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Hybrid Polyoxotungstates as Second-Generation POM-Based Catalysts for Microwave-Assisted H_2O_2 Activation

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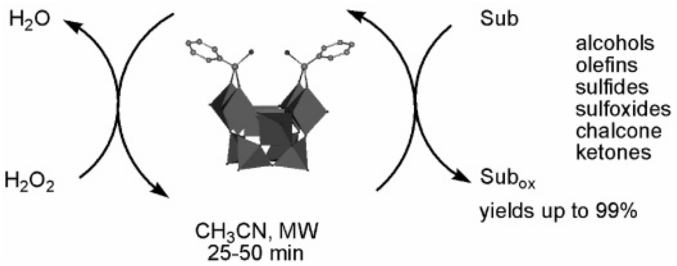
ABSTRACT



Organic–inorganic hybrids synthesized from lacunary polyoxotungstates (POMs) have been screened as oxidation catalysts with H_2O_2 under MW irradiation. Yields up to 99% have been obtained in 25–50 min depending both on the POM structure and on the organic moiety. The reaction scope, optimized with the best performing catalyst $[\gamma\text{-SiW}_{10}O_{36}(PhPO)_2]^{4-}$, includes epoxidation of terminal and internal double bonds, alcohol oxidation, and sulfoxidation, as well as oxygen transfer to electron-deficient substrates as chalcone, ketones, and sulfoxides.

Among catalytic protocols using hydrogen peroxide as terminal oxidant, those involving competent W(VI)-peroxides are generally characterized by negligible decomposition pathways and good to excellent selectivities.[1] Tungstate-based systems, using H_2WO_4 or Na_2WO_4 as catalyst precursors, have advanced into efficient synthetic methods for alkene oxidation.[2,3] Moreover, the solvent-free setup of the Noyori manifold (Na_2WO_4, phosphonic acid, $Q^+HSO_4^-$) represents a significant improvement toward sustainable transformations.[4] In such a ternary system, the phosphonic acid additive appears to be crucial for high catalytic activity toward alkenes (yields up to 99% in 2−4 h at 90 °C).[4b] However, because of the complexity of H_2O_2 equilibria with mono- or polynuclear tungsten precursors, speciation of the competent intermediates and their dynamic behavior is a major issue.[5,6] This hampers both a precise understanding of the mechanistic scenario and a reliable drawing of

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(3) (a) Prandi, J.; Kagan, H. B.; Mimoun, H. *Tetrahedron Lett.* **1986**, *27*, 2617−2620. (b) Venturello, C.; D'Aloisio, R. *J. Org. Chem.* **1988**, *53*, 1553−1557. (c) With $H_3PW_{12}O_{40}$ as percursor: Ishii, Y.; Yamawaki, K.; Ura, T.; Yamada, H.; Yoshida, T.; Ogawa M. *J. Org. Chem.* **1988**, *53*, 3587−3593. (d) Sato, K.; Aoki M.; Ogawa, M.; Hashimoto, T.; Noyori, R. *J. Org. Chem.* **1996**, *61*, 8310−8311. (e) Villa de, A. L.; Sels, B. F.; De Vos, D. E.; Jacobs, P. A. *J. Org. Chem.* **1999**, *64*, 7267−7270.

(4) (a) Sato, K.; Aoki, M.; Noyori, R. *Science* **1998**, *281*, 1646−1647. (b) Noyori, R.; Aoki, M.; Sato, K. *Chem. Commun.* **2003**, 1977−1986.

(5) Prandi and Ishi-Venturello systems have been shown to evolve to reactive di- or tetranuclear peroxides such as $\{[WO(O_2)_2]_2O\}^{2-}$and $\{PO_4[WO(O_2)_2]_4\}^{3-}$. In Noyori's proposal, the aggregation state is unknown.

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structure–reactivity correlations spanning the diverse catalytic routines.[2,5] In this light, an appealing alternative is represented by H_2O_2-stable polyoxotungstates (POM), displaying persistent structures under oxidation turnovers.[2,7,8] Worthy of notice is the catalytic performance of $[\gamma\text{-SiW}_{10}O_{34}(H_2O)_2]^{4-}$ with selectivity up to >99% in the epoxidation of internal and terminal double bonds (2−10 h at 32 °C).[8] This latter catalyst is characterized by a divacant structure, featuring a tetra-oxygenated, nucleophilic site on the POM surface and four W(VI) atoms capable of H_2O_2 coordination.[9]

In this system, two major drawbacks are represented by protonation equilibria, likely engaging the lacunary site, which alter the POM solubility and reactivity[10] and by a thermally induced catalyst deactivation. A convenient remedy can be provided by the covalent functionalization of the POM lacunary oxygens through the attachment of organic moieties.[11,12] Such a hybrid way to the POM synthesis imparts a strong stabilization of the vacant structure while generating catalyst diversity that might also include the most desirable chiral upgrade. The key strategy is to provide the W(VI) sites with proximal stereoelectronic effectors, which are expected to tune the reactivity of the competent oxidant.[11,12] Herein we report on (i) the MW-assisted fast screening[13] of hybrid Keggin 9-11 polyoxotungstates as epoxidation catalysts, (ii) a remarkably wide reaction scope accessed through the combined used of the most performing catalyst and MW irradiation, and (iii) LFER studies under conventional and MW-induced dielectric heating. The first evidence of enantioselective oxygen transfer mediated by a chiral hybrid POM is also included. As corollary, the stability of the different catalytic systems has been addressed by FT-IR, heteronuclear NMR and ESI-MS techniques (see Supporting Information).

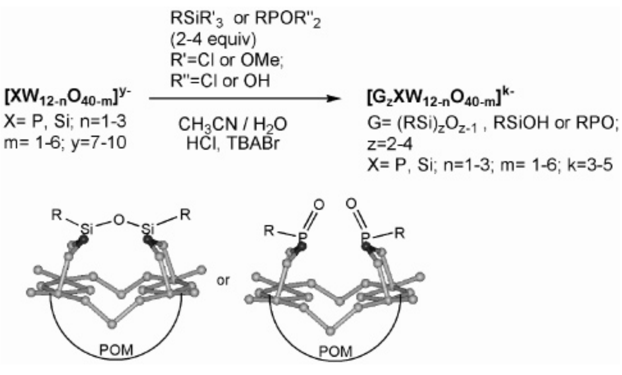
Hybrid complexes were prepared from lacunary polyoxotungstates and organosilanes or phosphonic reagents according to straightforward literature protocols (Scheme 1 and Supporting Information).[14] Their reactivity was screened for *cis*-cyclooctene epoxidation under MW irradiation (Table 1).[13]

Table 1. MW-Assisted *cis*-Cyclooctene Epoxidation with H_2O_2 Catalyzed by Hybrid $[G_zXW_{12-n}O_{40-m}]^{k-}$ [a]

catalyst	POM[b]	G (*z*)	epoxide yield (%)[c]
1	$\alpha\text{-PW}_{11}O_{39}{}^{7-}$	PhSi (2)	54
2		PhPO (2)	92
3[d]	$\alpha\text{-SiW}_{11}O_{39}{}^{8-}$	PhSi (2)	48[e]
4		PhPO (2)	85
5[d]		MeSi (2)	28[e]
6	$\gamma\text{-PW}_{10}O_{36}{}^{7-}$	PhSi (2)	73
7	$\gamma\text{-SiW}_{10}O_{36}{}^{8-}$	PhSi (2)	91[e]
8		PhPO (2)	97
9		$NH_2(CH_2)_2Si$ (2)	97[e]
10		$Ph(CH_2)_2Si$ (2)	75[e]
11	$\alpha\text{-PW}_9O_{34}{}^{9-}$	PhSi (4)	92
12		PhPO (2)	87
13	$\alpha\text{-SiW}_9O_{34}{}^{10-}$	PhSi (4)	>99[e]

[a] POM, 0.8 μmol; *cis*-cycloctene, 0.5 mmol; H_2O_2 (35%), 0.1 mmol; CH_3CN (0.6 mL); MW irradiation for 50 min at 240 W; T_{bulk} = 120 °C. [b] Lacunary precursor used as TBA salts. [c] Calculated with respect to initial H_2O_2. [d] POM used as Ph_4P^+ salt. [e] After 100 min of irradiation.

Scheme 1. Surface Derivatization of Lacunary Polyoxotungstates



MW-induced dielectric heating is efficiently used by these poly-charged catalysts, behaving as MW-activated molecular heat carriers.[15] Furthermore, functionalization of the lacunary site prevents the thermal rearrangement of the POM structure.[16] The catalyst performance is strongly dependent on the structure/composition of the inorganic framework as well as on the nature of the organic moiety decorating the POM surface. A superior performance, with yields in the range

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(9) The tetraperoxo complex derived from addition of H_2O_2 to the four lacunary W(VI) of α-Keggin $[CoW_{11}O_{39}]^{9-}$ has been characterized by X-ray analysis and found to be reactive in the epoxidation of 2-cyclohexenol. See: Server-Carrió, J.; Bas-Serra, J.; Gonzàlez-Nuñez, M. E.; Garcìa-Gastaldi, A.; Jameson, G. B.; Baker, L. C. W.; Acerete, R. *J. Am. Chem. Soc.* **1999**, *121*, 977−984.

(10) The catalytic activity of the lacunary complex is highly dependent on the pH at which it is isolated. For a discussion on the speculated structure of the active catalyst, see: Musaev, D. G.; Morokuma, K.; Geletii, Y. V.; Hill, C. L. *Inorg. Chem.* **2004**, *43*, 7702−7708.

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(12) (a) Bonchio, M.; Carraro, M.; Scorrano, G.; Fontananova, E.; Drioli, E. *Adv. Synth. Catal.* **2003**, *345*, 1119−1126. (b) Bonchio, M.; Carraro, M.; Scorrano, G.; Bagno A. *Adv. Synth. Catal.* **2004**, *346*, 648−654.

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(14) (a) Weeks, M. S.; Hill, C. L.; Schinazi, R. F. *J. Med. Chem.* **1992**, *35*, 1216−1221. (b) Mayer, C. R.; Fournier, I.; Thouvenot, R. *Chem. Eur. J.* **2000**, *6*, 105−110. (c) Niu, J.; Li, M.; Wang, J. *J. Organomet. Chem.* **2003**, *675*, 84−90. (d) Mayer, C. R.; Thouvenot, R. *J. Chem. Soc., Dalton Trans.* **1998**, 7−13. (e) Mayer, C. R.; Herson, P.; Thouvenot, R. *Inorg. Chem.* **1999**, *38*, 6152−6158. (f) Sun, Z.-G.; Liu, Q.; Liu, J.-F., *Polyhedron* **2000**, *19*, 125−128. (g) Kim, G.-S.; Hagen, K. S.; Hill C. L. *Inorg. Chem.* **1992**, *31*, 5316−5324. (h) Ammari, N.; Hervé, G.; Thouvenot, R. *New. J. Chem.* **1991**, *15*, 607−608.

(15) Roberts, B. A.; Strauss, C. R. *Acc. Chem. Res.* **2005**, *38*, 653−661.

(16) Nonfunctionalized lacunary POMs evolve to saturated W_{12}-derivatives under MW-assisted catalysis.

85−97% after 50 min irradiation, is registered for phenylphosphonate derivatives, in agreement with Noyori's observation.[4] In particular, the [γ-$SiW_{10}O_{36}(PhPO)_2]^{4-}$ species features both high stability and excellent epoxidation selectivity (catalyst **8** in Table 1).

With this catalyst and under MW irradiation, the oxidation scope has been expanded to include, in addition to highly reactive substituted olefins, alcohols, and sulfides, also electron-poor alkenes, ketones and sulfoxides (Table 2).

Table 2. MW-Assisted Oxidations with H_2O_2 Catalyzed by [γ-$SiW_{10}O_{36}(PhPO)_2]^{4-}$

entry[a]	substrate	product	time (min)	yield (%) [b]
1	cyclooctene	cyclooctene oxide	50	97
2[c]	cyclohexene	cyclohexene oxide	25	99
3	*trans*−2-octene	2,3-epoxyoctane	25	99
4[d]	1-octene	1,2-epoxyoctane	50	79[e]
5[d]	1-hexene	1,2-epoxyhexane	50	50[f]
6	chalcone	chalcone oxide	50	29[g]
7	cyclopentanol	cyclopentanone	50	>99
8	cyclohexanol	cyclohexanone	50	95
9	1-pentanol	1-pentanal	50	59[h]
10	benzyl alcohol	benzaldehyde	10	>99
11[d]	cyclobutanone	γ-butyrolactone	50	62[g,i]
12	cyclohexanone	adipic acid	100	75[g,j]
13	methyl *p*-tolylsulfide	methyl *p*-tolylsulfoxide	25	>99
14	methyl *p*-tolylsulfoxide	methyl *p*-tolylsulfone	25	>99

[a] POM (TBA salt), 0.8 μmol; substrate, 0.5 mmol; H_2O_2 (35%), 0.1 mmol in CH_3CN (0.6 mL); T_{bulk} = 90−120 °C at MW irradiation power = 180−240 W. [b] Calculated with respect to initial H_2O_2. [c] H_2O_2 (70%), 0.1 mmol. [d] POM, 2.4 μmol; substrate, 1.5 mmol, H_2O_2 (70%), 0.3 mmol. [e] Heptanoic acid formed as byproduct. [f] α-Hydroxy hexanoic and pentanoic acids formed as byproducts. [g] H_2O_2 partially decomposed. [h] Pentanoic acid formed as byproduct. [i] The uncatalyzed reaction proceeds with 27% yield. [j] POM, 2.4 μmol; substrate, 0.5 mmol; H_2O_2 (70%), 1.5 mmol.

Indeed, the best performance has been obtained in the oxidation of internal olefins, secondary and benzylic alcohols, and organic sulfur compounds with good to excellent yield of H_2O_2 conversion after just 10−50 min of MW irradiation and 0.8% catalyst loading. Of particular interest is the oxygen transfer to chalcone and to cyclic ketones (entries 6, 11, and 12 in Table 2). Both oxidations are rarely documented for electrophilic d^0-peroxometal complexes.[17−19]

To gain insights into such mechanistic dichotomy, selectivity probes have been searched through kinetic and LFER studies. The two-step consecutive oxidation of methyl *p*-tolyl sulfide, catalyzed by [γ-$SiW_{10}O_{36}(PhPO)_2]^{4-}$, occurs with pseudo-first-order rate constants, leading to sulfoxide with $k_S = 2.5 \times 10^{-3}$ s^{-1} and sulfone with $k_{SO} = 2.4 \times 10^{-4}$ s^{-1}.[20] The resulting selectivity factor, k_S/k_{SO} = 10, is one order of magnitude lower than that obtained by typical d^0-electrophiles.[18]

Indeed, Hammett correlations determined for *p*-substituted thioanisoles afford negative ρ constants with rather small values under either conventional ($\rho^+ = -0.54$) or MW-induced heating ($\rho^+ = -0.38$, Figure 1A and entries 1 and 2 in Table 3).[21] Furthermore, a mechanistic umpolung to a nucleophilic-type oxidation is observed in the oxygen transfer to analogous sulfoxides yielding a curved Hammett plot (Figure 1B and entries 3 and 4 in Table 3).[19,22]

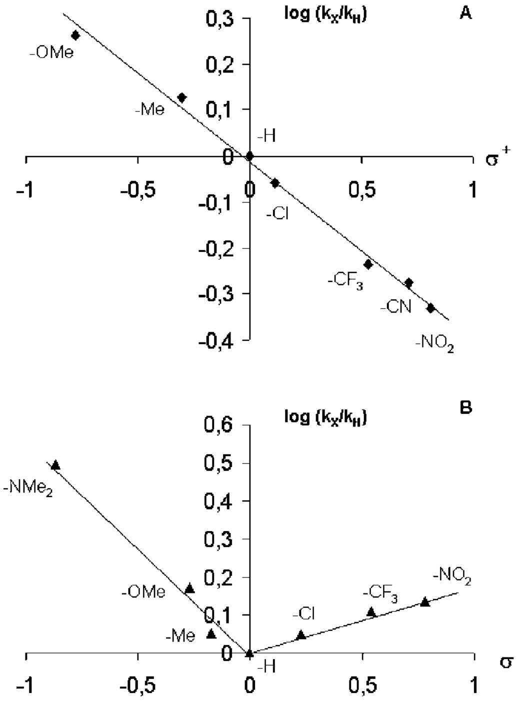

Figure 1. Hammett correlation of log(k_X/k_H) vs σ^+ or σ for the oxidation of *p*-substituted thioanisoles (A) and corresponding sulfoxides (B) catalyzed by [γ-$SiW_{10}O_{36}(PhPO)_2]^{4-}$ under MW irradiation (see experimental conditions in Table 3).

Table 3. Hammett Correlation Parameters for the Oxygen Transfer to Aromatic Sulfides and Sulfoxide by [γ-$SiW_{10}O_{36}(PhPO)_2]^{4-}$ under MW-Assisted or Conventional Conditions

entry	substrates	*T* (°C)	ρ (σ < 0)	ρ (σ > 0)
1[b]	*p*-X(C_6H_4)SCH_3	25	−0.54	
2[c]	*p*-X(C_6H_4)SCH_3	MW	−0.38	
3[b]	*p*-X(C_6H_4)S(O)CH_3	25	−0.55	0.21
4[c]	*p*-X(C_6H_4)S(O)CH_3	MW	−0.58	0.18

[a] POM, 0.8 μmol; competing substrates, 0.25 mmol; 35% H_2O_2, 0.1 mmol; 0.6 mL of CH_3CN. [b] Time = 12 h. [c] T_{bulk} = 120 °C, MW irradiation power 240 W, time =25 min.

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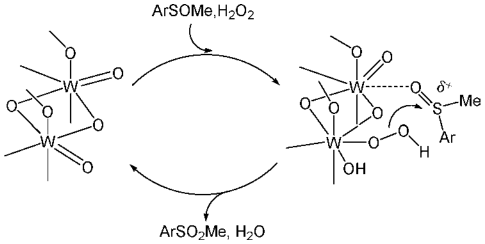
Noteworthy, LFER conventional experiments performed at 25 °C indicate that under MW irradiation the oxidation selectivity is unaffected, despite the strong acceleration of the overall process (Table 3).

Converging lines of evidence delineate a weak electrophilic character for the competent oxidant, turning to a biphilic nature with respect to sulfoxide oxidation.[19] This behavior is likely to be stimulated by the catalyst polynuclear W(VI) framework, which may foster a dual activation of both the oxidant and the sulfoxide by coordination to proximal Lewis acid sites on the polyoxotungstate surface (Scheme 2).

Scheme 2. Proposed Mechanism for the Nucleophilic Oxidation of Aromatic Sulfoxides with H_2O_2 by $[\gamma\text{-SiW}_{10}O_{36}(PhPO)_2]^{4-}$



Kinetic evidence of the sulfoxide coordination is indeed provided by a rate saturation effect on increasing the substrate concentration.[23] On the other hand, speciation and structural characterization of a postulated POM-based peroxide remains elusive. FT-IR, ESI-MS, and ^{183}W and ^{31}P NMR spectra of $[\gamma\text{-SiW}_{10}O_{36}(PhPO)_2]^{4-}$, before and after incubation with H_2O_2, are basically unaltered.[24] Therefore, the catalytic effect might be explained by the formation of a transient η^1-hydroperoxo intermediate via association equilibria of H_2O_2 to the POM precursor (Scheme 2).[25] The asymmetric binding of the peroxo-ligand, not evolving to a bidentate η^2-coordination mode, would also give reason of the atypical selectivity behavior, with respect to classical d^0 η^2-peroxo-metal complexes.[17,21]

A further point concerns the steric constrains of stereospecific oxygen transfer to (*Z*)- and (*E*)-alkenes. Competitive epoxidation of diastereomeric 2-hexenes, performed at 35 °C by the title catalyst, shows a reactivity ratio $Z/E > 9$. Such marked *Z* preference speaks in favor of a POM-based peroxide as the competent oxidant.[26] Future investigation will focus on asymmetric catalysis, which represents the most desiderable implementation of such POM-based hybrids. To probe the impact of a chiral functionality attached to the POM surface, the lacunary $[\gamma\text{-SiW}_{10}O_{36}]^{8-}$ has been decorated with enantiopure (*R*) or (*S*) 1-aminoethylphosphonic acid (Scheme 1). With this catalyst, a preliminary result has been achieved in the enantioselective sulfoxidation of methyl *p*-tolylsulfide. Under the conditions explored,[27] the sulfoxide is recovered in 20% yield, 100% selectivity, enantiomeric excess (ee) up to 24% and the same configuration with respect to the chiral inductor. Structural and spectroscopic characterization of the chiral hybrid POM as well as optimization of the stereo-electronic features of the organic moiety are currently being investigated.

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Supporting Information Available: Experimental procedures, spectral details, and kinetic studies. This material is available free of charge via the Internet at http://pubs.acs.org.

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(20) γ-SiW$_{10}$O$_{36}$(PhPO)$_2$]$^{4-}$ (TBA salt) 0.8 μmol; substrate 0.5 mmol; H_2O_2 (35%) 1.36 mmol in CH_3CN (0.6 mL), $T = 50$ °C.

(21) Analogous LFE correlations, obtained for a series of electrophilic peroxides, yield ρ values close to −1. See: (a) Bonchio, M.; Campestrini, S.; Conte, V.; Di Furia, F.; Moro, S. *Tetrahedron* **1995**, *51*, 12363-12372. (b) Vassell, K. A.; Espenson, J. H. *Inorg. Chem.* **1994**, *33*, 5491−5498.

(22) Lindsay Smith, J. R.; Gilbert, B. C.; Mairata i Payeras, A.; Murray, J.; Lowdon, T. R.; Oakes, J.; Pons i Prats, R.; Walton, P. H. *J. Mol. Catal. A: Chem.* **2006**, *251*, 114−122 and references therein.

(23) The initial concentration of methyl *p*-tolylsulfoxide was varied in the range 1.3×10^{-2} to 5.7×10^{-1} M; reaction conditions and saturation plot are included in Supporting Information.

(24) ^{183}W NMR, obtained after incubation with 40 equivalents of H_2O_2, confirm the maintenance of the catalyst structure (C_2v, with the following signal pattern: −108.0 (2W), −115.8 (4W), and −156.4 (4W, d, $J^2{}_{PW}$ = 11.0 Hz. No other resonance was observed in the range 600−1300 ppm. ^{31}P{H} NMR shows a single peak at 18.7 ppm. ESI-MS characterization of the catalyst recovered after MW irradiation yields one signal at m/z = 896.9, corrresponding to $[HSiW_{10}O_{36}(PhPO)_2]^{3-}$.

(25) Prabhakar, R.; Morokuma, K.; Hill, C. L.; Musaev, D. G. *Inorg. Chem.* **2006**, *45*, 5703−5709.

(26) This value is similar to that obtained with the parent catalyst $[\gamma\text{-SiW}_{10}O_{34}(H_2O)_2]^{4-}$ (13.9).[8c] See also: Goto, Y.; Kamata, K.; Yamaguchi, K.; Uehara, K.; Hikichi, S.; Mizuno, N. *Inorg. Chem.* **2006**, *45*, 2347−2356 and references therein.

(27) (*R*)- or (*S*)-POM = 22 mg; substrate = 14.2 μmol; 35% H_2O_2 = 14.2 μmol, in CH_3CN = 0.5 mL, 72 h at T = −10 °C.