Glycol-modified molybdate catalysts for efficient singlet oxygen generation from hydrogen peroxide

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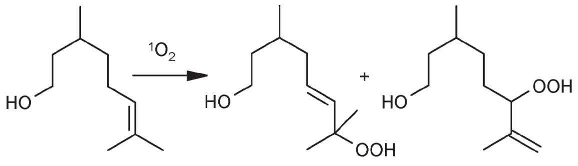
Pretreatment of molybdate-exchanged layered double hydroxides in polyalcohols such as ethylene glycol affords heterogeneous catalysts showing largely improved oxidant efficiency compared to the unmodified materials.

The confinement of molybdate (MoO_4^{2-}) anions to the surface of layered double hydroxides (LDHs, $[M^{II}_{1-x}M^{III}_x(OH)_2][X^{n-}]_{x/n}\cdot zH_2O$) is by now a recognized route to heterogeneous catalysis for the generation of singlet molecular oxygen ($^1O_2$) from hydrogen peroxide.[1] Although these Mo-LDH catalysts show improved catalytic activity compared to soluble molybdate, immobilization leads to a significant drop of the H_2O_2 efficiency, presumably because a relatively large amount of the formed $^1O_2$ is quenched by collision with the support matrix. Indeed, the surface of an LDH is covered with numerous hydroxyl groups, which are known to be efficient $^1O_2$ quenchers.[2] As a consequence, the oxidant efficiency of Mo-LDHs in the peroxidation of β-citronellol, a typical olefinic compound, is at most half of that observed for homogeneous MoO_4^{2-}. Therefore, overstoichiometric amounts of H_2O_2 are required to reach complete substrate conversion. Herein we report that the pretreatment of Mo-LDHs in polyalcohols such as ethylene glycol significantly improves the oxidant efficiency of the catalysts compared to the parent Mo-LDHs.

First, a (NO_3^-)-[Mg,Al]LDH support with a Mg/Al molar ratio of 2/1 was prepared by co-precipitation of Mg(II) and Al(III) nitrate salts in the presence of aqueous NaOH. Next, partial ion exchange of nitrate for molybdate yielded (MoO_4^{2-},NO_3^-)-[Mg,Al]LDH containing 0.2 mmol MoO_4^{2-} per gram.[1] This material was used for further treatment with various glycols.[3–6] The general procedure involved heating air-dry Mo-LDH (1 g) in ethylene glycol (50 mL) for 12 h at 80 °C.[3] The product (Mo-LDH-EG) was centrifuged, thoroughly washed with acetone, and air-dried at room temperature. A similar treatment of the Mo-LDH was carried out in different glycols, simple alcohols and other polar organic solvents.

The H_2O_2 efficiency of the various catalysts was assessed by chemical trapping of the formed $^1O_2$ with β-citronellol. This olefin contains two types of allylic hydrogen atoms and reacts with $^1O_2$ to yield an equimolar mixture of allylic hydroperoxides. Quantification of the formed allylic hydroperoxides by GC analysis allows the determination of the H_2O_2 efficiency. In the presence of citronellol, $^1O_2$ generated from H_2O_2 (eqn (1)) can either react with this trap (eqn (2)) or can be physically quenched by the solvent, the solid catalyst, or citronellol itself (eqn (3)). The reaction was carried out at 25 °C in *N*,*N*-dimethylformamide (DMF) as the solvent. H_2O_2 (50 wt.%) was added in small portions (Mo/H_2O_2 = 1/50) in order to favour the formation of the labile oxotriperoxo-Mo species.[1] The citronellol/Mo molar ratio was 100/1.

$$2H_2O_2 \xrightarrow{Mo-LDH-EG} 2H_2O + {}^1O_2 \qquad (1)$$



(2)

$$^1O_2 \xrightarrow[\text{solid}]{\text{solvent}\ \text{citronellol}} {}^3O_2 \qquad (3)$$

In Fig. 1, the yield of citronellol hydroperoxides is plotted against the number of equivalents (equiv.) of H_2O_2 added with respect to citronellol. Theoretically, if the above-mentioned physical quenching processes are not operating, 2 equiv. of H_2O_2 are sufficient for complete conversion of citronellol (100% H_2O_2 efficiency). Fig. 1 clearly shows that the H_2O_2 utilization of the Mo-LDHs pretreated in glycolic solvents is more efficient than that of the parent Mo-LDH. The efficiency increases from 20% for the unmodified Mo-LDH to about 60% for Mo-LDH-EG.

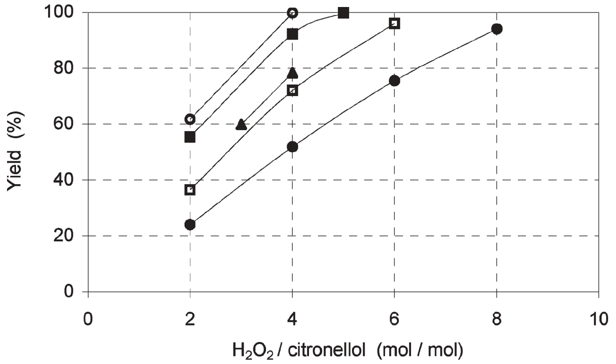


Fig. 1 Peroxidation of citronellol with unmodified Mo-LDH (●) and Mo-LDHs treated in 1,2-propanediol (○), ethylene glycol (■), glycerol (▲), and 1,3-propanediol (□). Reaction conditions: 0.5 g of Mo-LDH-X (0.1 mmol Mo), 10 mmol citronellol, H_2O_2 added in 5 mmol portions, 10 mL of DMF, 25 °C. GC analysis after centrifugation and reduction with $(CH_3)_3P$. Hydroperoxide selectivity >95% in all cases.

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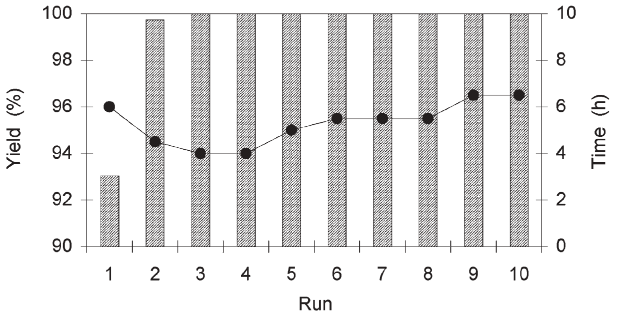


Fig. 2 Hydroperoxide yield and reaction time (●) for the peroxidation of citronellol catalyzed by Mo-LDH-EG. (Yield axis starts at 90%.) Reaction conditions: 1 g of Mo-LDH-EG (0.2 mmol Mo), 20 mmol citronellol, 80 mmol H_2O_2 added in 10 mmol portions, 10 mL of DMF, 25 °C. Hydroperoxide selectivity >99% in all cases.

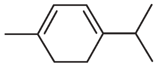
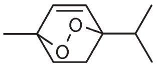
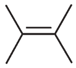
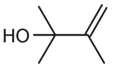
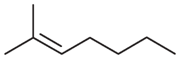
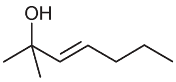
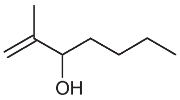
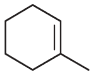
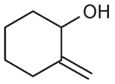
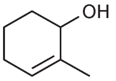
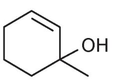
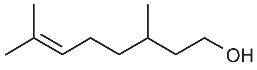
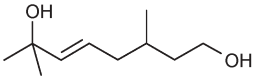
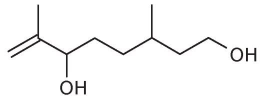
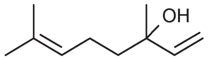
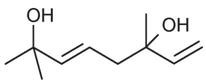
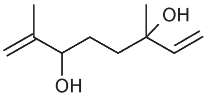
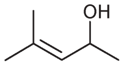
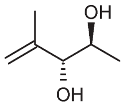
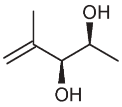
Complete conversion of citronellol is obtained using 4 equiv. of H_2O_2, whereas the unmodified Mo-LDH requires at least 8 equiv. of H_2O_2. Treatment in 1,2-propanediol yields a slightly more efficient catalyst than Mo-LDH-EG. On the other hand, 1,3-propanediol and glycerol provide less efficient catalysts compared to Mo-LDH-EG, but the efficiency is still significantly higher than that observed for Mo-LDH. In contrast, treatment of Mo-LDHs in 2-methoxyethanol, 2,2,2-trifluoroethanol, simple alcohols such as *tert*-butanol or ethanol, or other polar organic solvents such as DMF under similar conditions did not result in an improvement of the oxidant efficiency compared to the unmodified Mo-LDH catalyst. Apparently, the presence of a glycolic moiety in the modifying agent is of primary importance for the preparation of a heterogeneous catalyst showing high oxidant efficiency.

Having identified Mo-LDH-EG as a highly efficient catalyst, the recycling and reuse of this material were examined. At the end of the reaction, the solid Mo-LDH-EG was recovered by simple centrifugation, washed with acetone, and the catalyst along with replenished reagents and solvent was reused for nine cycles with minimal loss of activity (Fig. 2). The oxidant efficiency remained equally high during all runs. This recycle experiment clearly shows that the efficiency-enhancing effect of the EG treatment is stable in time. Moreover, elemental analysis (ICP-MS) showed no leaching of molybdate from the LDH support.

Characterization of the Mo-LDH-EG catalyst by X-ray diffraction, infrared spectroscopy and solid-state NMR indicated that ethylene glycol is interacting with aluminium located at the outer surface and at the edges of the LDH crystals; intercalation does not occur to any significant extent. At this time we presume that the EG pretreatment induces a transformation of the outer LDH surface, *e.g.*, by relocating the molybdate ions, or by changing the sorption properties of the surface. Both factors likely favour the access of citronellol to the $^1O_2$-producing centres, or alternatively, the easy escape of $^1O_2$ from the LDH surface.

In order to explore the synthetic scope of the Mo-LDH-EG catalyst, the peroxidation of some typical olefinic compounds was attempted (Table 1).† Dienes such as α-terpinene (Entry 1) react with $^1O_2$ *via* a [4 + 2]-cycloaddition and yield the corresponding endoperoxides as the product. On the other hand, alkyl-substituted

Table 1 Peroxidation of olefinic compounds with singlet oxygen generated from Mo-LDH-EG and H_2O_2[a]

Entry	Substrate	H_2O_2 (equiv.)	*t* (h)	Products	Distribution (%)	Conversion (%)	Selectivity (%)
1		3.3	3		—	98	86
2		3	2.5		—	99	99
3		4	3.5	 	53 : 47	97	99
4		5	4.5	  	42 : 15 : 43	98	99
5		4	3.5	 	49 : 51	96	99
6[b]		4	5		52 : 48	87	98
7[c]		8	5		47 : 53	94	99
8		4	3.5	 	42 : 58	92	99
9		5	5		42 : 58	99	99
10		8	13	 	59 : 41[d]	88	98
11[c]		16	15		61 : 39[d]	89	91

[a] Reaction conditions: 5 mmol olefin and 0.25 g of Mo-LDH-EG (Mg/Al = 2, 0.2 mmol Mo/g) were stirred at 25 °C in 5 mL of DMF. H_2O_2 (50 wt.%) was added in 2.5 mmol portions. GC analysis after centrifugation and reduction with excess $(CH_3)_3P$ (except for Entry 1). [b] 5 mL of methanol. [c] Unmodified Mo-LDH. [d] Pairs of enantiomers.

alkenes react with $^1O_2$ *via* the ene reaction, and mixtures of regioisomeric allylic hydroperoxides with a unique product distribution are obtained.[7] This is illustrated by the oxidation of simple acyclic and cyclic alkyl-substituted alkenes such as 2,3-dimethyl-2-butene (Entry 2), 2-methyl-2-heptene (Entry 3) and 1-methyl-1-cyclohexene (Entry 4). These substrates typically require 3 to 5 equiv. of H_2O_2 to reach complete conversion. Reduction of the allylic hydroperoxides yields the corresponding allylic alcohols. Although product mixtures are obtained in most cases, many of these compounds are difficult to obtain by other synthetic procedures. The regioselectivity of the reaction of $^1O_2$ generated from Mo-LDH-EG and H_2O_2 is similar to known solution photochemistry. For example, 1-methyl-1-cyclohexene gave a hydroperoxide mixture showing the same product distribution pattern as that observed for photooxidations.[8] Oxyfunctionalized alkenes such as the monoterpene citronellol (Entry 5) cleanly yield the allylic hydroperoxide products, no oxidation of the primary alcohol functionality being observed. Photooxidation of citronellol is the first step in the preparation of rose oxide, a well-known perfumery ingredient used in rose and geranium perfumes.[9] Reaction in methanol as the solvent is somewhat slower and slightly less efficient than in DMF (Entry 6). Using the unmodified Mo-LDH catalyst instead of Mo-LDH-EG, twice as much H_2O_2 is required to reach high conversions (Entry 7). For comparison, the peroxidation of citronellol in methanol using homogeneous MoO_4^{2-} requires 4 equiv. of H_2O_2 for complete conversion, whereas in DMF, 6 equiv. are required to reach 80% conversion.[10] Other heterogeneous catalysts such as $La(OH)_3$ (12 equiv.)[11] or La-zeolites (8 equiv.)[12] show far less efficient utilization of H_2O_2. For linalool (Entry 8), a monoterpene containing an allylic alcohol functionality, peroxidation occurs at the isolated, electron-rich 6,7-double bond. Epoxidation of the less electron-rich, allylic double bond was not observed. Using 5 equiv. of H_2O_2, full conversion of linalool is obtained after 5 h (Entry 9). The derived allylic alcohols are intermediates for 3,7-dimethyl-1,5,7-octatrien-3-ol, which can be used as a perfume or flavouring component.[13] Next, Mo-LDH-EG was used for the peroxidation of allylic alcohols to the corresponding hydroperoxy homoallylic alcohols.[14] Mesitylol (4-methyl-3-penten-2-ol, Entry 10) was selected as a typical allylic alcohol showing relatively low reactivity towards $^1O_2$. The photooxygenation of mesitylol is the first step in the synthesis of 1,2,4-trioxanes. Some of these compounds show high antimalarial activity against *Plasmodium falciparum*.[15] Use of 8 equiv. of H_2O_2 resulted in 90% conversion. Very high selectivity towards the hydroperoxy homoallylic alcohols was observed. Notably, almost no epoxidation of the double bond and no oxidation of the secondary alcohol group were observed. Using the unmodified Mo-LDH catalyst, twice as much H_2O_2 is required to reach similar conversions in the peroxidation of mesitylol (Entry 11). Moreover, the hydroperoxide selectivity is rather low due to competitive epoxidation of the double bond. The stereoselectivities of the peroxidation catalyzed by Mo-LDH-EG in aqueous DMF are in accordance with known photochemical oxidations in polar organic solvents.[14] Thus, relatively low diastereoselectivities are observed due to competitive hydrogen bonding of the allylic alcohol group with DMF and water, rather than with the attacking $^1O_2$.

In conclusion, pretreatment of Mo-LDHs in glycols yields heterogeneous catalysts showing superior H_2O_2 efficiency compared to the unmodified materials.

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Notes and references

† Products were identified by GC-MS, ^1H and ^{13}C NMR and by comparison with authentic samples prepared by photochemical oxidation in the presence of tetraphenylporphine (chloroform) or rose bengal (methanol) as photosensitizer. CAUTION: H_2O_2 and alkyl hydroperoxide solutions are strongly oxidizing and should be handled with appropriate precautions.

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