in ethanol (EtOH, 5 mL). The use of acetic acid (AcOH) as solvent in the homogeneous MTO oxidation of alkyl phenols has been previously reported.[27] In our procedure we selected ethanol as reaction solvent to avoid the formation of peroxyacetic acid,[25] the presence of which in the medium can influence the efficiency and the selectivity of the transformation. H_2O_2 (2.0 mmol, 30% aqueous solution) was added to the suspension and the mixture was stirred at room temperature or at 45°C. The oxidation results are summarized in Table 1 and Scheme 1. In the absence of the catalyst, less than 2% conversion of substrates took place under otherwise



1: R^1=R^3=R^4=H, R^2=Me
2: R^2=R^3=H, R^1=R^4=Me
3: R^3=H, R^1=R^2=R^4=Me
4: R^1=R^2=R^4=H, R^3=Et

5: R^1=R^4=H, R^2=Me
6: R^2=H, R^1=R^4=Me
7: R^1=R^2=R^4=Me

Scheme 1.

identical conditions. The oxidations with the MTO/H_2O_2 catalyst system were performed as references. Catalysts were recovered by filtration at the end of the reaction after washing with EtOH and were used in successive oxidations under identical conditions (vide infra).

Irrespective of the experimental conditions, all *para*-unsubstituted alkyl phenols, compounds **1**–**3**, afforded selectively the corresponding alkyl *para*-benzoquinones. The oxidation of **1** with the MTO/H_2O_2 system at room temperature gave 2-methyl-1,4-benzoquinone **5** in moderate yield (Table 1, entry 1). The reaction temperature has a remarkable effect on the transformation since at 45°C better conversion of phenol and higher yield of quinone (73 and 86%, respectively) were obtained (Table 1, entry 2). Oxidations with poly(4-vinylpyridine)/supported MTO systems were successively performed at 45°C. Treatment of **1** with the PVP-2%/MTO catalyst under similar experimental conditions afforded **5** in 79% conversion and 83% yield (Table 1, entry 3). In a similar way, the oxidation performed with PVP-25%/MTO gave **5** as the only recovered product. In this case low conversion but higher yield were obtained (Table 1, entry 4). PVPN-2%/MTO showed a behaviour similar to PVP-2%/MTO (Table 1, entry 5). It is worthy of note that all poly(4-vinylpyridine)/MTO systems retain their selectivity and catalytic activity in the oxidation of **1**. Probably, in accord with the mechanism previously proposed for the MTO catalytic oxidation of phenols in AcOH,[27] the reaction involves the initial formation of arene oxide intermediates (not shown). Under similar experimental conditions at least the same extent of conversions of 2,6-dimethyl phenol **2** and yields of 2,6-dimethyl-1,4-benzoquinone **6** were achieved, with the PVP-2%/MTO or PVPN-2%/MTO systems being the most active catalysts (Table 1, entries 6–8). These results suggest that the oxidation of 2,6-dialkyl-substituted phenols is independent of the steric effect of the substituents even in the case of heterogeneous systems. As expected for catalysts with electrophilic properties, the more electron-rich phenol **3** with PVP-2%/MTO gave higher substrate conversion and yield of the corresponding 2,3,6-trimethyl-1,4-benzoquinone **7** (TMBQ) than phenols **1** and **2** (Table 1, entry 9). TMBQ is a key intermediate in the manufacture of vitamin E.[33] The oxidation of *para*-substituted 4-ethylphenol **4** with PVP-2%/MTO was very slow, and less than 30% of conversion of the substrate was obtained. Moreover, the oxidation showed a different selectivity and the 4-methyl-1,2-benzoquinone **8** and the quinone methide derivative **9** were isolated in low yields as the only recovered products (Table 1, entry 10). We have not investigated in detail the mechanism of formation of the quinone methide **9**. Adam and co-workers[25] described the MTO-catalysed oxidation of 2,6-di-*tert*-butyl-4-methyl phenol in acetic acid to give 2,6-di-*tert*-butyl-4-methyl-2,5-cyclohexadien-1-one-4-ol in 30% yield.[34] Based on these data it is reasonable to suggest that the unisolable reactive 4-ethyl-2,5-cyclohexadien-1-one-4-ol intermediate occurs in the initial step of the oxidation of **4**. Acid-catalysed elimination of water due to the strong Lewis acid character of MTO, may afford quinone methide **9**. Table 2 shows that poly(4-vinylpyridine)/MTO systems are stable enough to perform at least five recycling experiments with similar conversion and selectivity.

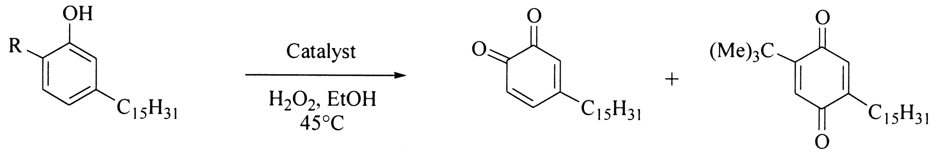
In view of the synthetic utility of poly(4-vinylpyridine)/MTO catalysts to prepare biologically active benzoquinone derivatives, we studied the oxidation of some natural phenols obtained from cardanol, 3-*n*-pentadecylphenol **10**,[35] and 2-*tert*-butyl-5-*n*-pentadecylphenol **11**.[36] Cardanol is the main component of the roasted cashew nut shell liquid (CNSL) that is a side-product from the mechanical processing of the nut of *Anacardium occidentale* L., a process of considerable industrial importance in view of the edibility of the kernel.[37] Benzoquinones of cardanol derivatives show several biological activities and have been recently used as starting materials to prepare the corresponding hydroquinone and catechol derivatives.[38] These latter compounds show antioxidant activity higher than similar commercial products, such as 2,6-di-*tert*-butyl-4-phenol (BHT) and 2,6-di-*tert*-buty-4-methoxy phenol (DBHA).[39] In spite of the high number of chemical transformations reported for cardanol derivatives, to the best of our knowledge, there are no heterogeneous catalytic procedures for the selective synthesis of cardanol *ortho*- and *para*-benzoquinones. Oxidation of compounds **10** and **11** were performed under the experimental conditions previously described (Scheme 2). We started to study the oxidation of compound **10** using the reference system MTO/H_2O_2 in EtOH at 45°C. The 4-*n*-pentadecyl-1,2-benzoquinone **12** was obtained in low conversion and yield as the only recovered product (Table 3, entry 1). Probably, the poor mass balance observed, even at partial consumption of the starting substrate, may be due to formation of water-soluble ring-opened products, as a consequence of over-oxidation side-processes. When the oxidation was performed with the PVP-2%/MTO/H_2O_2 system, the *ortho*-benzoquinone **12** was again obtained as the only recovered product in moderate yield (Table 3, entry 2). On the other hand, the reported oxidation was very selective and other possible benzoquinone isomers or products of benzylic oxifunctionalization were not detected in the reaction mixture.[40] It is reasonable to suggest that this high selectivity may be due to the presence of the bulky 3-*n*-pentadecyl side-chain. This hypothesis is in accordance with

Table 2. Stability of poly(4-vinylpyridine)/MTO catalyst in the oxidation of 3-methylphenol **1**

Catalyst	Conversion (%)				
	Run no. 1	Run no. 2	Run no. 3	Run no. 4	Run no. 5
PVP-2%/MTO	79 (83)[a]	74 (78)	79 (83)	71 (85)	75 (83)
PVP-25%/MTO	58 (92)	57 (86)	50 (90)	56 (87)	56 (87)
PVPN-2%/MTO	71 (79)	67 (73)	72 (80)	71 (73)	63 (80)

The reactions were performed in ethanol (5 mL) at 45°C with H_2O_2 (35% aqueous solution) using a value of the catalyst loading factor of 1.0.

[a] Values of the benzoquinone yields are given in parentheses and are normalized to 100% of conversion.



10-11 **12** **13**

10: R=H
11: R=tert-butyl

Scheme 2.

Table 3. Poly (4-vinylpyridine)/MTO catalysed oxidation of cardanol dertivatives **10**,**11**

entry	Catalyst	Substrate	Conversion (%)	Product(s)	Yield(s)[a] (%)
1	MTO	**10**	38	**12**	46
2	PVP-2%/MTO	**10**	43	**12**	53
3	PVP-25%/MTO	**10**	56	**12**	61
4	PVPN-2%/MTO	**10**	41	**12**	50
5	MTO	**11**	41	**13**	38
6	PVP-2%/MTO	**11**	58	**13**	71
7	PVP-25%/MTO	**11**	75	**13**	98
8	PVPN-2%/MTO	**11**	62	**13**	96

Under otherwise specified all the reactions were performed in ethanol (5 mL) at 45°C, with H_2O_2 (35% aqueous solution) using a value of the catalyst loading factor of 1.0.

[a] Refers to isolated materials. Yields normalized to 100% conversion.

our previous findings on the oxidation of cardanol derivatives with the MTO/H_2O_2 system in AcOH,[28] and further supported by previously described oxidation of cresol **1** for which *para*-benzoquinone was the only recovered product likely due to the absence of steric hindrance by methyl group. Better results were obtained with the PVP-25%/MTO catalyst (Table 3, entry 3), while PVPN-2%/MTO showed a reaction pathway similar to PVP-2%/MTO (Table 3, entry 4).

With the more electron-rich 2-*tert*-butyl-5-*n*-pentadecyl phenol **11**, highest conversion of substrate and yield of benzoquinone were generally observed. Thus, while the control experiment for **11** exhibits only moderate substrate conversion and product yield (Table 3, entry 5), 58% conversion of substrate and 71% yield of **13** were recovered in the presence of PVP-2%/MTO (Table 3, entry 6). These data indicate that the presence of a bulky *tert*-butyl substituent in the C-2 position of **11** switches the selectivity of the oxidation toward the formation of *para*-benzoquinone. Moreover, the best results were obtained in the oxidation of **11** with PVP-25%/MTO and PVPN-2%/MTO catalysts. In fact **13** was recovered in high yield (Table 3, entries 7 and 8). Table 4 shows that in these oxidations, PVP-2%/MTO, and PVPN-2%/MTO catalysts, are stable enough to perform at least five recycling experiments with similar conversions and selectivities.

It is noteworthy that in the oxidation of cardanol derivatives **10** and **11**, poly(4-vinylpyridine)-supported MTO systems are more reactive than their homogeneous counterparts, even if usually a catalytic species loses part of its catalyst efficiency after the heterogenation process (see for example Table 3, entry 5 versus entries 6–8). This apparent anomaly may be in part explained on the basis of data reported by ten Brinke and co-workers, on the order–disorder transition of the system poly(4-vinylpyridine)/3-*n*-pentadecyl phenol **10**.[41] The poly(4-vinylpyridine)-supported MTO oxidations of anisoles **14–16** were carried out in ethanol in analogy to reported transformations of phenol derivatives to quinones. The results in Table 5 show that the benzoquinones **17**, **19**, and **22** (Scheme 3) can be obtained from moderate to good yields (30–90% based on converted starting material) depending on the nature of substrate and catalyst. In the absence of the catalyst, less than 2% conversion of substrate took place under otherwise identical conditions. The oxidation of 1,2-dimethoxy-4-methylbenzene with MTO in ethanol was observed to slowly afford benzoquinone **17** in fair yield (Table 5, entry 1). A side-product, that after spectroscopic characterization was assigned to be a dienone derivative, 2-methoxy-4-methyl-2,5-cyclohexadien-1-one-4-olo **18**, was also recovered. According to data reported by Adam and co-workers,[25] the formation of **18** may be explained with the presence of a reactive arene oxide intermediate further involved in a catalysed demethylation

Table 4. Stability of poly(4-vinylpyridine)/MTO catalysts in the oxidation of 2-*tert*-butyl-5-*n*-pentadecyil phenol **11**

Catalyst	Conversion (%)				
	Run no. 1	Run no. 2	Run no. 3	Run no. 4	Run no. 5
PVP-25%/MTO	75 (98)[a]	76 (93)	71 (97)	75 (96)	76 (97)
PVPN-2%/MTO	62 (96)	65 (91)	63 (93)	60 (98)	61 (96)

Under otherwise specified all the reactions were performed in ethanol (5 mL) at 45°C, with H_2O_2 (35% aqueous solution) using a value of the catalyst loading factor of 1.0.

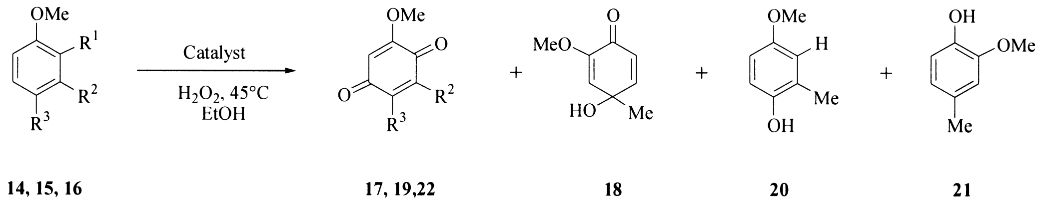
[a] Values of the benzoquinone yields are given in parentheses and are normalized to 100% of convertion.

Table 5. Poly(4-vinylpyridine)/MTO catalysed oxidation of anisole derivatives

Entry	Catalyst	Subtrate	Conversion (%)	Product(s)	Yield(s)^a (%)
1	MTO	**14**	35	**17** (**18**)	21 (25)
2	PVP-2%/MTO	**14**	45	**17** (**18**)	45 (15)
3	PVP-25%/MTO	**14**	41	**17** (**18**)	42 (12)
4	PVPN-2%/MTO	**14**	47	**17** (**18**)	48 (6)
5	MTO	**15**	61	**19** (**20**) [**21**]	24 (34) [18]
6	PVP-2%/MTO	**15**	65	**19** (**20**) [**21**]	22 (36) [7]
7	PVP-25%/MTO	**15**	63	**19** (**20**) [**21**]	17 (47) [10]
8	PVPN-2%/MTO	**15**	73	**19** (**20**) [**21**]	37 (25) [8]
9	MTO	**16**	30	**22**	32
10	PVP-2%/MTO	**16**	25	**22**	96

Under otherwise specified the reactions were performed in ethanol (5 mL) at 45°C, with H_2O_2 (35% aqueous solution) using a value of the catalyst loading factor of 1.0.

[a] Refers to isolated materials. Yields normalized to 100% conversion.



14: R^1=OMe, R^2=H, R^3=Me
15: R^1=R^3=H, R^2=Me
16: R^1=R^2=H, R^3=CH_2CH_2OH

17: R^2=H, R^3=Me
19: R^2=Me, R^3=H
22: R^2=H, R^3=CH_2CH_2OH

Scheme 3.

process. Noteworthy, while fair conversions were again obtained with the poly(4-vinylpyridine)/MTO catalysts (Table 5, entries 2–4), a better selectivity was observed and benzoquinone **17** began the major product by using the best catalyst system PVP-2%/MTO (Table 5, entry 2). Irrespective of the experimental conditions only a poor selectivity was obtained in the oxidation of 1-methoxy-3-methylbenzene **15**, for which along with benzoquinone **19**, phenols **20** and **21** were recovered in appreciable yield (Table 5, entries 5–8). With the exception of the PVPN-2%/MTO catalytic system, 2-methyl-4-methoxy phenol **20** was recovered as the most abundant reaction product. This compound may be further oxidized with MTO in AcOH to give benzoquinone **19** in quantitative yield.

Finally, we studied the oxidation of the anisole derivative **16** that is an easily available methyl ether derivative of tyrosol, one of the main components of the vegetation water of *Olea europea* (Scheme 3).[42] The oxidation was studied with the PVP-2%/MTO catalyst as a representative poly(4-vinylpyridine)/MTO system (Table 5, entries 9 and 10). In this case, the benzoquinone **22** was obtained as the only recovered product in high yield, showing again an high selectivity for the oxidation.

3. Conclusions

Poly(4-vinylpyridine)/MTO systems are efficient and selective catalysts for the conversion of alkyl-substituted phenols to the corresponding benzoquinones, using environment friendly, easily available, and low cost H_2O_2 as the oxygen atom donor. Independently from the catalyst used in the transformation, values of the loading factor of the catalyst higher than 1.0 did not give an appreciable increase in the conversion of substrate. All catalysts were stable systems for at least five recycling experiments. In the case of *para*-unsubstituted phenols with small alkyl side-chains **1–3**, the corresponding *para*-benzoquinones were selectively obtained in high yields (70–90% based on converted starting material), by using PVP-2%/MTO system as the most active catalyst. With the *para*-substituted phenol **4** a different selectivity was observed, and the *ortho*-benzoquinone **8** became the main reaction product, along with the quinone methide derivative **9**. When the poly(4-vinylpyridine)/MTO catalysts were applied for the oxidation of natural *para*-unsubstituted phenols with a longer alkyl side-chain, cardanols **10** and **11**, the regioselectivity of the reaction was found to be dependent on the nature and the position of the substituents. In particular, the presence of an alkyl substituent on the C-2 position of the phenolic ring appears to direct the selectivity of the oxidation from *ortho*-benzoquinone to *para*-benzoquinone. The suggestion that PVP/MTO catalysts may organize the cardanol substrates on the surface of their particles by means of specific and selective molecular recognition processes is at least in part confirmed by the higher conversions and yields to corresponding benzoquinones than MTO in homogeneous phase. Under similar experimental conditions, poly(4-vinylpyridine)/MTO systems are able to oxidize anisole derivatives to the corresponding *para*-benzoquinones even if moderate conversions and yields, as well as and poor mass balances, were generally observed.

4. Experimental

NMR spectra were recorded on a Bruker (200 MHz) spectrometer and are reported in δ values. Mass spectra were recorded on a VG 70/250S spectrometer with an electron beam of 70 eV. Elemental analyses were performed by a Carlo Erba 1106 analyser. Infrared spectra were recorded on a Perkin–Elmer 298 spectrophotometer using NaCl plates. For the SEM photographs, samples were spitter-coated with gold (20 nm). All solvents are ACS reagent grade and were redistilled and dried according to standard procedures. Chromatographic purifications were performed on columns packed with Merck silica gel 60, 230–400 mesh for flash technique. Thin layer chromatography was carried out using Merck platen Kieselgel 60 F254.

4.1. Starting materials

Poly(4-vinylpyridine)/MTO catalysts were prepared as previously reported.[29] In summary, PVP-2%, PVP-25%, and PVPN-2%[43] were suspended in ethanol at room temperature and the appropriate amount of powdered MTO was added at room temperature. After 1 h the mixture was cooled at 0°C and the catalyst recovered by filtration. Under otherwise specified, poly(4-vinylpyridine) catalysts were prepared with a loading factor (that is mmol of MTO for 1 g of support) equal to 1.0. Catalysts were used after washing with ethyl acetate. Phenol derivatives **1**–**4** were obtained from a commercial source (Aldrich). 3-*n*-Pentadecyl phenol **10** was prepared by hydrogenation of distilled cardanol.[44] 2-*tert*-Butyl-5-*n*-pentadecylphenol **11** was prepared starting from 3-*n*-pentadecyl phenol as previously reported.[45] Anisole derivatives were prepared starting from the corresponding phenols under usual experimental conditions by reaction with K_2CO_3 and MeI in dry DMF at room temperature.

4.2. Oxidation of phenol and anisole derivatives: general procedure

To the suspension of 146 mg of the appropriate catalyst (loading 1.0) in 5.0 mL of ethanol was added the phenol (1.0 mmol) to be oxidized and H_2O_2 (2.0 mmol, 35% water solution). The reaction mixture was stirred at 40°C under a nitrogen gas atmosphere for 10–14 h and monitored by gas chromatography(GC), using dodecane as an internal standard. The GC analysis was performed using a OV-1 column (25 m×0.30 mm and 0.25 mm film thickness) and an isothermal temperature profile of 100°C for the first 5 min, followed by a 15°C/min temperature gradient to 280°C for 10 min. The injector temperature was 280°C. The suspension was filtered and the recovered catalyst was washed five times with 10 mL of ethyl acetate each time. After drying under high vacuum, the catalyst was used for further reaction to evaluate its stability. The filtrate was treated with a low amount of manganese dioxide (MnO_2) at 25°C to decompose the excess of H_2O_2 and filtered. The organic solvent was dried under Na_2SO_4 and removed under reduced pressure. The crude was purified by flash-chromatography (*n*-hexane/EtOAc) and the reaction products were identified by spectroscopic analyses, mass spectrometry, and comparison with authentic commercial samples.

4.2.1. 2-Methyl-1,4-benzoquinone (5). 92%; solid; mp 68–70°C (from EtOAc) (lit.,[46] 67–70°C).

4.2.2. 2,6-Dimethylbenzoquinone (6). 85%; solid; mp 72–73°C (from EtOAc) (lit.,[47] 71–73°C).

4.2.3. 2,3,5-Trimethylbenzoquinone (7). 98%; solid; mp 28–29°C (from EtOAc) (lit.,[48] 29°C).

4.2.4. 4-Ethyl-1,2-benzoquinone (8). 37%; oil; ν_{max} (KBr) 750, 975, 1250, 1545, 1660, 2855, 2920; δ_H [$CDCl_3$, 200 MHz] 1.55 (3H, m, CH_3), 2.60 (2H, m, CH_2), 6.70 (1H, m, CH), 6.80 (1H, m, CH), 7.13 (1H, m, CH); δ_C [$CDCl_3$, 20 MHz] 14.96 (CH_3), 32.58 (CH_2), 126.66 (CH), 129.92 (CH), 143.54 (CH), 152.03 (C), 179.71 (C), 180.68 (C); *m/z* 136 (M^+, 31%). Anal. calcd for $C_8H_8O_2$: C (68.85%), H (4.95%), O (26.20); Found C (68.71%), H (5.00%), O (26.29%).

4.2.5. Quinone methide derivative (9). 11%; oil; ν_{max} (KBr) 750, 980, 1250, 1541, 1659, 2855, 2920; δ_H [$CDCl_3$, 200 MHz] 1.56 (3H, m, CH_3), 6.60 (1H, m, CH), 6.63–6.80 (4H, m, CH); δ_C [$CDCl_3$, 200 MHz] 12.49 (CH_3), 122.85 (CH), 138.91 (CH), 139.41 (CH), 141.69 (C), 143.06 (CH), 186.34 (C); *m/z* 120 (M^+, 28%). Anal. calcd for C_8H_8O: C (79.97%), H (6.71%), O (13.32); Found C (80.03%), H (6.68%), O (13.29%).

4.2.6. 4-*n*-Pentadecyl-1,2-benzoquinone (12). 61%; oil; ν_{max} (KBr) 750, 975, 1000, 1250, 1655, 2850, 2920; δ_H [$CDCl_3$, 200 MHz] 0.82 (3H, t, J=6.0 Hz, CH_3), 1.20 (24H, m, CH_2), 1.45 (2H, m, CH_2), 2.5 (2H, m, CH_2), 6.51 (1H, m, CH), 6.68 (2H, m, CH); δ_C [$CDCl_3$, 200 MHz] 14.04 (CH_3), 22.62 (CH_2), 27.73 (CH_2), 28.96 (CH_2), 29.26 (CH_2), 29.30 (CH_2), 29.43 (CH_2), 29.62 (CH_2), 31.87 (CH_2), 132.29 (CH), 136.16 (CH), 136.73 (CH), 149.66 (C), 187.44 (C), 187.75 (C); *m/z* (EI) 318 (M^+, 79%). Anal. calcd for $C_{21}H_{34}O_2$: C (79.19%), H (10.76%), O (10.05); Found C (79.05%), H (10.83%), O (10.12%).

4.2.7. 2-*tert*-Butyl-5-*n*-pentadecyl-1,4-benzoquinone (13). 98%; solid; mp 51–53°C (from EtOAc) (lit.,[rifn] 51–53°C].

4.2.8. 2-Methoxy-5-methyl-1,4-benzoquinone (17). 48%; oil; ν_{max} (KBr) 735, 971, 1020, 1251, 1665, 2850, 2920; δ_H [$CDCl_3$, 200 MHz] 1.97 (3H, s, CH_3), 3.73 (3H, s, CH_3), 5.54 (1H, s, CH), 6.46 (1H, s, CH); δ_C [$CDCl_3$, 200 MHz] 15.57 (CH_3), 56.09 (CH_3), 107.39 (CH), 131.08 (CH), 146.69 (C), 158.56 (C), 181.95 (C), 187.75 (C); *m/z* (EI) 152 (M^+, 39%). Anal. calcd for $C_8H_8O_3$: C (63.15%), H (5.30%), O (31.55); Found C (63.21%), H (5.19%), O (31.60%).

4.2.9. 2-Methoxy-4-methyl-2,5-cyclohexadien-1-one-4-olo (18). 25%; oil; ν_{max} (KBr) 755, 977, 1000, 1253, 1658, 2860, 2920; δ_H [$CDCl_3$, 200 MHz] 1.45 (3H, s, CH_3), 3.66 (3H, s, CH_3), 5.72 (1H, J=2.7 Hz, CH), 6.26 (1H, m, CH), 6.89 (1H, m, CH); δ_C [$CDCl_3$, 200 MHz] 23.82 (CH_3), 55.01 (CH_3), 80.29 (CH), 115.60 (CH), 129.11 (CH), 150.19

(C), 151.86 (C), 180.88 (C); *m*/*z* (EI) 154 (M^+, 39%). Anal. calcd for $C_8H_{10}O_3$: C (62.33%), H (6.54%), O (31.13); Found C (62.20%), H (6.70%), O (31.10%).

4.2.10. 2-Methoxy-5-methyl-1,4-benzoquinone (19). 37%; oil; ν_{max} (KBr) 740, 985, 1251, 1665, 2850, 2920; δ_H [$CDCl_3$, 200 MHz] 2.04 (3H, s, CH_3), 3.77 (3H, s, CH_3), 5.86 (1H, s, CH), 6.53 (1H, s, CH); δ_C [$CDCl_3$, 200 MHz] 15.49 (CH_3), 56.27 (CH_3), 107.27 (CH), 133.82 (CH), 142.10 (C), 158.0 (C), 181.11 (C), 186.10 (C); *m*/*z* (EI) 152 (M^+, 45%). Anal. calcd for $C_8H_8O_3$: C (63.15%), H (5.30%), O (31.55); Found C (63.21%), H (5.19%), O (31.60%).

4.2.11. 2-Methyl-4-methoxyphenol (20). 47%; oil; ν_{max} (KBr) 750, 805, 1223, 1359, 1495, 2850, 2920, 3450; δ_H [$CDCl_3$, 200 MHz] 2.21 (3H, s, CH_3), 3.73 (3H, s, CH_3), 6.62 (1H, d, J=2.4 Hz, CH), 6.66 (1H, s, CH), 6.69 (1H, d, J=2.4 Hz, CH); δ_C [$CDCl_3$, 200 MHz] 16.09 (CH_3), 55.57 (CH_3), 111.79 (CH), 115.48 (CH), 116.58 (CH), 124.92 (C), 147.80 (C), 153.49 (C); *m*/*z* (EI) 138 (M^+, 91%). Anal. calcd for $C_8H_{10}O_2$: C (69.54%), H (7.30%), O (23.16); Found C (69.67%), H (7.21%), O (23.12%).

4.2.12. 2-Methoxy-4-methylphenol (21). 18%; oil; bp 22°C (from EtOAc) [lit.,[28] 22°C].

4.2.13. 2-Methoxy-4[1′-ethanyl-2′-olo]1,4-benzoquinone (22). 96%; oil; ν_{max} (KBr) 740, 985, 1253, 1668, 2853, 2921; δ_H [$CDCl_3$, 200 MHz] 2.66 (2H, t, J=6.0 Hz, CH_2), 3.79 (3H, s, OCH_3), 3.82 (2H, t, J=6.0 Hz, CH_2), 5.91 (1H, s, CH), 6.60 (1H, s, CH); δ_C [$CDCl_3$, 20 MHz] 51.94 (CH_2), 75.64 (CH_3), 80.24 (CH_2), 127.0 (CH), 151.84 (CH), 166.52 (C), 178.0 (C), 201.0 (C), 204.50 (C); *m*/*z* (EI) 182 (M^+, 29%). Anal. calcd for $C_9H_{10}O_4$: C (61.22%), H (6.16%), O (32.62); Found C (61.08%), H (6.25%), O (32.67%).

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