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Recent advances in green catalytic oxidations of alcohols in aqueous media

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ABSTRACT

Catalytic oxidations of alcohols, with dioxygen or hydrogen peroxide as the primary oxidant, in aqueous reaction media are reviewed. Selective alcohol oxidations with hydrogen peroxide generally involve early transition elements, mostly tungsten, molybdenum and vanadium, in high oxidation states and peroxometal complexes as the active oxidants. Aerobic oxidations, in contrast, involve oxidative dehydrogenation, usually catalyzed by late transition elements, *e.g.* water soluble palladium(II)-diamine complexes, or supported nanoparticles of Pd or Au as hybrid species at the interface of homogeneous and heterogeneous catalysis. Alternatively, water soluble organocatalysts, exemplified by stable N-oxy radicals such as TEMPO and derivatives thereof, in conjunction with copper catalysts, are efficient catalysts for the aerobic oxidation of alcohols. Metal-free variants of these systems, *e.g.* employing nitrite or nitric acid as a cocatalyst, are also effective catalysts for aerobic alcohol oxidations. Finally, enzymatic aerobic oxidations of alcohols employing oxidases as catalysts are described. In particular, the laccase/TEMPO system is receiving much attention because of possible applications in the selective oxidations of diols and carbohydrates derived from renewable resources.

1. Introduction

Selective oxidations of primary and secondary alcohols to the corresponding aldehydes (or carboxylic acids) and ketones, respectively, are pivotal reactions in organic synthesis. Traditional methods involve stoichiometric inorganic or organic oxidants such as hexavalent chromium, manganese dioxide or the Swern or Dess-Martin reagents, respectively [1]. Although such methods have broad scope they are very atom inefficient, involve the use of toxic and/or hazardous reagents and generate copious amounts of inorganic or organic waste. Consequently, there is an on-going quest for sustainable catalytic technologies, with broad substrate scope, using oxygen or hydrogen peroxide as the primary oxidants [2,3]. However, hypochlorite is widely favored as an oxidant in the pharmaceutical and fine chemical industries, rather than oxygen or hydrogen peroxide, because of the potential explosion hazards associated with the use of the latter oxidants. We note, however, that the use of water as an inert, non-inflammable solvent alleviates this problem. Nonetheless, hypochlorite is inexpensive and the relatively low tonnages involved in pharma and fine chemicals mean that the generation of one or more equivalents of sodium chloride waste is not really an issue.

Similarly, the use of environmentally unfriendly organic solvents as reaction media should, where possible, be avoided. In this context, water has several advantages: it is abundantly available, inexpensive, odorless, non-toxic and non-inflammable. Indeed, a variety of commercially important catalytic processes, such as hydrogenation, carbonylation, hydroformylation, olefin metathesis, polymerization and telomerization, is already performed in an aqueous medium at industrial scale [4]. These processes generally involve catalysis by low-valent transition metal complexes of phosphine ligands, and organometallic compounds as key intermediates. Replacement of the hydrophobic phosphine ligands used in organic media with highly water soluble hydrophilic equivalents, *e.g.* sulfonated triarylphosphines, allows such reactions to be conducted in aqueous/organic biphasic media. In contrast, catalytic oxidations generally involve transition metals in high oxidation states, coordinated to relatively simple hard nitrogen and/or oxygen-containing ligands, and coordination complexes as reactive intermediates. For example, in heme-dependent oxygenase and peroxidase enzymes active high-valent oxoiron intermediates are stabilized by coordination to a macrocyclic porphyrin ligand

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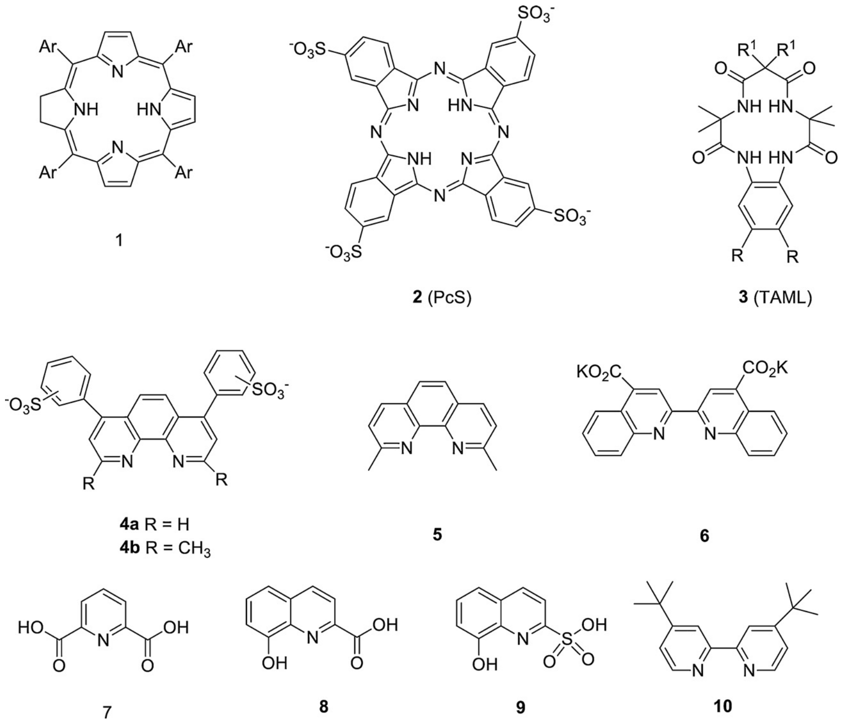

Fig. 1. Examples of water soluble ligands in catalytic oxidations.

in the active site of the enzyme. Strong coordination of water to the hard metal center can suppress coordination of hydrophobic substrates, resulting in catalyst inhibition or deactivation by hydrolysis. Another distinguishing feature of catalytic oxidations ensues from the susceptibility of most organic ligands to degradation under oxidizing conditions. For this reason, readily oxidizable phosphines are not suitable ligands for oxidation catalysts.

The aerobic oxidation of water soluble alcohols, diols and carbohydrates, over heterogeneous noble metal catalysts (Pt, Pd, Ru) in aqueous media has been extensively studied and dates back to the introduction of the term catalysis by Berzelius in the early 19th century [5,6]. The current drive toward the replacement of petroleum hydrocarbon feedstocks, derived from fossil resources, by carbohydrates derived from renewable raw materials [7] is stimulating a renaissance in catalytic oxidations of carbohydrate feedstocks and water is definitely the solvent of choice for these reactions. In the oxidation of alcohol substrates which are sparingly soluble in water two strategies have been employed for catalyzing oxidation in an aqueous/organic biphasic system. In the first category the substrate is dissolved in, or forms itself, an organic phase while the oxidant, and possibly also the catalyst, resides in the aqueous phase. A phase transfer agent is employed to transfer the catalyst and/or oxidant to the organic phase where the reaction takes place. Many catalytic oxidations with water soluble oxidants, such as hydrogen peroxide, hypochlorite and persulfate, fall into this category. In the second category the substrate is contained in a separate organic phase and the catalyst and oxidant are dissolved in the water phase where the reaction takes place. The product is separated as the organic phase and the catalyst, contained in the aqueous phase, is easily recovered and recycled.

In this review we shall focus on the use of four types of catalyst: (a) water soluble metal salts and complexes, (b) metal nanoparticles as hybrid species at the interface of homogeneous and heterogeneous catalysis [8], (c) water soluble organocatalysts such as stable N-oxy radicals [9], and (d) enzymes [3g] in the oxidation of simple alcohols and, to a lesser extent, diols and carbohydrates.

2. Water soluble ligands

A selection of water soluble ligands that have been used in catalytic oxidations with oxygen or hydrogen peroxide is shown in Fig. 1. Early work generally involved biomimetic oxidations employing water soluble derivatives of porphyrins **1** and the structurally related phthalocyanines **2** [10]. A major issue associated with the use of porphyrins and, to a lesser extent, phthalocyanines is, in addition to their cost, their susceptibility toward oxidative degradation. *In vivo* the ligand can be replenished by intracellular synthesis by the host microorganism but this is not an option *in vitro*. Consequently, there is a definite need for oxidatively stable macrocyclic ligands. This led Collins and coworkers [11,12] to develop a series of iron(III) complexes of oxidatively and hydrolytically stable tetraamido macrocyclic ligands (TAMLs) of general structure **3**, which are efficient activators of aqueous hydrogen peroxide, over a broad pH range. They have a variety of potential uses, *e.g.* to replace chlorine bleaching in the pulp and paper industry and in waste water treatment but applications in organic synthesis have, to our knowledge, not been reported. In the last decade a variety of water soluble metal complexes of chelating diamine and pyridine carboxylate-type ligands (see Fig. 1 for examples) have become popular as catalysts for catalytic oxidations in aqueous media.

3. Tungsten and vanadium catalysts

DiFuria and Modena and coworkers [13] were the first to report the tungstate catalyzed oxidation of alcohols with aqueous hydrogen peroxide, in a biphasic system composed of water and 1,2-dichloroethane using a tetraalkylammonium salt as a phase transfer agent. Noyori and coworkers [14,15] optimized this methodology to afford an extremely effective, chloride- and organic solvent-free system using 1.1 equiv. of 30% H_2O_2 at 90 °C and the lipophilic methyltrioctylammonium bisulfate, $[CH_3(n\text{-}C_8H_{17})_3N]^+HSO_4^-$, as a phase transfer agent (Fig. 2). Substrate catalyst ratios as high as 400.000 were used, affording turnover