A high-performance selective oxidation system for the facile production of fine chemicals†

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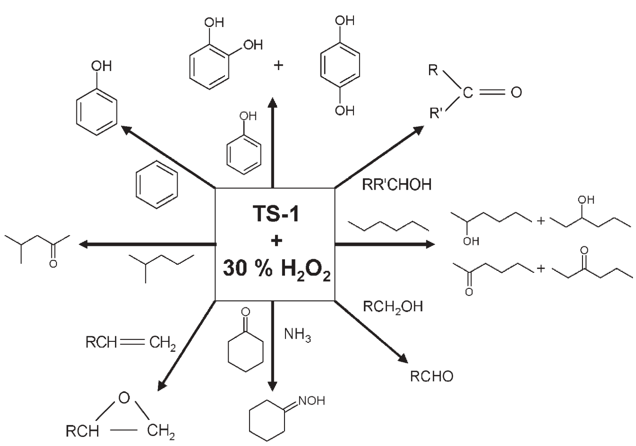
Mn^{III}AlPO-5 and Cr^{VI}AlPO-5 redox (microporous) catalysts are effective, in the presence of dissolved acetylperoxyborate (APB) under mild conditions (333–373 K), and much superior to the titanosilicate, TS-1 (also a single-site heterogeneous catalyst), in the selective oxidation of primary, secondary, benzylic and other unsaturated alcohols, *p*-cymene, methyl cyclohexene and other speciality organics which are of value in the fine-chemical and pharmaceutical industries.

Of the many effective catalytic systems that have emerged[1–3] in recent years to replace stoichiometric ones like CrO_3–H_2SO_4, pyridinium chlorochromate, $KMnO_4$ and $KHSO_5$ for selective oxidation[4] of organic compounds, one of the most versatile and powerful is the combination of H_2O_2 with the single-site[5,6] microporous titanosilicate known as TS-1.[7,8] An indication of its utility is seen in Scheme 1.

In the course of a wide-ranging study of the selective oxidation of a large number of substrates that would yield, by the desired selective oxidation, materials of value in fine-chemical and pharmaceutical contexts, we have found that the widely-used TS-1 oxidation catalyst is distinctly inferior to Mn^{III}-framework-substituted microporous aluminophosphates (AlPO-5) which we (and others) earlier described,[9,10] along with similar MAlPOs (M ≡ Co^{III}, Mn^{III}, Fe^{III}), in relation to its high performance in the one-step conversion of cyclohexane to adipic acid.[11]



Scheme 1 Illustration of the range of selective oxidations effected by the titanosilicate, TS-1.

We have also shown previously[12] that when acetylperoxyborate, (APB), is dissolved in water it yields, *inter alia*, a mixture of hydrogen peroxide and peracetic acid, which, in the presence of a single-site redox microporous catalyst such as Fe^{III}AlPO-31 or Mn^{III}AlPO-5, releases its active oxygen in the vicinity of the active site where selective oxidation of the reactant freely ensues. (The ratio of H_2O_2 to peracetic acid increases with time after dissolution, as shown in Figure 2 of ref. 12).

Typical results for the oxidation of a number of aromatic, aliphatic and unsaturated alcohols are shown in Table 1. The oxidation of primary alcohols to their corresponding aldehydes is a fundamentally important reaction in the laboratory and in commercial practice. It is of considerable significance in the fine-chemical industry since vital ingredients and high-value intermediates (such as perfumes) can be so generated. It is worth noting here that secondary alcohols are generally more reactive compared to primary alcohols and the Jones oxidation (sodium dichromate–H_2SO_4 in acetone) is normally effective here, as over-oxidation is difficult. With primary alcohols, however, the Jones oxidation is not very effective as the aldehyde formed is further oxidized to the acid *via* the hydrate. Hydroxyapatite-supported palladium nanoclusters[13] have proved effective in the oxidation of activated alcohols (where the carbon is attached to a phenyl group such as phenylethanol, and benzyl alcohol), but these catalysts were not very effective for the oxidation of primary alkyl alcohols such as 1-octanol. Good yields (high turnovers) have been reported with gold nanocrystals[14] using an aqueous base and with biphasic catalyst systems,[15] but the corresponding monoacid and not the aldehyde was the major product in most cases. Very recently, Hutchings *et al*[16] have shown that Au/Pd–TiO_2 catalysts display high turnovers and remarkable selectivity (to the aldehyde) for the oxidation of primary alkyl alcohols and a range of other straight-chain, benzylic and other unsaturated alcohols.

It is clear (from Table 1) that the redox active centres (Mn^{III}, Cr^{VI})[17] in the aluminophosphate microporous framework (pore diameter 7.3 Å) is very much more effective than the Ti^{IV} active centre in the microporous silicalite (TS-1) framework (pore diameter 5.5 Å), and that the yields of the desired product with the first of these catalysts are superior to those of the latter. Interestingly, in most cases (with the exception of *p*-cresol and 2-methoxy-4-methyl phenol) non polar solvents (such as dichloromethane, DCM) were particularly effective in facilitating high

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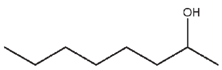
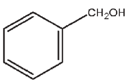
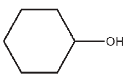
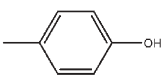
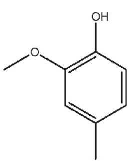
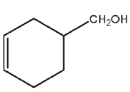
† Electronic supplementary information (ESI) available: Experimental and analytical details, including results on leaching and recycle tests are provided. See DOI: 10.1039/b618090f

Table 1 Comparative performance of TS-1 and Mn^{III}/Cr^{VI}AlPO-5 in the oxidation of primary, secondary and benzylic alcohols using APB[a]

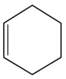
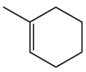
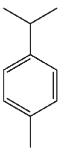
Substrate	Catalyst	T/K	t/h	Sub : oxidant mol ratio	Solvent	Conv.[b] actual (mol%)	Oxidant[b] efficiency (mol%)	Product distribution (mol%) (actual)			
								1-octanol	octanal	octanoic acid	others
	CrAlPO-5	343	1	3 : 1	DCM	12.6	37.9	87.2	12.4	0.3	—
	TS-1	413	3	1 : 1	DCM	56.3	56.3	43.5	12.7	43.5	—
								2-octanol	2-octanone	others	
	MnAlPO-5	368	3	3 : 1	DCM	21.9	65.8	78.0	21.5	0.5	
	CrAlPO-5	413	3	1 : 1	DCM	45.4	45.4	54.5	44.5	1.2	
	TS-1	368	3	3 : 1	DCM	7.2	21.7	93.0	7.1	—	
								benzyl alcohol	benzaldehyde	benzoic acid	others
	MnAlPO-5	333	1	3 : 1	DCM	23.8	71.5	76.0	21.7	1.0	1.3
			3	3 : 1	DCM	28.7	86.2	71.0	25.6	1.4	1.8
	CrAlPO-5	333	3	3 : 1	DCM	11.9	35.4	88.0	11.7	—	—
	TS-1	343	1	3 : 1	DCM	4.1	12.5	96.0	4.0	—	—
			3	3 : 1	DCM	8.2	24.7	92.0	8.1	—	—
								cyclohexanol	cyclohexanone	ε-caprolactone	others
	MnAlPO-5	333	3	1 : 1	DCM	76.4	76.4	23.5	76.2	—	—
	TS-1	333	3	1 : 1	DCM	65.0	65.0	34.8	64.8	—	—
	MnAlPO-5	333	3	1 : 3	CH_3CN	86.3	86.3	13.5	44.1	30.0	12.0
	CrAlPO-5	333	3	1 : 3	CH_3CN	71.2	71.2	28.5	32.0	36.5	2.3
	TS-1	333	3	1 : 3	CH_3CN	67.3	67.3	32.5	67.2	—	—
								p-cresol	4-hydroxy-benzaldehyde	4-hydroxy-benzoic acid	4-methyl catechol
	MnAlPO-5	353	3	3 : 1	acetone	9.2	27.4	90.5	2.6	6.7	—
	TS-1	353	3	3 : 1	acetone	5.6	16.9	94.5	—	5.6	—
								2-methoxy-4-methyl-phenol	vanillin	vanillic acid	others
	MnAlPO-5	373	3	1 : 1	CH_3OH	5.3	5.3	94.5	4.5	0.8	0.5
	TS-1	373	3	1 : 1	CH_3OH	No reaction					
								1,2,3,6-tetra-hydrobenzyl alcohol	aldehyde	acid	epoxide/ others
	MnAlPO-5	333	1	3 : 1	DCM	7.2	21.5	92.5	6.0	1.3	—
	MnAlPO-5	363	1	1 : 1	DCM	36.9	36.9	63.0	2.5	34.4	—
	TS-1	333	3	3 : 1	DCM	No reaction					
	Pd/C	333	1	3 : 1	DCM	10.5	32.5	90.0	8.3	2.1	—
	Pd/C	333	1	3 : 1	CH_3CN	18.0	54.8	82.2	2.2	—	16.0

[a] Catalyst ≡ 0.25 g; solid APB ≡ 3.49 g (10.54 mmol). [b] See ESI† for further experimental and analytical details.

selectivites towards the desired product (*i.e.* to the corresponding aldehyde or ketone) compared to polar (aprotic) solvents (such as tetrahydrofuran, acetonitrile or acetone). The choice of solvent and substrate:oxidant mole ratio play a significant influence in the oxidation of cyclohexanol to either cyclohexanone or ε-caprolactone. It also noteworthy (Table 1) that the combination of APB and a strategically designed single-site redox nanoporous catalyst is effective in catalyzing reactions of major significance in the fine-chemical industry. For example, vanillin is used extensively in the food industry as a flavouring and antibacterial agent, and is an important constituent in non-food items such as air fresheners and body lotions. Benzaldehyde, on the other hand, finds extensive use in synthesizing other organic intermediates, ranging from pharmaceuticals (*e.g.* mandelic acid), plastic additives, photographic chemicals and certain aniline dyes. The single-site microporous aluminophosphate catalyst (Mn^{III}AlPO-5), in combination with APB, is much superior in performance and affords higher selectivities to the desired aldehydes compared to TS-1. Further, in the oxidation of 1,2,3,6-tetrahydrobenzyl alcohol (1,2,3,6-tetrahydrobenzaldehyde is an important intermediate for producing epoxy monomers that have applications in high-speed photocurable coatings, adhesives and printing ink applications), the combination of APB and Mn^{III}AlPO-5 produces yields that are much higher than TS-1 (which is inactive for this reaction), and selectivities that are comparable to conventionally-used Pd/C catalysts.

We have also compared Mn^{III}AlPO-5 with TS-1 in the epoxidation of both cyclohexene and 1-methyl-cyclohexene and in the selective oxidation of *p*-cymene (Table 2). In general, epoxidation reactions with a number of catalysts (including the Shell (Ti^{IV}–SiO_2 catalyst) is markedly sensitive to deactivation by

Table 2 Comparative performance of Mn^{III}AlPO-5 and TS-1 in the oxidation of olefins and *p*-cymene using APB[a]

Substrate	Catalyst	*T*/K	*t*/h	Sub : oxidant (mol ratio)	Solvent	Conv.[b] actual mol%	Oxidant[b] efficiency mol%	Product distribution (mol%) (actual)			
								cyclohexene	epoxide	diols	others
	MnAlPO-5	333	3	3 : 1	DCM	32.3	96.9	67.5	31.9	0.5	—
	MnAlPO-5	333	3	3 : 1	CH_3CN	31.8	95.3	68.0	30.8	1.1	—
	MnAlPO-5	333	3	3 : 1	—	15.1	45.3	85.0	6.7	3.4	5.0
	TS-1	333	3	3 : 1	CH_3CN	22.0	67.3	77.9	16.7	2.9	2.5
	TS-1	333	3	3 : 1	DCM	15.3	45.9	84.5	12.2	3.0	—
								1-methyl-1-cyclohexene	epoxide	others	
	MnAlPO-5	333	3	3 : 1	DCM	32.6	97.8	67.3	31.0	1.5	
	MnAlPO-5	333	3	3 : 1	CH_3CN	31.5	94.4	68.3	29.0	2.5	
	MnAlPO-5	333	3	3 : 1	—	23.7	71.2	76.5	5.4	18.3	
	TS-1	333	3	3 : 1	CH_3CN	28.0	85.3	71.5	5.2	23.1	
	TS-1	333	3	3 : 1	DCM	12.0	36.1	87.8	7.5	4.4	
								p-cymene	cuminaldehyde	4-isopropyl-benzoic acid	others
	MnAlPO-5	373	3	3 : 1	acetone	6.9	19.8	93.0	5.0	0.5	1.3
	MnAlPO-5	373	1	1 : 1	acetone	9.2	9.2	90.6	9.0	0.3	—
	TS-1	373	1	1 : 1	acetone	No reaction					
	TS-1	373	1	3 : 1	acetone	No reaction					

[a] Catalyst ≡ 0.25 g; solid APB ≡ 3.49 g (10.54 mmol). [b] See ESI† for further experimental and analytical details.

strongly coordinating ligands, especially water. The rationale behind choosing TS-1 for comparison (in the epoxidation reactions) was that, TS-1, due to its hydrophobicity, would be less susceptible for deactivation in the presence of water, and has been proven to be a good epoxidation catalyst using aqueous peroxides (H_2O_2). Although TS-1 does exhibit some activity for the epoxidation reaction, it is distinctly inferior in terms of overall selectivity for the desired epoxide product compared to Mn^{III}AlPO-5 as a single-site catalyst. More significantly, it did not exhibity any appreciable activity for the oxidation of *p*-cymene under comparable conditions (Table 2). The choice of solvent in the epoxidation reactions, again has a moderate influence, but reactions carried out in the absence of an organic solvent were inferior both in terms of activity and selectivity. Further, experiments analogous those reported earlier,[12,17] were carried out to rule out the possibility of leaching.†

Many other organic compounds that yield products such as vitamins, fragrances, flavours and general pharmaceutical and agrochemical intermediates have been selectively oxidized using APB and an appropriate single-site solid catalyst.[18,19] From Tables 1 and 2, it is clear that acetylperoxyborate (APB) in combination with a single-site microporous AlPO-based catalyst is dintinctly superior (1-octanol being the only exception), both in terms of activity and selectivity, to the widely-used microporous single-site titanosilicate (TS-1), for the oxidation of alcohols and for the epoxidation of olefins. The high activities, selectivities and the relatively mild conditions employed with the former of these catalysts, coupled with ease of transport, storage and stability of the solid oxidant, augurs well for the future use of APB in conjunction with other single-site catalysts for fine-chemical, pharmaceutical and agrochemical applications.[18,20]

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