*Marcello Crucianelli, Francesco De Angelis*
*Dipartimento di Chimica,*
*Ingegneria Chimica e Materiali*
*Università dell'Aquila*
*cruciane@univaq.it*
*Raffaele Saladino*
*Dipartimento di Agrobiologia*
*ed Agrochimica*
*Università della Tuscia*
*saladino@unitus.it*

# IMMOBILIZATION OF MTO

## Part 1: A way to enhance oxidative catalysts versatility

**From an academic and industrial point of view, the interest in the development of environment friendly heterogeneous catalytic processes gained recently an ever increasing importance.** The results obtained in the last five years, in the selective oxidative functionalization of many different organic substrates by means of the novel polymer supported methyltrioxorhenium/$H_2O_2$ catalytic systems, are presented.

### Methyltrioxorhenium as an efficient and selective oxidative catalyst

The oxidative functionalization of organic compounds under controlled conditions is, from an industrial point of view, one of the most important technologies for the conversion of petroleum products or renewable materials to fine chemicals, commodities, cosmetic, food and pharmacological products. In this scenario, environmental and pollution concerns tempt the chemical community to move towards the drastic reduction of the environmental immission of toxic wastes. The best way for reducing hazardous waste is the use of environmental friendly primary oxidants such as hydrogen peroxide ($H_2O_2$) and dioxygen ($O_2$) [1].

*Devoted to prof. Elio Santacesaria in honour of his 65th birthday and of his constant contribution to innovative new processes development in industrial chemistry.*

Methyltrioxorhenium ($CH_3ReO_3$, MTO) [2], in combination with hydrogen peroxide (or urea hydrogen peroxide adduct, UHP), has become in recent years an important catalyst for a variety of synthetic transformations, such as oxidation of olefins, alkynes, aromatic derivatives, sulfur compounds, amines and other nitrogen-containing compounds, phosphines, Baeyer-Villiger rearrangement, and oxygen insertion into C-H bonds [3].

The reactive intermediates for these oxidations are monoperoxo $[MeRe(O)_2O_2]$ (A) and bis-peroxo $[MeReO(O_2)_2]$ (B) $\eta^2$-rhenium complexes. The catalytic cycle of MTO/ $H_2O_2$ system for the oxidation of a generic substrate (S) is reported in Scheme 1. Noteworthy, the oxygen atom transfer from MTO peroxo complexes to S always involves a concerted mechanism avoiding the formation of less selective oxygen-centered radical species.

As a general reaction pattern, in conventional solvents, the complex (B) was found to be more reactive than (A). The opposite occurs for reactions driven in ionic liquids [4].

Although effective for numerous transformations, the most important drawback of this catalyst is the high Brönsted and Lewis acidity and the significative toxicity of rhenium towards biological systems.

## Polymer-Supported MTO Systems

With the aim of developing clean and safe oxidation processes, the preparation of novel heterogeneous rhenium compounds based on the heterogenation of MTO on inorganic, organic or mixed supports have been reported [5]. The heterogenation of MTO is an important green technology because it allows for an easier recovery of the catalyst, decreases the toxicity of reaction wastes and sometimes improves and tunes the selectivity and reactivity of the oxidation [6].

In this context, we described few years ago the preparation of novel heterogeneous rhenium compounds of general formula (polymer)*f*/(MTO)*g* (the *f*/*g* quotient expresses the ratio by weight of the two components) by heterogenization of MTO on poly(4-vinylpyridine) and poly(4-vinylpyridine *N*-oxide) 2% and 25% cross-linked with divinylbenzene (I-IV, Fig. 1) and on polystyrene 2% cross-linked with divinylbenzene (V, Fig. 1) [7], applying an extension of both the "mediator"concept [8] and the microencapsulation technique [9]. All the new MTO compounds were characterized by FT-IR, scanning electron microscopy (SEM), and wide-angle X-ray diffraction (WAXS).

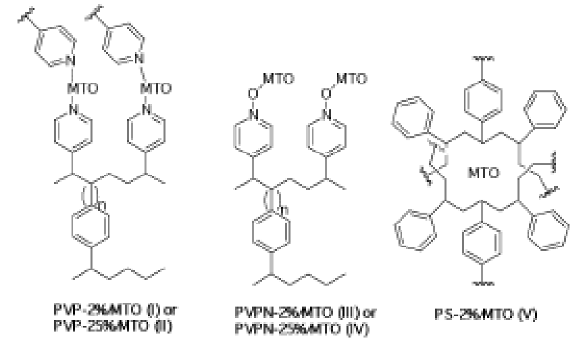
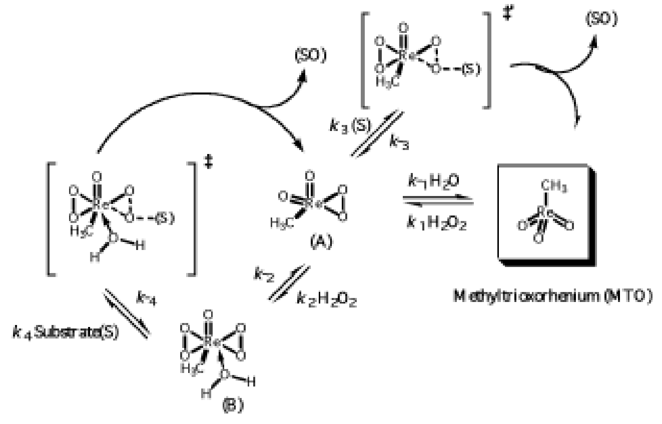
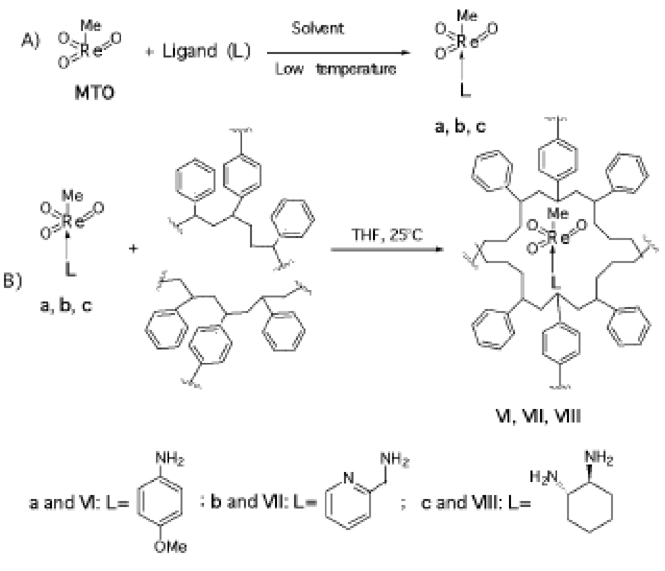


Fig. 1 - Structures of poly(4-vinylpyridine)/MTO, poly(4-vinylpyridine-N-oxide)/MTO and polystyrene/MTO catalysts



Scheme 1 - Catalytic cycle of MTO/$H_2O_2$ system

A different morphology was observed for the catalyst particles depending on the reticulation grade of the support. Particles with irregular surface were obtained at low value of the reticulation grade, while a regular spherical shape was obtained with largest value of this parameter. A second family of polymer supported MTO catalysts has been prepared through microencapsulation of complexes between MTO and different Lewis bases. Lewis base adducts of MTO with nitrogen-containing ligands such as pyridine,



Scheme 2 - Polymer supported MTO-Lewis base adducts pyridine derivatives, pyrazole and others, are known to influence significantly the oxidation processes, for example, decreasing the formation of diols in epoxidation reactions, especially in the case of sensitive substrates, and increasing the catalytic efficiency. MTO reacts with monodentate and bidentate nitrogen ligands to give trigonal bipyramidal and distorted octahedral adducts, respectively [3]. On the basis of these data a series of amine-MTO compounds a-c has been synthesized and used to prepare microencapsulated Lewis base adducts of MTO, compounds VI-VIII (Scheme 2).

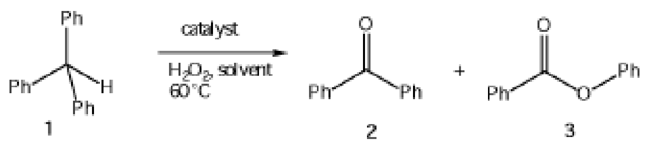
This methodology opens the way to novel chiral polymer supported MTO systems.

## Recent advances in the application of polymer supported catalysts

### *Oxy-functionalization of hydrocarbon derivatives*

The selective oxy-functionalization of hydrocarbons and their derivatives is a very important tool for the conversion of petrochemical feedstocks into industrial commodities and specialty chemicals. In spite of its astonishing and large diffusion in the field of oxidative catalysis, few examples describing the employment of MTO in the oxy-functionalization of hydrocarbons have been reported in the literature.

Polymer supported MTO compounds are efficient and selective catalysts for the oxy-functionalization of C-H bonds in representative hydrocarbon derivatives (leading to the corresponding alcohols or ketones), using $H_2O_2$ as oxidant.



Scheme 3 - Catalytic oxidation of triphenylmethane 1

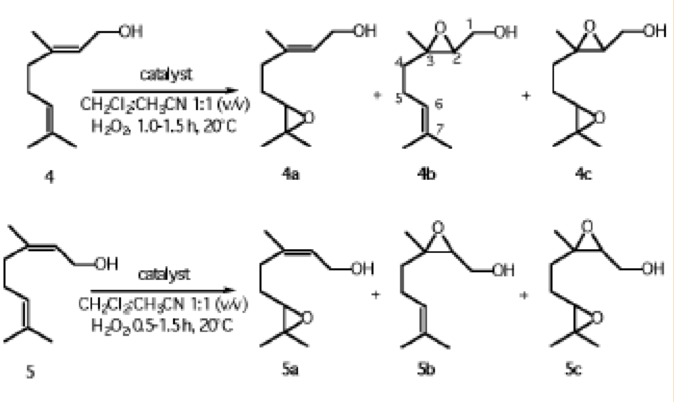
The oxidation of triphenylmethane 1 with poly(4-vinylpyridine) and poly(4-vinylpyridine) *N*-oxide MTO catalysts I-IV (Fig. 1), in EtOH at 60 °C, gave benzophenone 2 as the main product, along with low amounts of phenylbenzoate 3 (Scheme 3). Traces of triphenylcarbinol and phenol were also detected in the reaction mixture by gas-chromatography/mass-spectrometry (GC/MS) analysis. The reaction proceeds through the formation of triphenylcarbinol as an intermediate [10].

As a general reaction pattern, catalysts I, II based on poly(4-vinylpyridine) were more reactive and selective than corresponding poly(4-vinylpyridine) *N*-oxide derivatives III and IV. The value of the reticulation grade of the support also tuned the efficiency of the oxidative process in both types of catalysts, the highest yield of 2 being obtained with 2% cross-linked polymers. The behaviour of microencapsulated catalyst V was similar to that of catalyst PVP-2/MTO I. Better results were obtained changing the reaction solvent from EtOH to acetic acid (AcOH), because acidic solvents are usually able to enhance the reactivity of MTO. Moreover, irrespective of the catalyst used in the oxidation, an increase of substrate conversion and product yield was observed, when the reaction temperature was increased to 80 °C [11].

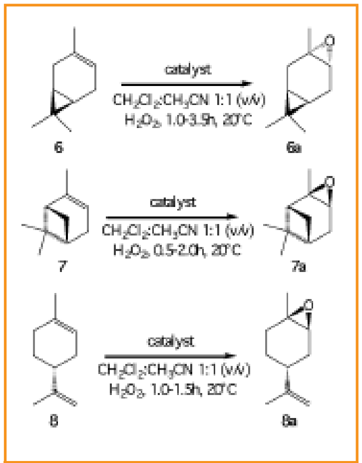
When the oxidation of 1 was performed with microencapsulated MTO/2-aminomethyl pyridine adduct VII, an improvement of both substrate conversion and product yield was observed with respect to PS/MTO V. Polymer supported MTO catalysts I-V showed to be stable systems and were recovered and recycled for at least five times without any appreciable loss in selectivity. It is noteworthy that the oxidative dearylation of tertiary aromatic hydrocarbons to ketones has been previously performed only by use of stoichiometric oxidants or homogeneous catalysts, but there are no general examples describing the use of $H_2O_2$ with heterogeneous systems. Similar results have also been observed in ionic liquids. Indeed, various hydrocarbons including triphenylmethane, are efficiently oxidized to corresponding ketones or alcohols by heterogeneous MTO catalyst systems I-V in 1-*n*-butyl-3-methylimidazolium hexafluorophosphate [BMIM][$PF_6$] and 1-ethyl-3-methylimidazolium bis-triflic amide [EMIM][$Tf_2N$], using $H_2O_2$ as environment friendly oxidant. In several cases the activity of heterogeneous catalysts in ionic liquids was greater than that observed in molecular solvents. Again, catalysts were easily recycled and used for successive transformations with similar selectivity and reactivity [12].

### *Oxidation of olefins, monoterpenes and glycals*

Allylic monoterpenes such as geraniol 4 and nerol 5 have been selectively oxidised, with high conversion levels, at the non-allylic double bonds in accord with the electrophilic character of the oxidant, affording the corresponding 6,7-epoxides 4a and 5a. Low amounts of 2,3-epoxides 4b and 5b and bis-epoxides 4c and 5c, were also formed in the reaction mixture (Scheme 4) [13]. The regioselectivity observed in the oxidation of 4 and 5 is consistent with the results showed by MTO in homogeneous phase, in which case double bonds with the highest HOMO coefficients are oxi-



Scheme 4 - Catalytic oxidation of monoterpenes 4 and 5



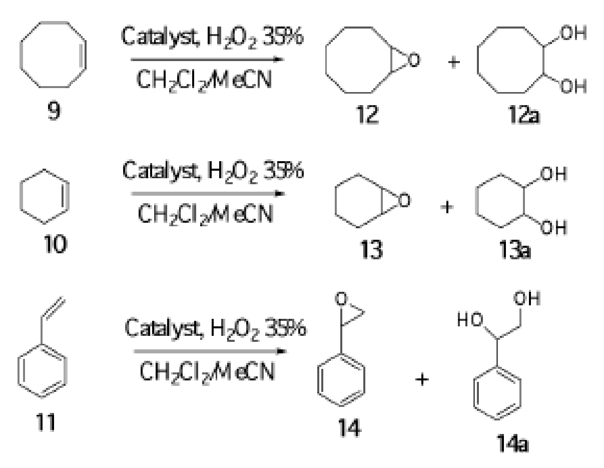
Scheme 5 - Catalytic oxidation of cyclic monoterpenes 6-8

dized. Noteworthy, products of nucleophilic ring opening of the oxiranyl ring or derived from acidic rearrangement of geraniol and nerol epoxides, were not recovered in these experimental conditions.

In the oxidation of cyclic monoterpenes 6-8, polymer-supported MTO catalysts showed, in some cases, a higher reactivity and facial selectivity than their homogeneous counterpart (Scheme 5) [13]. As an example the oxidation of (*S*)-(+)-carene 6 gave the *trans*-3,4-epoxycarene 6a as the only recovered product with both excellent substrate conversions and product yields: no traces of *cis*-3,4-epoxycarene or the corresponding diols were observed in the reaction mixture. Also highly sensitive terpenic epoxides, such as a-pinene oxide, have been selectively obtained in excellent yields by means of polymer-supported MTO catalysts. Thus, the oxidation of 1-(*R*)-a-pinene 7 afforded the corresponding oxide 7a, as the unique recovered product (Scheme 5).

A further high selectivity of heterogeneous MTO compounds in comparison of the homogeneous counterpart was observed in the oxidation of (*R*)-(+)-limonene 8 to *trans*-1,2-epoxide 8a (Scheme 5). Moreover, in the oxidation of olefins as cyclooctene 9 and cyclohexene 10 with microencapsulated bidentate Lewis base adducts of MTO, VII and VIII (Scheme 2), the corresponding epoxides 12 and 13 were obtained in quantitative conversion of substrate and yield of products, being the formation of diols 12a and 13a totally absent (Scheme 6) [14]. Noteworthy, catalysts VII and VIII were more reactive than their parent compounds b and c, VIII being the most reactive catalyst. Microencapsulated adducts VII and VIII were more efficient than b and c also during the synthesis of the sensitive styrene oxide 14 obtained by oxidation of styrene 11 (Scheme 6). Under the same conditions MTO and catalysts a and VI showed lowest selectivity, affording appreciable amounts of diol 14a.

The higher activity and selectivity of Lewis base adducts VII and VIII with respect to their homogeneous parent compounds b and c can be ascribed to the microencapsulation process. Usually, Lewis base

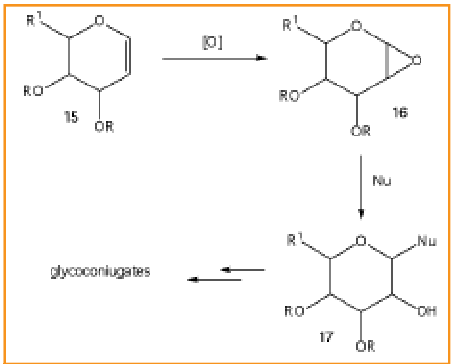


Scheme 6 - Catalytic oxidation of olefins 9, 10 and styrene 11

## RIASSUNTO

### *Immobilizzazione del MTO. Una via per aumentare la versatilità dei catalizzatori ossidativi*

*L'interesse nel settore della ricerca universitaria e dell'industria, verso lo sviluppo di nuove metodologie catalitiche in fase eterogenea ecocompatibili, ha visto negli ultimi anni uno sviluppo crescente. In questo articolo si presentano i risultati ottenuti negli ultimi cinque anni, nella funzionalizzazione selettiva, in condizioni ossidanti, di diverse tipologie di composti organici mediante l'utilizzo di sistemi catalitici supportati su matrici polimeriche basati sul sistema metiltriossorenio/*$H_2O_2$.



Scheme 7 - Domino epoxidation-methanolysis of glycals 15

ligands of MTO undergo exchange reactions in the presence of water (even in the case of more stabilizing bidendate ligands) by hydroxide nucleophilic substitution followed by fast decomposition of the complex with formation of methane and perrhenate [15]. Probably, the low-polarity of the microenvironment inside the polystyrene capsules stabilizes the fluxional behaviour of the MTO adducts, inducing beneficial effects on the catalyst properties. Under these experimental conditions microencapsulated Lewis base adducts VII and VIII are more reactive and selective in comparison of compound VI containing a monodentate ligand, probably because of the known higher stability of the complexes between MTO and bidentate ligands. In general, among the bidentate ligands, aliphatic compounds appear to be more efficient than aromatic compounds.

While catalysts VII-VIII quantitatively convert olefins to cycloalkene oxides at room temperature using environmental friendly $H_2O_2$ as oxidant, a low reaction temperature (-10 °C) was necessary to obtain similar results in terms of reactivity and selectivity, in the oxidation of monoterpenes such as 6 and 7 (Scheme 5) [14].

The efficient activation of $H_2O_2$ by polymer supported MTO catalysts in the epoxidation of the C=C double bond has also been used to design a novel strategy for the domino epoxidation-methanolysis of glycals, as a new entry for glycoconiugates synthesis (Scheme 7) [16].

The epoxidation of glycals is not a trivial task, due also to the sensitive nature of 16, particularly in acidic media. This transformation is usually performed using dimethyldioxirane (DMDO). DMDO is unstable, has to be freshly prepared and poses serious safety problems connected with its potential explosiveness. Therefore, its replacement with safer and more stable oxidants, particularly for large-scale preparations, is a valuable task. Heterogeneous poly(4-vinylpyridine)/MTO compounds I-IV, and microencapsulated polystyrene/MTO systems V, VII-VIII were effective as catalysts for the oxidation of structurally diversified and differently protected glycals. The facial diastereoselectivity of the oxidation ranged from satisfactory to excellent depending on the substrate, and could be optimized by ample screening of the catalysts. The heterogeneous catalysts VII and VIII based on MTO-amine complexes b and c microencapsulated in polystyrene (Scheme 2), generally afforded the best stereoselectivities. Under optimized conditions, all the substrates displayed synthetically meaningful selectivities, up to 100% for arabinal derivatives.

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