Available online at www.sciencedirect.com

ScienceDirect

Coordination Chemistry Reviews 251 (2007) 2367–2385

COORDINATION CHEMISTRY REVIEWS

www.elsevier.com/locate/ccr

Review

Transition metal complexes as electrocatalysts—Development and applications in electro-oxidation reactions

Kwong-Chak Cheung, Wing-Leung Wong, Dik-Lung Ma, Tat-Shing Lai, Kwok-Yin Wong*

Department of Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

Received 1 October 2006; accepted 2 April 2007
Available online 5 April 2007

Contents

Abstract

In this review, the utilization of coordination compounds as electrocatalysts in a number of electro-oxidation reactions including oxidation of olefins, alcohols, water, glucose, nitric oxide and other small molecules is discussed. The coordination compounds function either as redox mediators and/or oxidative catalysts in the electrocatalytic reactions. Applications of the electrocatalysts in electro-synthesis, biosensing and biofuel cells are discussed with reference to the role played by the coordination compounds in these processes or technologies.

Keywords: Electro-oxidation; Electrocatalysts; Transition metal complexes

1. Introduction

Many redox reactions are catalyzed by transition metal complexes. When these redox reactions are coupled with an elec-

---

* Corresponding author.
E-mail address: bckywong@polyu.edu.hk (K.-Y. Wong).

0010-8545/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ccr.2007.04.004

trochemical cell, the electrode can act as an oxidant or reductant to generate an active species from the transition metal complex, which then catalyzes the oxidation or reduction of specific substrate. The electrode potential at which the redox reaction occurs can be tuned by changing the transition metal or the spectator ligands, thus the oxidation or reduction of substrates can be carried out at modest potential with high efficiency. Moreover, the selectivity of the reaction can also be modified by changing the spectator ligands and it is feasible to provide active centers with high selectivity for the redox reaction. The use of transition metal complexes as catalysts in electrochemical reactions is a promising approach in the development of electro-synthesis and electrochemical sensors. In this context, the electrochemical approach would be appealing for the following reasons: (i) chemical oxidants or reductants used in synthesis or analysis are replaced by the electrode to give a clean reaction mixture and (ii) the reaction rate and selectivity can be manipulated by varying the electrode potential and/or the choice of electrocatalyst.

Over the past several decades, electrochemical reactions catalyzed by transition metal complexes have received considerable attention. In the literature, there has been an explosion of research activity in these fields. However, most previous reviews gave a general account on electrocatalytic reactions with focus on reduction of organics and small molecules such as carbon dioxide, nitrogen and protons [1,2]. There is no review that focuses on oxidation reactions only.

This review aims to give an overview of electrocatalysis by transition metal complexes in oxidation reactions, including the electrocatalytic oxidation of olefins, alcohols, water, glucose, nitric oxide and some small molecules. The role played by the transition metal complexes and the active species involved in the electrocatalytic reactions will be highlighted in the discussions.

1.1. General principle of electrocatalysis

Similar to chemical reactions, many electrode reactions occur only at high overpotentials because of unfavorable kinetics. For such electrochemical reactions to be useful, it is necessary to find an electrocatalyst that will lower the overpotential and speed up the rate of reaction. The objective of electrocatalysis is therefore to seek alternative, lower energy activation pathways which allow such electrode reactions to occur at high current density and at low overpotential. Electrocatalysis is important to many applications in electrochemistry since the energy efficiency of any electrochemical cell is determined in part, by the potential of the anode and cathode. There are two basic different types of electrocatalysis: heterogeneous and homogeneous. These two types of electrocatalysis are shown in Figs. 1 and 2, respectively.

1.1.1. Heterogeneous electrocatalysts

The heterogeneous electrocatalytic process involves the immobilization of the transition metal complexes on the electrode surface [3]. The process involves three steps:

1. Transfer of substrate from bulk solution to the electrode surface or within the double layer.
2. Exchange of electrons between the electrode and the substrate.
3. Removal of the products from the electrode, which may involve desorption.

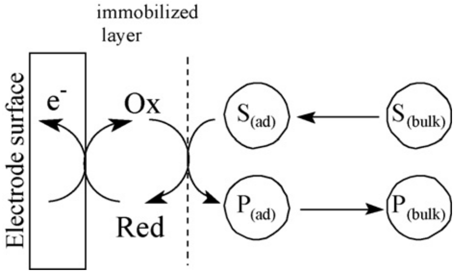


Fig. 1. Schematic diagram of heterogeneous electrocatalysis.

As shown in Fig. 1, the catalyst is coated or adsorbed on the electrode surface as an “electron shuttle” to transport electrons from/to the substrate. The product then desorbs or diffuses away from the electrode surface into the bulk solution.

1.1.2. Homogeneous electrocatalysts

In homogeneous electrocatalysis the substrate does not exchange electrons with the electrode directly, but with some intermediates or mediators [3]. Electron transfers and chemical reactions can then take place in the bulk solution. The principle difference between the heterogeneous and homogeneous case is that in the former the redox couple is physically attached to the electrode surface whereas in the latter case it is free to diffuse through the solution. In Fig. 2A the mediator and reactant are both present in the same solution. In the second example (Fig. 2B) the substrate is present in a secondary phase, and it is necessary to introduce a transfer reagent into the system to shuttle between two phases. Savéant and co-workers further differentiate homogenous electrocatalysis into redox catalysis and chemical catalysis [4]. In the former the catalyst couple merely plays the role of an electron carrier (mediator) whereas the transitory formation of catalyst-substrate adduct occurs in the latter.

2. Electrocatalytic oxidation of olefins

The electrocatalysts for olefin oxidation are dominated by metal-oxo catalysts. Metal-oxo complexes are strong oxidizing agents that have been extensively investigated over the past 20 years [5–8]. The metal-oxo species can be electrogenerated *in situ* from the metal-aquo complexes. After the reaction with olefins, the metal-oxo complexes are reduced to the metal-aquo complexes, which are then regenerated at the electrode surface [9,10]. In the following sections, the electro-oxidation of olefins with transition metal-oxo complexes of ruthenium, iron, manganese, chromium and osmium are discussed.

2.1. Ruthenium-oxo complexes

Electrocatalytic oxidation of olefins with ruthenium-oxo complexes as catalysts is rare. The first example was reported

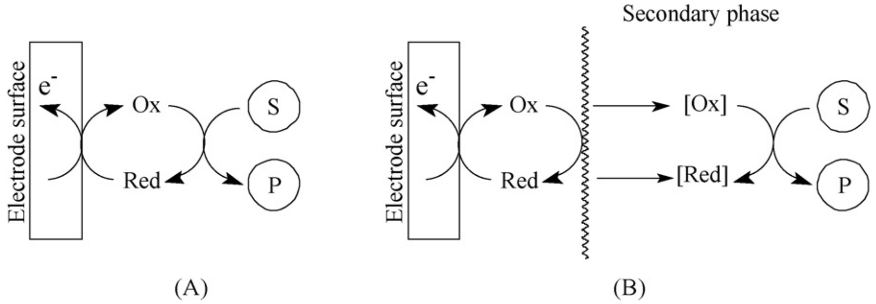
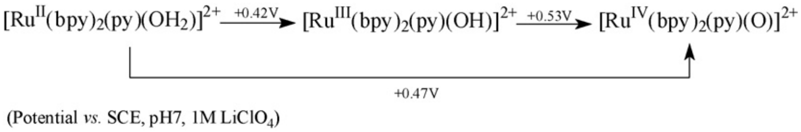
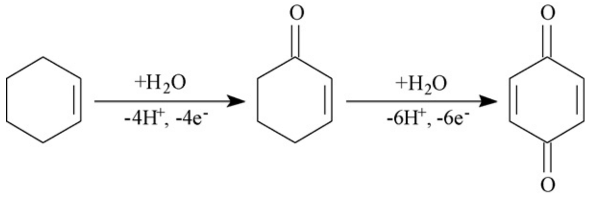


Fig. 2. (A and B) Schematic diagrams of homogeneous electrocatalysis.



$$[Ru^{II}(bpy)_2(py)(OH_2)]^{2+} \xrightarrow{+0.42V} [Ru^{III}(bpy)_2(py)(OH)]^{2+} \xrightarrow{+0.53V} [Ru^{IV}(bpy)_2(py)(O)]^{2+}$$

Scheme 1.

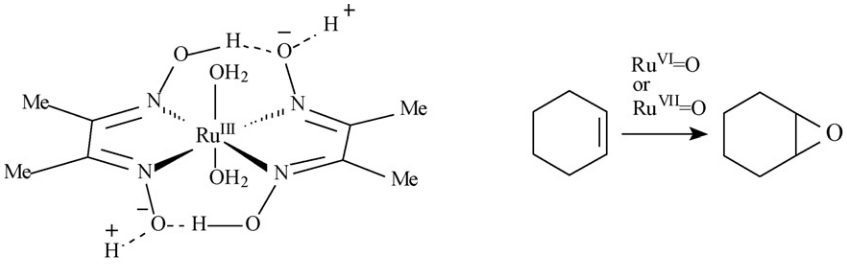


Scheme 2.

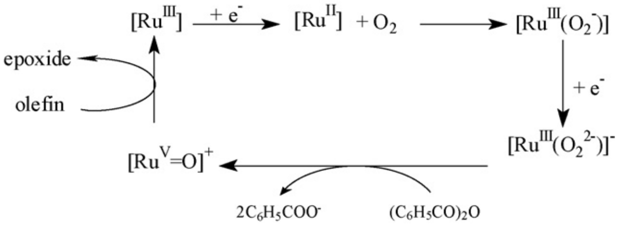
by Meyer and co-workers for the oxidation of various substrates including alkenes [11–13]. The system involves a net $2e^-$ oxidation of the complex *cis*-$[Ru^{II}(bpy)_2(py)(OH_2)]^{2+}$ (bpy = 2,2′-bipyridine, py = pyridine) in aqueous solution resulting in the reversible formation of the mono-oxo Ru^{IV} complex, $[Ru^{IV}(bpy)_2(py)O]^{2+}$, which is a moderately strong oxidant. In the $[Ru^{IV}(bpy)_2(py)O]^{2+}/[Ru^{II}(bpy)_2(py)(OH_2)]^{2+}$ system, the Ru^{IV}=O in a buffered solution is rapidly reduced to $[Ru^{II}(bpy)_2(py)(OH_2)]^{2+}$ when an unsaturated organic compound was added. Both the Ru^{IV}/Ru^{III} and Ru^{III}/Ru^{II} couples are reversible (Scheme 1), thus the oxidation reaction can be made catalytic by using an external source of oxidizing equivalents to regenerate the $[Ru^{IV}(bpy)_2(py)O]^{2+}$ in aqueous solution. In addition, the study also demonstrated that over 75% of the $[Ru^{II}(tpy)(bpy)(OH_2)]^{2+}$ catalyst (tpy = 2,2′:6′2″-terpyridine) can be recovered after more than 100 catalytic cycles in the allylic oxidation of cyclohexene (Scheme 2) [12].

High-valent ruthenium-oxo complexes of dimethylglyoxime (dmg) were used by Taqui Khan et al. [14] in the electrocatalytic oxidation of cyclohexene and cyclooctene to the corresponding epoxides with 38% and 34% yields, respectively. Controlled potential electrolysis was performed at +0.75 V *versus* SCE in a pH 2.5 medium (Scheme 3). The active ruthenium-oxo catalysts, $[Ru^{VI}(H\text{-}dmg)_2(H_2O)(O)]^{2+}$ and $[Ru^{VII}(H\text{-}dmg)_2(O)_2]^+$, were generated *in situ* at the electrode surface by electrochemical oxidation of the precursor $[Ru^{III}(H\text{-}dmg)_2(H_2O)_2]^+$ under acidic solution conditions. The Ru(III)-complex exhibits three redox couples with $E_{1/2}$ values of +0.183, +0.357 and +0.522 V *versus* Ag/AgCl at pH 1.1 that correspond to the redox couples of $Ru^{IV/III}$, $Ru^{VI/IV}$ and $Ru^{VII/VI}$, respectively.

In addition, Taqui Khan et al. also investigated the ruthenium(III)-Schiff-base complex $[Ru^{III}$(Naphdien)Cl] (Naphdien = bis(2-hydroxynaphthaldehyde)) as the electrocatalyst to activate dioxygen for the epoxidation of olefins in the presence of benzoic anhydride in DMF [15]. The redox chemistry of the ruthenium complex, which catalyzes the electrochemical reduction of dioxygen for metal-oxo formation and substrate oxidation, was studied by cyclic voltammetry. The results were consistent with an initial one-electron reduction of Ru^{III} to Ru^{II}, which then reacts with O_2 to form an $[Ru^{III}–O_2{}^-]$ adduct. Further one-electron reduction of the dioxygen adduct produces a Ru^{III}-peroxo complex $[Ru^{III}–O_2{}^{2-}]^-$ as shown in Scheme 4. The Ru^V-oxo complex is readily formed by the



Scheme 3.



Scheme 4.

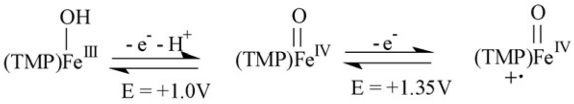
heterolytic cleavage of the O–O bond with benzoic anhydride [15,16]. In a controlled potential electrolysis (−0.25 V *versus* SCE) using cyclohexene and *cis*-cyclooctene as substrates, epoxides were produced selectively as the product and no allylic oxidation product was obtained.

Recently, Cheng et al. reported the electrocatalytic oxidation of styrene by a high-valent ruthenium(VI)-dioxo porphyrin complex [17]. The Ru^{II}(CO)(TMP) complex (TMP = *meso*-tetramesitylporphyrin) was chemically oxidized with *m*-chloroperbenzoic acid to give the corresponding $Ru^{VI}(O)_2$(TMP) dioxo-complex, which can be further oxidized to the porphyrin cation radical, $Ru^{VI}(O)_2(TMP)^{\bullet+}$ at +1.32 V. These electrogenerated ruthenium-dioxo porphyrin radicals were found to be the reactive species that oxidized styrene to phenylacetaldehyde with 96% yield (Scheme 5). The sterically hindered dioxoruthenium(VI) *meso*-tetramesitylporphyrin complex prevented dimer formation in the oxidation reaction. Consequently the reactive intermediate, $Ru^{VI}(O)_2(TMP)^{\bullet+}$, can be generated electrochemically. The oxidation products (benzaldehyde and phenylacetaldehyde, without epoxides) are thus quite different from those obtained by conventional oxidants in the presence of ruthenium porphyrins.

2.2. *Iron-oxo complexes*

Generation of iron-oxo species from iron porphyrin is an interesting topic because of its relevance to the cytochrome P-450 chemistry [18,19]. Iron porphyrins are known to be oxidized with peroxidic oxidants to give active iron-oxo species, which has been taken as a model for cytochrome P-450 type oxygen transfer reactions in biological systems [20–23].

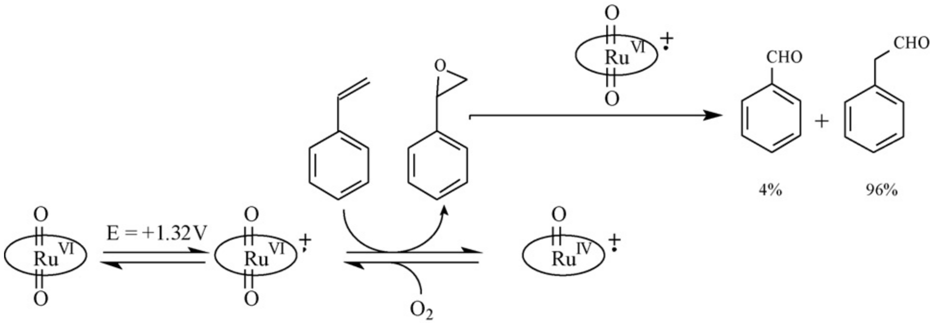
Iron(III) porphyrins have been investigated as electrocatalysts for epoxidation of olefins by Groves and co-worker in the 1980s [18]. The cyclic voltammogram of (TMP)Fe^{III}(OH) in dichloromethane with 0.1 M tetrabutylammonium perchlorate shows two couples. The first reversible couple at +1.0 V *versus* Hg/HgO corresponds to the Fe^{IV}/Fe^{III} couple, and the second couple at +1.35 V represents the porphyrin ring oxidation (Scheme 6). The (TMP)Fe^{III}(OH) complex was found to catalyze the epoxidation of olefins electrochemically. Constant-potential electrolysis of a solution containing styrene, *cis*- or *trans*-β-methylstyrene, cyclohexene, cyclooctene, or norbornene can produce an average of 15 equiv. of the corresponding epoxides over a period of 4 h.



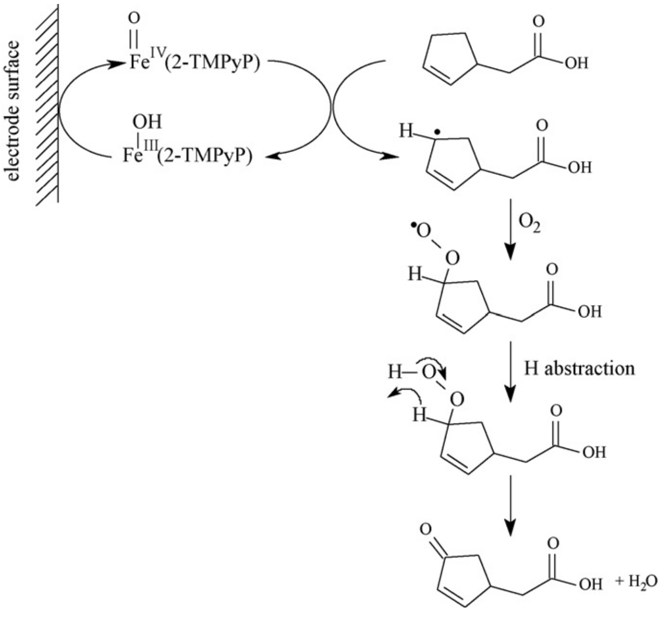
Scheme 6.

High-valent fluoroiron porphyrin intermediates, which were generated by one-electron oxidation of a difluoroiron(III) tetraphenylporphyrin at +0.68 V *versus* SCE, were explored as catalysts for electro-oxidation of hydrocarbons including olefins and tertiary alkanes [24]. The cyclic voltammogram of the Fe^{III} porphyrin in dichloromethane is quasi-reversible as a consequence of the EC mechanism. Bulk electrolysis of olefins such as cyclohexene and *cis*-stilbene with electrogenerated reactive intermediates such as (TPP)$Fe^{IV}F_2$ and (TPP)(F)Fe^{IV}=O (TPP = *meso*-tetraphenylporphyrin) gave an overall yield of epoxides greater than 90%.

Electrocatalytic oxygenation of alkenes in aqueous media at room temperature with a high-valent water-soluble iron porphyrin catalyst was reported by Su and co-worker [25,26]. The high valent iron-oxo porphyrins, [O=Fe^{IV}(2-TMPyP)] and [O=Fe^{IV}(2-TMPyP)(OH)] (2-TMPyP = tetrakis(*N*-methyl-2-pyridyl)porphyrin), were generated electrochemically by one-electron oxidation of (2-TMPyP)Fe^{III}(OH) complex in pH 9 and 14 buffer solution, respectively. Moreover, the reactive iron(IV)-oxo species, O=Fe^{IV}(2-TMPyP), generated *in situ* at +0.7 V *versus* Ag/AgCl, is able to oxidize 2-cyclopentene-1-acetic acid to cyclopent-2-ene-4-one-1-acetic acid in the presence of dioxygen (Scheme 7) via an allylic hydrogen abstraction mechanism [25]. When (TSMP)$Fe^{III}(H_2O)$ (TSMP = *meso*-tetrakis(3-sulfonatomesityl)porphyrin) was used as the catalyst for the electro-oxidation reaction in a pH 5.0 buffer solution, a turnover number of 93 with 68% current efficiency was achieved [26].



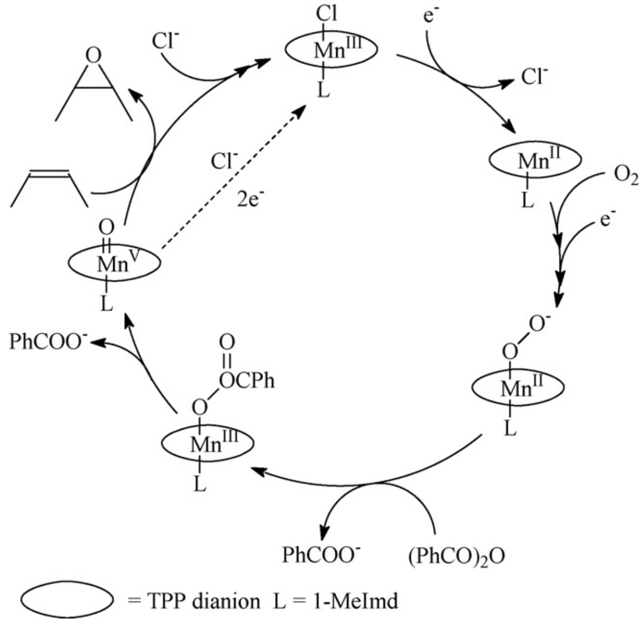
Scheme 5.



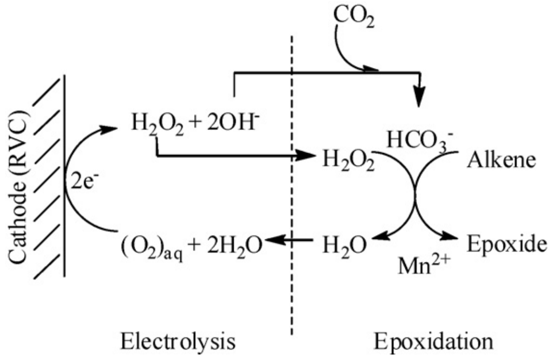
Scheme 7.

2.3. Manganese-oxo complexes

The use of manganese porphyrin as electrocatalyst for the epoxidation of olefins was first reported by Murray and co-workers [27,28]. The electrocatalytic cycle is shown in Scheme 8. The catalytic cycle is initiated by one-electron electrochemical reduction of $Mn^{III}(TPP)Cl$ to $Mn^{II}(TPP)$ with the loss of chloride ligand, which is followed by dioxygen binding that promotes a second one-electron reduction to generate a Mn^{II}-superoxo complex. This $[Mn^{II}(TPP)O_2{}^{-}]$ complex further reacts with benzoic anhydride to give a metallo-acylperoxy complex that undergoes O–O bond heterolysis to yield a high-valent manganese-oxo porphyrin $(TPP)Mn^{V}{=}O$. This complex is able to transfer one oxygen atom to olefins to give epoxides [28]. In addition, the high-valent Mn^{V}-oxo porphyrin can be prepared directly by chemical oxidation of $Mn^{III}(TPP)Cl$ complex with hydrogen peroxide (H_2O_2) as the oxidant, which is generated by electrochemical reduction of dioxygen in aqueous solutions [29]. The $Mn^{III}(TPP)Cl$ system has also been modified by Devynck and co-workers by deposition onto carbon electrodes for electro-activation of dioxygen and electrocatalytic oxidation of alkenes [30,31]. A catalytic efficiency up to 500 turnovers of catalyst per hour and a Faradaic yield up to 98% were achieved.



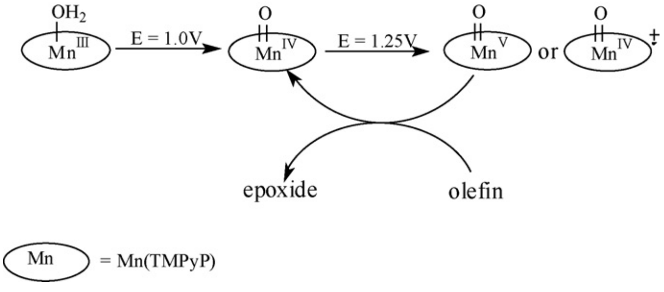
Scheme 8.



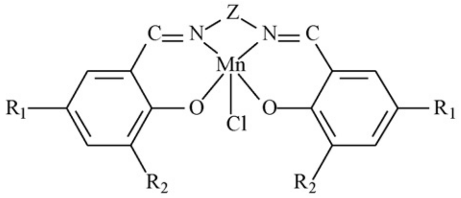
Scheme 9.

Recently, a novel approach for green-production of epoxides was reported by Wong and co-workers [32,33]. The epoxidation reaction combines the *in situ* electrogeneration of H_2O_2 with an alkaline- or metal-catalyzed epoxidation system using ionic liquid as the reaction medium (Scheme 9). A number of lipophilic alkenes were epoxidized selectively within 4–5 h with isolated yield up to 90% [32].

The water-soluble manganese porphyrin $Mn^{III}(TMPyP)$ has also been investigated by Su and co-workers for the electrocatalytic oxidation of alkenes in aqueous media [34–36]. Electro-oxidation of $Mn^{III}(TMPyP)$ complex at +1.0 V *versus* Ag/AgCl leads to the formation of the manganese(IV)-oxo porphyrin $(TMPyP)Mn^{IV}{=}O$ in aqueous medium. Further one-electron oxidation at +1.25 V would generate an unstable Mn-oxo species postulated to be $(TMPyP)Mn^{V}{=}O$ or $[(TMPyP)Mn^{IV}{=}O]^{\bullet+}$. In the electrocatalytic epoxidation of water-soluble alkene (Scheme 10), the catalytic efficiency was found to decrease rapidly after the first cycle. The deactivation of the catalytic process was attributed to the deposition of



Scheme 10.



Z = bridging ligand such as cyclohexyl or phenyl

R_1, R_2= H, Cl, OCH_3, NO_2

Fig. 3. Structure of the substituted manganese Schiff-base complexes [38].

the reaction product at the electrode surface, which blocks the heterogeneous electron transfer.

Apart from manganese porphyrins, manganese Schiff-base complexes were also utilized as electrocatalysts for alkene epoxidation. In 1990, Murray and co-workers reported the use of $[Mn^{III}(salen)]$ complex in electrochemical epoxidation of olefins in the presence of dioxygen and benzoic anhydride in acetonitrile solution [37]. The mechanism of the epoxidation reaction for the $[Mn^{III}(salen)]$ system, which involves the formation of Mn^V-oxo species from the $Mn^{III}(salen)$ complex followed by oxygen atom transfer to olefins, is analogous to that of manganese porphyrins. The yield of epoxides produced by the $[Mn^{III}(salen)]$ system is up to 48% (current yields), and the best turnover per molecule of catalyst is only up to 2.4 because of the short lifetime of the Schiff-base catalysts.

A similar $[Mn^{III}(salen)]$ system, in which the Schiff-base ligands in the complexes bear different substituents on the aromatic ring and contain different units bridging the two enamine nitrogen atoms as shown in Fig. 3, has also been reported by Moutet and Ourari for electrocatalytic epoxidation of olefins with dioxygen [38]. These modified $Mn^{III}(salen)$ complexes gave better turnovers (up to 6.6) and current efficiencies (up to 50%) in the electrocatalytic epoxidation of cyclooctene than that based on the unsubstituted $Mn^{III}(salen)$ complex. The best results were obtained with 2-methyl-imidazole as the co-catalyst and benzoic acid as the activator.

The use of chiral manganese Schiff-base complexes for enantioselective electrocatalytic epoxidation of olefins was reported by Wong and co-worker [39]. The chiral $Mn^{III}(salen)$ catalyst was also immobilized onto the electrode surface by electropolymerization. In this study, both homogeneous and electropolymerized chiral $Mn^{III}(salen)$ complexes were investigated as electrocatalysts for epoxidation of styrene and *trans*/*cis*-stilbene with dioxygen. The immobilized $Mn^{III}(salen)$ catalyst showed a turnover number up to 1250 and an enantiomeric excess up to 77% in the electrocatalytic epoxidation reaction. A similar electrocatalytic system for asymmetric epoxidation was reported by Tanaka et al. in a CH_2Cl_2/aqueous NaCl biphasic media [40].

2.4. *Chromium-oxo complexes*

Chromium porphyrins have also been explored as electrocatalysts for oxidation of organic substrates but the number of reports are far less than those with manganese and iron porphyrins. The reason could be due to the slow kinetics in the electrogeneration of chromium-oxo species [41]. Moreover, chromium-oxo porphyrins are less active to alkenes than their manganese analogues. The (*meso*-tetraphenylporphyrin) chromium(V)-oxo species was first reported by Murray and Creager for electrochemical epoxidation of olefins [42]. The reactive $[O{=}Cr^V(TPP)]^+$ Cr-oxo species can be generated by one-electron oxidation of $[O{=}Cr^{IV}(TPP)]$ complex, which is prepared by the reaction of [Cr(TPP)Cl] and iodosobenzene. In addition, the chromium(V)-oxo species can quantitatively transfer an oxygen atom to the olefinic substrate to produce epoxide and itself regenerated to the $[Cr^{III}(TPP)]^+$ state (Scheme 11). In a controlled-potential electrolysis of $[O{=}Cr^{IV}(TPP)]$ with excess norbornene at +0.88 V *versus* SSCE for 10 min, 98% yield of epoxides was obtained. Another analogous system with the $(Br_8TPP)Cr^{IV}{=}O$ complex as the electrocatalyst for electrochemical oxidation of alkenes was also investigated in dichloromethane solution [43].

$$[(Cr^{IV}TPP)O] \longrightarrow [(Cr^{V}TPP)O]^+ + e^-$$

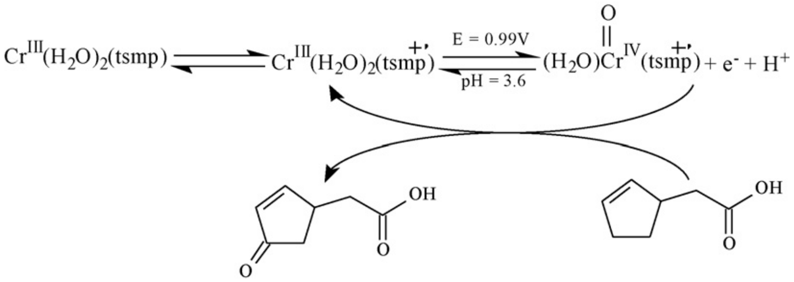
$$[(Cr^{V}TPP)O]^+ + \text{olefin} \longrightarrow [(Cr^{III}TPP)] + \text{epoxide}$$

Scheme 11.

Electrochemical epoxidation of alkenes in aqueous media with water-soluble chromium porphyrin as the catalyst was reported by Su and co-workers [44–46]. The $(H_2O)_2Cr^{III}(TSMP)$ complex (TSMP = *meso*-tetrakis(3-sulfonatomesityl)porphyrin) is readily oxidized to $(H_2O)_2Cr^{III}(TSMP)^{\bullet+}$ radical at a potential of +0.88 V *versus* Ag/AgCl in a buffered solution. Further reaction by one-electron oxidation of the $(H_2O)_2Cr^{III}(TSMP)^{\bullet+}$ radical at +0.99 V *versus* Ag/AgCl generates the reactive $O{=}Cr^{IV}(H_2O)(TSMP)^{\bullet+}$ species, which reacts with alkene to give enone at room temperature (Scheme 12). Interestingly, the analogous complex $(H_2O)_2Cr^{IV}{=}O(TSMP)$ shows no reactivity towards alkene oxidation under similar experimental conditions [46].

2.5. *Osmium-oxo complexes*

Tremendous success has been obtained with osmium catalysts in the enantioselective dihydroxylation of alkenes since the seminal work done by Criegee in the 1930s on the oxidative conversion of alkenes with osmium tetroxide [47–49]. The asymmetric dihydroxylation of alkenes is a famous piece of work by Sharpless and co-workers [50]. However, only very few reports using osmium-oxo complexes as electrocatalysts in asymmetric oxidation of alkenes can be found in the literature [51,52]. An iodine-assisted electrochemical asymmetric dihydroxylation of olefins in I_2–K_2CO_3–$K_2OsO_2(OH)_4$ or



Scheme 12.

I_2–K_3PO_4/K_2HPO_4–$K_2OsO_2(OH)_4$ solution with Sharpless' ligand was reported by Torii et al. [51]. Interestingly, I_2 as an alternative co-oxidant in the $K_2Os^{VI}O_2(OH)_4$ system was found to enhance the electro-dihydroxylation of styrene significantly in terms of both isolated yields and enantiomeric excess (ee). The cyclic voltammogram of $K_2Os^{VI}O_2(OH)_4$ in water with K_2CO_3 as the supporting electrolyte exhibits two oxidation peaks at $E_{pa} = -0.115$ and +0.225 V *versus* SCE, respectively at a platinum electrode. Addition of one equivalent of I_2 results in a decay of the first oxidation peak while two new oxidation peaks appear at more positive potential at $E_{pa} = +0.295$ V and $E_{pa} = +0.506$ V. These oxidation peaks are characteristic of the oxidation of iodide anions (I^-) because I_2 oxidizes the osmium(VI) complex and itself is reduced in the $K_2Os^{VI}O_2(OH)_4$ solution (Scheme 13). Electrolysis of styrene in a I_2 (0.5 equiv.)—K_3PO_4/K_2HPO_4–$K_2OsO_2(OH)_4$–$(DHQD)_2$PHAL system ($(DHQD)_2$-PHAL = (l,4-bix(9-*O*-dihydroquinidine) phthalazine) afforded the diol in 96.2% yield with 96.5% ee.

3. Electrocatalytic oxidation of alcohols

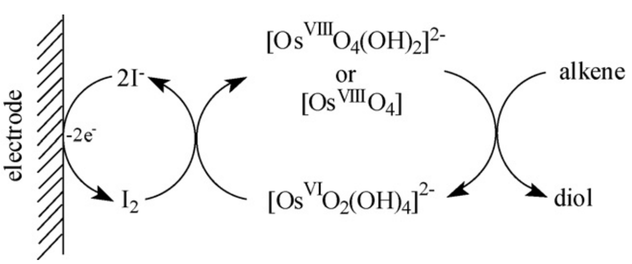
The electrocatalytic oxidation of alcohols such as methanol is an important topic because of its relation to fuel cell and energy research. The selective oxidation of alcohols to aldehydes or acids by electrochemical approach is useful in synthetic chemistry. Ruthenium and nickel complexes are the two main types of electrocatalysts in this category.

3.1. Ruthenium and other metal-oxo complexes

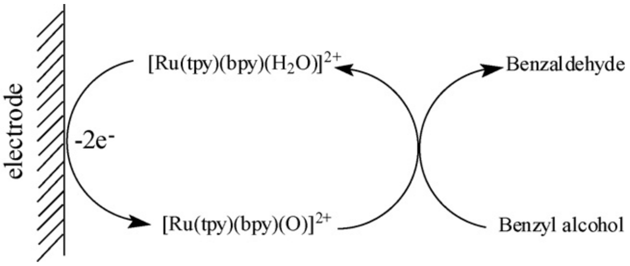
Among different types of metal complexes, polypyridyl ruthenium-oxo complexes are well known oxidants for alcohols oxidation [12]. The high valent Ru^{IV}-oxo species can be generated from the corresponding Ru^{II}-aquo complex via proton-couple electron transfer as shown in Scheme 1. The catalytic oxidation of benzyl alcohol with $[Ru(tpy)(bpy)(OH_2)]^{2+}$ is shown in Scheme 14.

In recent years, a number of new ruthenium-oxo complexes with diimines and modified polypyridyl ligands (Fig. 4) have been synthesized. The ruthenium-aquo species $[Ru(tpy)(\alpha,\alpha'\text{-diimine})(H_2O)]^{2+}$ (α,α'-diimine = $NC_5H_4C(H){=}N(C_6H_4)_nNH_2$, $n = 1$ and 2) reported by Lahiri and co-workers was found to undergo $2e^-/2H^+$ transfer in the oxidation process in both acidic and alkaline medium [53]. The electrogenerated Ru-oxo species catalyzes the oxidation of benzyl alcohol to benzaldehyde.

Modified polypyridyl ligands (Fig. 4) such as 4,4′-Me_2dppi (3,6-di-(4-methylpyrid-2-yl)pyridazine) were developed by Hill and co-workers [54] for studying ruthenium-oxo redox reactions. In the preparation of Ru-complex with 4,4′-Me_2dppi, two geometric isomers, *in*-$[Ru(tpy)(4,4'\text{-}Me_2dppi)(H_2O)]^{2+}$ and *out*-$[Ru(tpy)(4,4'\text{-}Me_2dppi)(H_2O)]^{2+}$ were formed. Both isomers can be oxidized electrochemically to generate $Ru^{IV}{=}O$, but the *out*-isomer is more active in catalyzing the oxidation of benzyl alcohol to benzylaldehyde due to the instability of the *in*-isomer. Some substituted benzyl alcohol derivatives such as 1-phenylethanol, 1-phenyl-1-propanol and 2-methyl-1-phenyl-1-propanol were studied as substrates in the bulk electrolysis. The catalytic rates were found to decrease linearly with the steric bulkiness of the alcohol. A similar polypyridyl ruthenium complex $[Ru(tpy)(Hbpp)(H_2O)]^{2+}$, (Hbpp = (3,5-bis(2-pyridyl)pyrazole)) was also investigated as electrocatalyst for oxidation of alcohol by Llobet and co-workers [55]. In addition, the ruthenium complex $[Ru(bpea)(bpy)(H_2O)]^{2+}$ with tridentate polypyridyl ligand bpea (bpea = (*N*,*N*-bis(2-pyridyl)ethylamine))) was also reported [56]. The Ru-oxo catalyst electrogenerated from the $[Ru(bpea)(bpy)(H_2O)]^{2+}$ complex is able to oxidize alcohol to benzaldehyde with 82%



Scheme 13.



Scheme 14.

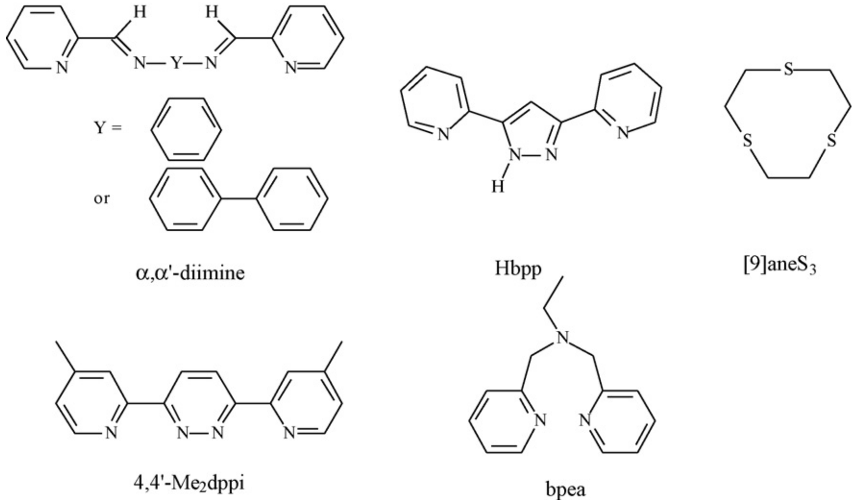


Fig. 4. Structure of various ligands.

current efficiency in 10 h. Apart from ruthenium complex, polypyridyl rhodium complexes $[Rh(tpy)(phen)(H_2O)]^{3+}$ has also reported for the electrocatalytic oxidation of benzyl alcohol [57]. But the rhodium(IV)-oxo system showed very low stability in the electrocatalytic oxidation.

Recently, a new ruthenium complex containing thioether type ligand [9]aneS_3 ([9]aneS_3 = 1,4,7-triihiacyclononane) $[Ru(phen)([9]aneS_3)(H_2O)]^{2+}$, was reported by Llobet and co-workers [58]. Although the complex is capable of catalyzing the oxidation of benzyl alcohol to benzaldehyde electrochemically, the Ru-oxo species is not stable enough and readily decomposed once generated from the corresponding Ru–OH_2 complex.

Generally speaking, ruthenium-oxo complexes are very active electrocatalysts in the oxidation of alcohols. However, the catalysts have a limited lifetime due to decomposition or ligand dissociation of the Ru-complex in the solution [59–61].

Some of the ruthenium complexes were immobilized onto the electrode surface to increase their stability. As pyrroles are known to undergo electropolymerization readily on electrode surface, the synthesis of various pyrrole-substituted pyridine, 2,2′-pyridine, 1,10-phenanthroline and 2,2′:6,2″-terpyridine ligands and the electropolymerization of their ruthenium complex have been achieved [1]. Recently, poly-$[Ru(bpea\text{-}pyr)(bpy\text{-}pyr)(H_2O)]^{2+}$ (Fig. 5) (bpea-pyr = bis-pyridin-2-ylmethyl-(3-pyrrol-l-propyl)amine, bpy-pyr = 4-methyl-4′-(4-pyrrol-1-yl-butyl)-[2,2′]-bipyridine) has been prepared as a polymer film on the electrode and was applied in the electro-oxidation of benzyl alcohol. This study demonstrated that the redox cycles of the immobilized Ru-catalyst increase significantly from 36 to 922 cycles as compared to its analogue in solution.

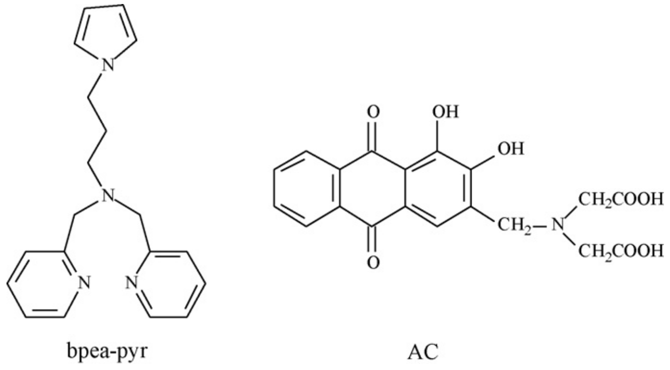


Fig. 5. Structure of bpea-pyr and AC ligands.

Polycyclic aromatic compounds such as anthracene, which adsorb strongly on electrode surface, are also common for electrode modification. Recently, Marques reported the use of adsorbed $[Ru(AC)(H_2O)_2]^-$ (AC = alizarin complexone) as catalyst in the electro-oxidation of benzyl alcohol [62]. Another example is $[Ru(tpy)(*bpy)(OH_2)]^{2+}$ (*bpy = 4′-methyl-(2,2′-bipyridine)-4-acetic acid), which can also be applied as adsorbed catalyst on graphite electrode for electro-oxidation [63,64]. In most of these cases, the catalysts can be grafted on the graphite felt resulting in significant improvement of rate of alcohol electro-oxidation.

Besides ruthenium, an indium-tin oxide electrode modified with the high valent *trans*-dioxorhenium catalyst was reported by Tanaka and co-workers [65] for the electro-oxidation of 1-phenylethanol to acetophenone. The results showed that while catalytic oxidation of 1-phenylethanol is difficult to occur in CH_2Cl_2 with free rhenium(V) complex as the catalyst, the electrocatalytic oxidation can be achieved with a higher catalyst turnover number and high current efficiency through immobilization of the rhenium(V) complex onto the electrode surface.

3.2. Nickel complexes

Nickel complexes are another important class of electrocatalysts for oxidation of alcohols. Certain nickel complexes were found to facilitate methanol oxidation with low overpotential. Representative examples include nickel(II) tetraazamacrocyclic complex [66], nickel(II) curcumin complex [67,68], nickel(II) vanillin porphyrin [69], nickel(II) tetrakis(*N*-methylpyridinium) porphyrin [70] and nickel(II) hematoporphyrin IX [71]. More-

$$\begin{array}{rcl}
NiO + OH^- & \rightleftharpoons & NiOOH + e^- \\
NiOOH + CH_3OH & \longrightarrow & NiOOH(CH_3OH)_{ads} \\
NiOOH(CH_3OH)_{ads} + NiOOH & \longrightarrow & NiO + NiOOH(\dot{C}H_2OH)_{ads} + H_2O \quad \text{(Eq 3.1)} \\
NiO + NiOOH(\dot{C}H_2OH)_{ads} + NiOOH & \longrightarrow & NiO + NiOOH(CHOH)_{ads} + H_2O \\
NiOOH(CHOH)_{ads} + NiOOH & \longrightarrow & NiO + NiOOH(\dot{C}OH)_{ads} + H_2O \\
NiOOH(\dot{C}OH)_{ads} + OH^- & \longrightarrow & NiO + HCOO^- + H_2O
\end{array}$$

Scheme 15.

over, the use of simpler ligands such as dimethylglyoxime to replace the macrocycles has also been explored [72,73].

Nickel complexes catalyze methanol oxidation to formate in alkaline medium. The mechanism for nickel oxide catalyzed oxidation of methanol as proposed by Fleischmann et al. [74] is shown in Scheme 15. The NiOOH generated from the oxidation of nickel oxides on the electrode was identified as the active catalyst for methanol oxidation. Methanol is then adsorbed onto the NiOOH surface. The reaction between the adsorbed methanol on NiOOH surface with NiOOH (Eq. (3.1)) is believed to be the rate determining step of methanol oxidation. After the oxidation step, proton abstraction occurs to give $HCOO^-$ as the product [71].

Recently, Ni(cyclam) (cyclam = 1,4,7,11-tetraazamacrocycle) was anchored with PAMAM (poly(amidoamine)) dendrimers and immobilized onto gold electrode surface as electrocatalyst [75]. The result showed that the surface-confined PAMAM dendrimer can increase the current density of methanol oxidation by a factor of 4 when comparing with modified electrodes without the dendrimer. This may be caused by the increase in methanol concentration at the electrode surface by the dendrimer.

Electrochemical oxidation of aliphatic alcohols such as ethanol, propanol, butanol [68,69] or even phenol [76] based on the nickel-system have also been investigated in recent years. The kinetics of oxidation were reported to be fastest in the case of methanol electro-oxidation.

4. Electrocatalytic oxidation of water

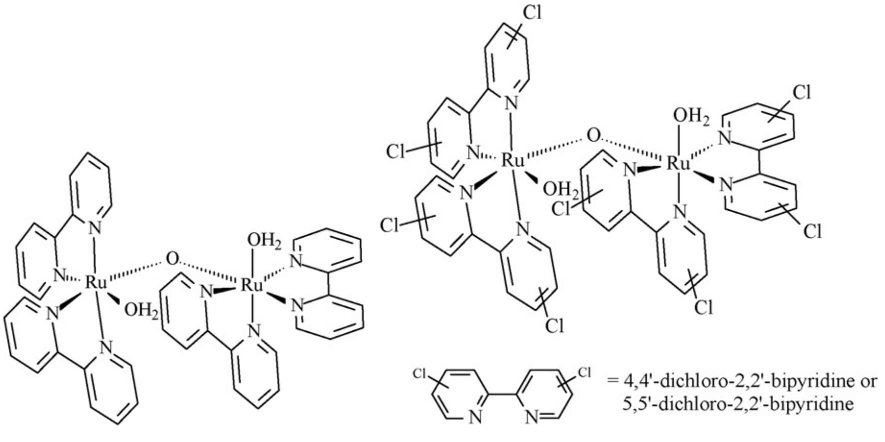
Water oxidation has been extensively studied due to its potential application in solar energy conversion [77]. The oxidation process as shown in Eq. (4.1) involves a four-electron process:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad (4.1)$$

This process occurs in the photosystem II in green plants. The catalyst in nature is a tetranuclear oxo-bridged manganese cluster which catalyzes the four-electron oxidation of water to dioxygen. To mimic this natural active center, many high-valent multinuclear μ-oxo bridged manganese complexes have been synthesized [77–79]. However, only few studies relative to their reactivity toward water oxidation have been published, and almost none of them described a non-ambiguous example of an active electrocatalyst [80]. On the other hand, some systems based on ruthenium-oxo complexes have been shown to be capable of oxidizing water to molecular oxygen. Recently, a short review article on ruthenium-oxo complexes for oxidation of water to dioxygen has been published by Llobet and co-workers [81]. Among these Ru-oxo species, the most well studied system is the μ-oxo dimer *cis,cis*-$[(bpy)_2(H_2O)Ru^{III}–O–Ru^{III}(OH_2)(bpy)_2]^{4+}$ (bpy = 2,2′-bipyridine) (Fig. 6a) first reported by Meyer and co-workers [82]. The active form of the catalyst is generally proposed to be the $O{=}Ru^{V}–O–Ru^{V}{=}O$ species [2,83]. The mechanism of water oxidation had been extensively studied by Hurst and co-workers [84,85]. The spectroelectrochemistry of the ruthenium μ-oxo dimers with chloro-substituted 2,2′-bipyridines (4,4′-dichloro or 5,5′-dichloro-2,2′-bipyridine) (Fig. 6b) was investigated by Wong and co-worker [86]. The $Ru^{III}–O–Ru^{IV}$ and $Ru^{IV}–O–Ru^{V}$ species were characterized and the $O{=}Ru^{IV}–O–Ru^{V}{=}O$ dimer was found to catalyze the water oxidation to give dioxygen at 1.3 V within 2 h.

Some non-μ-oxo binuclear ruthenium complexes have also been demonstrated as active electrocatalysts for water oxidation (Fig. 7). These include dimeric ruthenium complexes with btpyan (btpyan = 1,8-bis(2,2′:6′,2″-terpyridyl)anthracene) [87,88] and bpp (bpp = (3,5-bis(2-pyridyl)pyrazole)) [89] and diruthenium substituted polyoxometalate [90]. In the controlled-potential electrolysis of $[Ru_2(OH)_2(3,6\text{-}^tBu_2qui)_2(btpyan)]$ at 1.7 V *versus* Ag/AgCl with small amount of H_2O in 2-trifluoroethanol solution, dioxygen is evolved with a current density of 91% (21 turnovers). Interestingly, the turnover number was increased to 33,500 when the electrolysis was conducted in KOH/H_3PO_4 solution (pH 4) using a modified indium–tin oxide (ITO) electrode on which the Ru-catalysts were immobilized. It is suggested that the quinone bridge in the non-μ-oxo binuclear ruthenium complex plays an important role in water oxidation. The four electron oxidation of water was achieved by redox reactions in which not only the two Ru^{III}/Ru^{II} couples but also the two semiquinone/quinone couples of the ruthenium binuclear complex played a significant role.

The catalytic water oxidation of $[Ru_2{}^{II}(bpp)(tpy)_2(H_2O)_2]^{3+}$ (Fig. 8) with Ce^{IV} as the oxidant was conducted in 0.1 M triflic acid which gave dioxygen after 48 h with an efficiency of 73% with regard to the oxidant. The reaction rate of water oxidation by $[Ru_2{}^{II}(bpp)(tpy)_2(H_2O)_2]^{3+}$ is three times faster than that of *cis,cis*-$[(bpy)_2(H_2O)Ru^{III}–O–Ru^{III}(OH_2)(bpy)_2]^{4+}$ under similar experimental conditions. The increase in activity may be due to the favorable formation of molecular oxygen by the oxo–oxo coupling in $[Ru_2{}^{II}(bpp)(tpy)_2(H_2O)_2]^{3+}$ as the $Ru^{IV} = O$ groups in $[Ru_2{}^{IV}(bpp)(tpy)_2(O)_2]^{3+}$ are rigidly facing each other.



(a) (b)

Fig. 6. Structure of μ-oxo ruthenium dimers [82,86]. (a) $[(bpy)_2(H_2O)Ru^{III}ORu^{III}(OH_2)(bpy)_2]^{4+}$ and (b) $[(Cl_2bpy)_2(H_2O)Ru^{III}ORu^{III}(OH_2)(Cl_2bpy)_2]^{4+}$

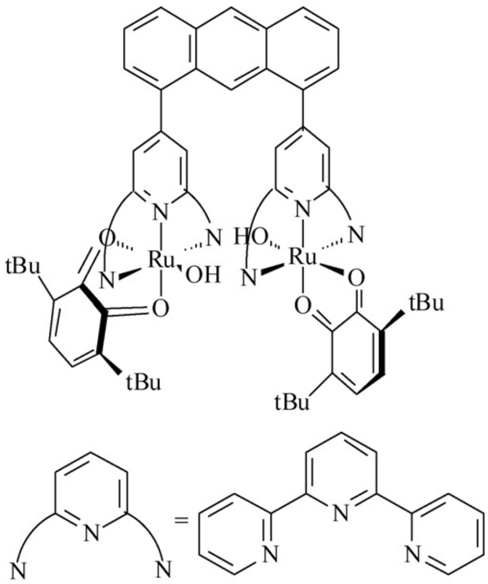


Fig. 7. Structure of $[Ru_2(OH)_2(3,6\text{-}^tBu_2qui)_2(btpyan)]$ [87].

The diruthienium-substituted polyoxometalate (POM) $[Ru_2^{III}Zn_2(H_2O)_2(ZnW_9O_{34})_2]^{14-}$ can serve as an electrocatalyst for water oxidation. The diruthenium-substituted POM can generated dioxygen at +0.750 V which is consistent with the E^0 of oxygen generation (E^0 = +0.760 V *versus* NHE at pH 8).

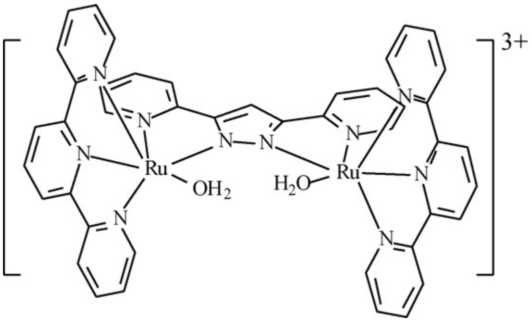


Fig. 8. Structure of $[Ru_2^{II}(bpp)(tpy)_2(H_2O)_2]^{3+}$ [89].

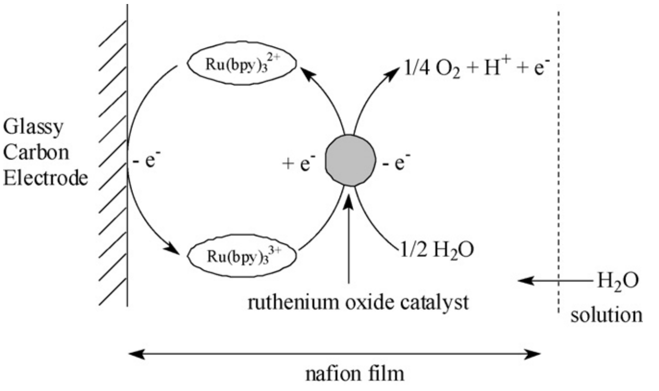


Fig. 9. Schematic representation of water oxidation reaction at the nafion-RuO_2-$Ru(bpy)_3{}^{2+}$ multi-component electrode [91].

The active centers for water oxidation were assigned to be Ru^V species.

Another successful example of electrode modification for water oxidation is the Nafion-RuO_2-$Ru(bpy)_3{}^{2+}$ multi-component electrode [91] (Fig. 9). In this electrocatalytic system, the current efficiency of water oxidation was improved remarkably compared to the Nafion-RuO_2 and $Ru(bpy)_3{}^{2+}$ electrodes. Redox mediation through $Ru(bpy)_3{}^{2+}$ was found to dominate over RuO_2 catalytic effect in the water oxidation mechanism. The catalytic activity of RuO_2 was affected by the temperature at which it was prepared.

5. Electrocatalytic oxidation of glucose mediated by metal complexes

5.1. Metal complexes as redox mediators in GOx-based oxidations

Electrocatalytic oxidation of glucose has been an important research area for almost four decades. The prodigious research effort in the development of a glucose biosensor is due to its valuable application in blood glucose assay serving 300 million people (5% of the world population) suffering from diabetes.

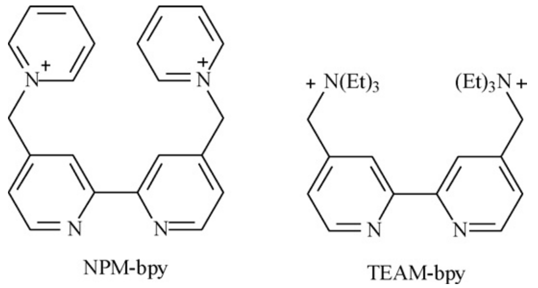


Fig. 10. Structure of some positively charged bipyridines [96].

Glucose oxidase (GOx) has been utilized as the recognition element and catalyst for glucose oxidation in the biosensor technology [92]. In order for the GOx to communicate effectively with the electrode, a redox mediator that exhibits reversible redox property is required [92–94].

Ferrocene derivatives [95] and osmium polypyridyl complexes [96] are the two major classes of redox mediator. To overcome the negatively charged active site of GOx, osmium complexes with positively charged bipyridyl ligands such as those shown in Fig. 10 were found to be effective mediators with very high electron transfer rates [97]. The development of glucose biosensors has been extensively reviewed in the literature [98] and will not be repeated here.

Instead of having the metal complex as a diffusing mediator, Heller and co-workers bound ferrocene moiety to the GOx protein to establish an electron tunneling path connecting the GOx/$FADH_2$ (FAD = flavin adenine dinucleotide) to the electrode. The covalent attachment was accomplished by the reaction of a carbodiimide activated ferrocenium/ferrocene carboxylate ester with lysine-amine resulting in ferrocene carboxamides or through imide bond formation by reacting an amino-derivatized of the ferrocene with a modified GOx (Fig. 11) [99]. The ferrocene-modified protein could communicate effectively with the electrode. Heller's group also attached a pyridine moiety to the protein using acryl chloride and diazonium salt. The covalently attached pyridine coordinates to the ruthenium pentamine moiety to create a new path for electron tunneling [100,101].

Similarly, Battaglini et al. reported that osmium redox centers can be covalently attached to GOx by using $[Os(bpy)_2Cl(pyCOOH)]^+$ and $[Os(bpy)_2Cl(pyCHO)]^+$ in which the pyridine ligand contained carboxy or carbonyl functional group for coupling to the amino groups in the protein [102]. Another coordinative approach for modifying GOx was demonstrated by Ryabov et al. [103]. GOx from *A. Niger* contains two imidazole side chains, His 516 and His 559 in close proximity to the FAD which serve as binding site for metal ions [104]. As depicted in Fig. 12, coordinative loading of the complexes *cis*-$[Ru(L)_2Cl_2]$ (L = bpy or phen) into the enzyme could be achieved without prior chemical modification of the protein. This simple method of coordinative modification afforded very high catalytic current even at high scan rates owing to the very high rate of the intramolecular electron transfer [104].

The redox mediators can also be anchored onto the electrode surface [105]. Willner and co-workers have constructed chiral ferrocene monolayers on a gold electrode through amide linkage to study the bio-electrocatalyzed oxidation of glucose [106,107] (Fig. 13).

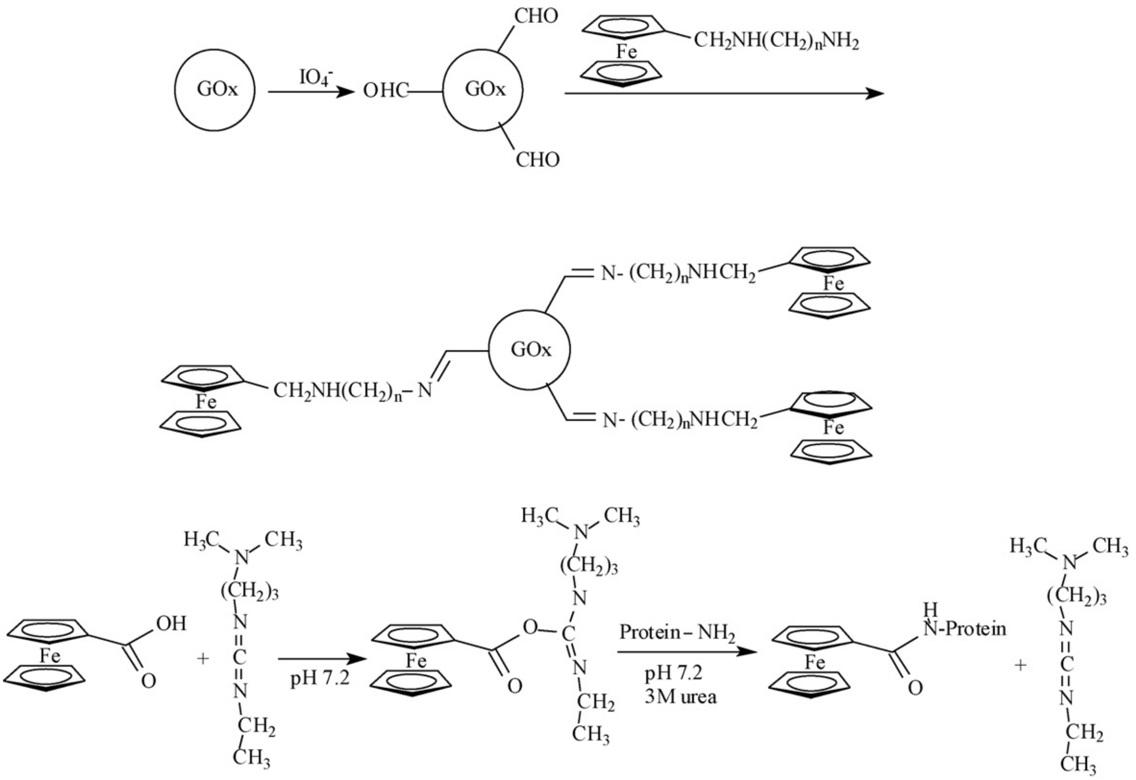


Fig. 11. Modification of GOx with carboiimide derivatized ferrocene [99].

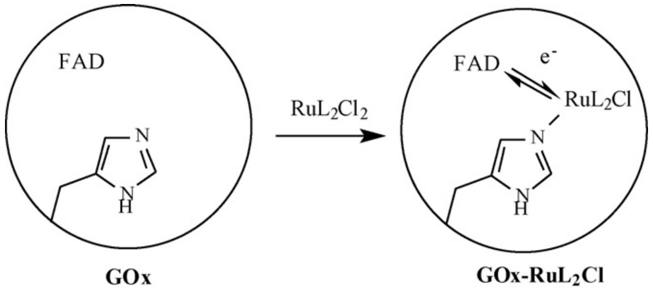


Fig. 12. Coordinative loading of ruthenium complex into GOx [104].

The use of conducting polymeric materials containing the redox mediators to modify the electrode is an alternative approach for obtaining an electroactive interface between the electrode and the GOx. The synthesis of electron conducting hydrogels for "wiring" GOx onto the electrode surface was developed by Heller and Gregg [108]. The electron-conducting hydrogels are crosslinked water-soluble polymers that contain non-leachable osmium polypyridyl-based redox centers. These hydrogels are not only capable of electrically wiring the GOx to the electrode but also permeable to glucose and gluconolactone [109,110]. Later on, a new generation of electron-conducting hydrogels (Fig. 14) was introduced by the same group [111,112]. The redox center was composed of Os^{2+} core, which were ligated by three bisimidazoles and linked covalently to the polyvinyl pyridine (PVP) polymer. It was found that long tethers for linking the redox centers could lead to high flexibility and fast electron diffusion. Coupled with an oxygen cathode of bilirubin oxidase in hydrogel, the glucose anode was applied to the construction of a miniature glucose/O_2 biofuel cell (Fig. 15) [113–115]. This system with osmium complex as the mediator has been reported to be the smallest low-cost biofuel cell.

5.2. Non-enzymatic electro-oxidation

In cases where high substrate specificity is not required (e.g. electrochemical detection in HPLC), a simple metal catalyst can be employed for the electro-oxidation of glucose and other carbohydrates. In this regard, ruthenium-oxo complexes were reported to be active catalysts for glucose oxidation. Examples included $[Ru(tpy)(phen)O]^{2+}$, $[(bpy)_2(O)Ru]_2O^{3+}$ and *cis*-$[Ru(6,6'\text{-}Cl_2bpy)_2(O)_2]^{2+}$ (tpy = 2,2′:6′,2″-terpyridine; phen = 1,10-phenanthroline; bpy = 2,2′-bipyridine) [116–118]. Among these examples, *cis*-$[Ru(6,6'\text{-}Cl_2bpy)_2(O)_2]^{2+}$ exhibited the best robustness due to the electron-withdrawing and steric effects of the chloro-substituents at the 6,6′-positions [118]. Kokon and co-workers recently employed a glucose oxidation electrode with $RuCl_2(azpy)_2$ (azpy = 2-phenylazopyridine) as the catalyst to produce 2-ketogluconic acid with considerable product selectivity. The conversion yield and product distribution were found to depend on the isomeric form of the ruthenium complexes used [119].

Araki and co-workers have explored the use of electropolymerizable supramolecular porphyrins for glucose oxidation [120–124]. Glassy carbon and gold electrode were modified with a tetraruthenated nickel porphyrin, designated as NiTRP (Fig. 16) by electropolymerization in alkaline medium. The modified electrodes were successfully employed as sensors for the analysis of glucose in parentheral nutrition solution by virtue of the catalytic activity of the Ni^{III}/Ni^{II} centers [123].

Cobalt phthalocyanine has also been incorporated in carbon paste electrode for carbohydrate oxidation. The modified electrode can be used for universal detection of various carbohydrates in liquid chromatography [125].

5.3. New developments

The use of nanotechnology in developing biosensors is an emerging trend. An example demonstrated by Jin and co-workers is the use of ferrocene-doped silica nanoparticles as redox mediator. The nanosilica surface exhibited high biocompatibility and the doped ferrocene inside maintain its high electron transfer efficiency as mediator. The biosensor was used to determine the glucose concentration in rat brain [126]. Dendritic macromolecules containing redox centers have also been an important class of material for developing catalysts, electronic materials and sensors. Alonso and co-workers immobilized GOx electrostatically onto carbon and platinum electrodes modified with ferrocene-cobaltocenium dendrimers (Fig. 17). The desirable functional properties of the biosensor derived from the thin film of heterometallic dendrimers included long-term stability, high sensitivity, expanded linear response range, and protection from interference by ascorbic acid [127].

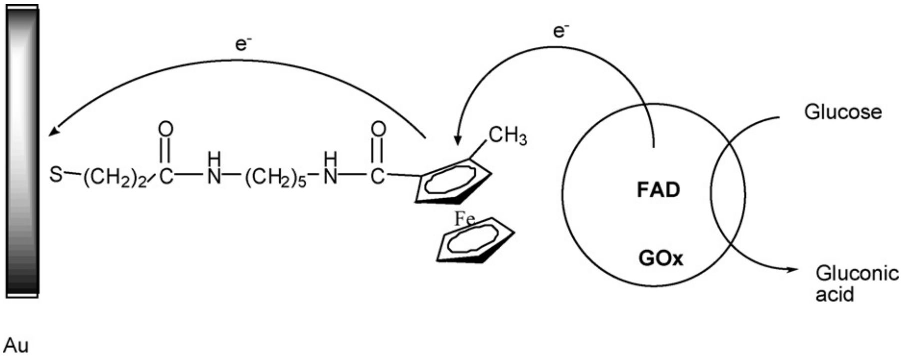
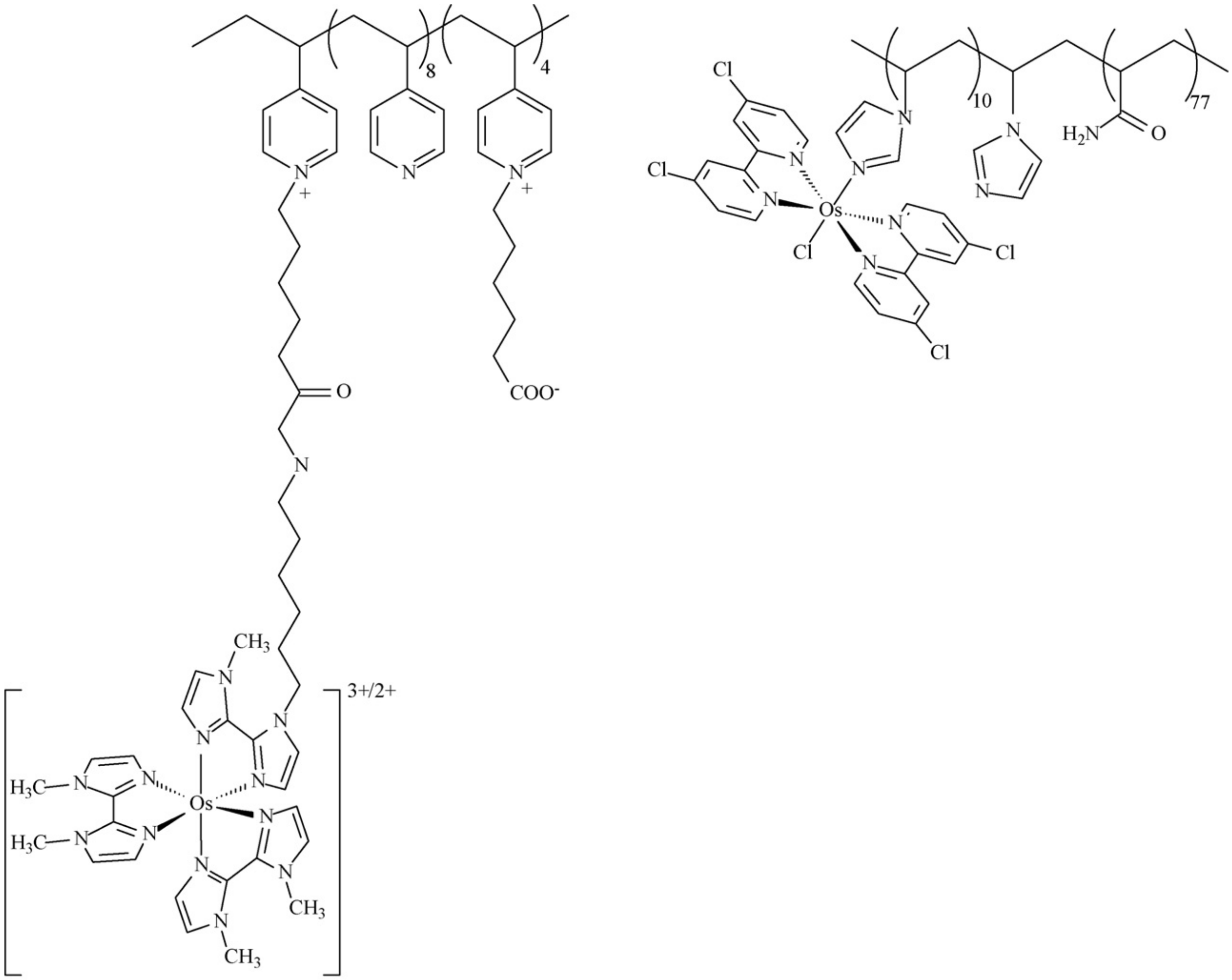


Fig. 13. Electrode modified with 2-methyl ferrocene carboxylic acid for glucose oxidation [106,107].



hydrogel *a*

hydrogel *b*

Fig. 14. Structures of the conducting hydrogel *a* and hydrogel *b* [115].

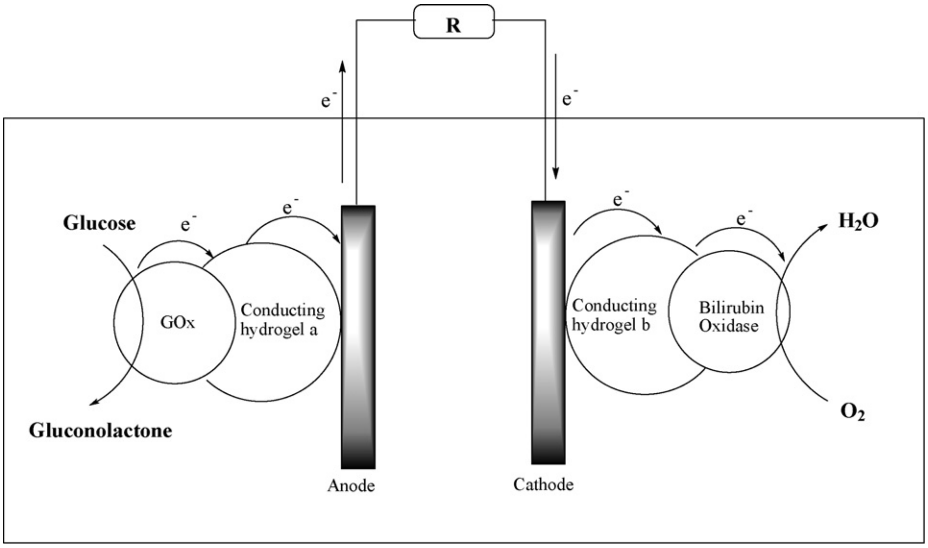


Fig. 15. Glucose/O_2 biofuel cell reported by Heller and co-workers [115].

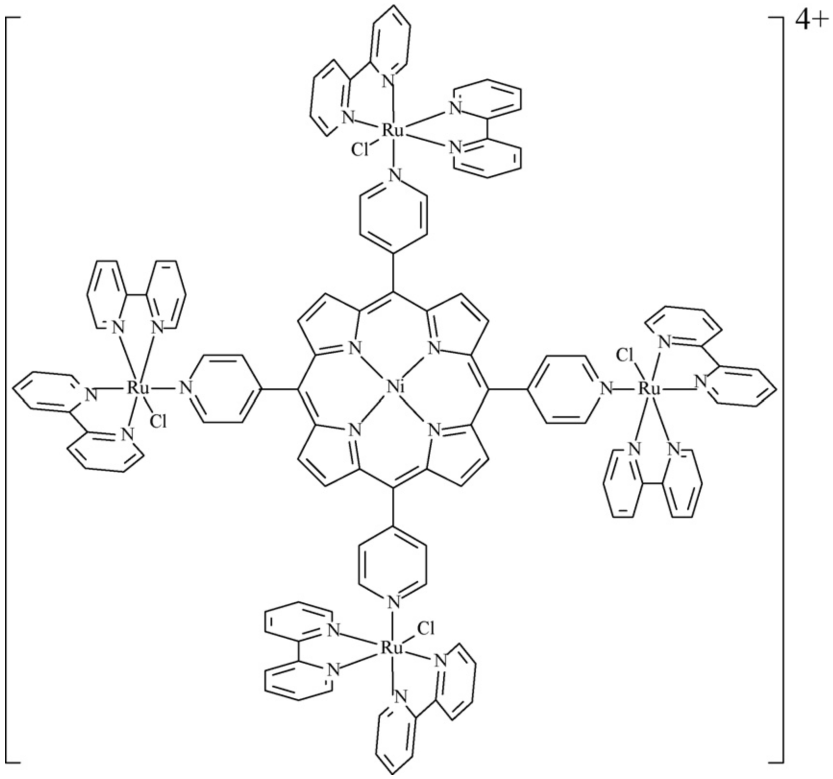


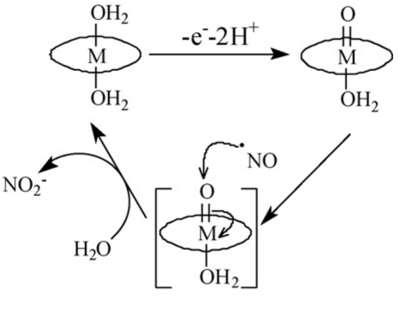
Fig. 16. Structure of tetraruthenated nickel porphyrin $(NiTRP)^{4+}$ [123].

6. Electrocatalytic oxidation of nitric oxide

The wide range of physiological functions associated with nitric oxide (NO) [128–140] makes the determination of NO in biological media important. However, the precise and accurate determination of NO is complicated by its low stability, low concentration and high reactivity with superoxide or other free radicals present in biological systems. The half-life of NO in physiological solutions can be as short as 6 s [141,142].

The determination of NO at ultra-low concentration *in vivo* is a challenging analytical problem and requires the design of sensors with high specificity, simplicity and sensitivity. In 1992, Malinski and Taha reported the use of polymeric nickel porphyrins coated on microelectrode for NO detection [143,144]. The sensor selectivity was enhanced by a Nafion membrane which minimized the penetration of anionic species such as nitrite to the electrode surface. The Nafion and nickel porphyrin coated carbon microsensor was reported to have a linear response up to 300 μM of NO with a detection limit of 10 nM. Later on, different metalloporphyrins including nickel [145–148], iron [149–154], cobalt [155,156], manganese [157–159], palladium [157] porphyrins and some other metal complexes [160,161] were reported to be effective catalysts for the electro-oxidation of NO. Nevertheless, the nature of this catalysis has not been clearly understood, with the role played by the metal ion still a subject of controversy. Ikeda and co-workers have proposed that a high valent metal oxo species is responsible for NO oxidation with the water-soluble iron(III)-*meso*-tetrakis (*N*-methylpyridinum-4-yl)porphyrin $[Fe^{III}(4\text{-TMPyP})]$ or manganese(III)-*meso*-tetrakis (*N*-methylpyridinum-4-yl)porphyrin $[Mn^{III}(4\text{-TMPyP})]$ as catalyst (Scheme 16) [152,162].

Besides metalloporphyrins, metallophthalocyanines are stable materials with good electrocatalytic properties towards NO oxidation [163,164]. Bedioui and co-workers have explored a wide variety of metallophthalocyanines, including cobalt, chromium, iron, nickel, manganese, copper and zinc phthalocyanines on their electrocatalytic properties (Fig. 18) [165–167]. When comparing different metallophthalocyanines, the influence of the metal ion on the catalytic activity is not significant. The best result was attained with nickel phthalocyanine with reaction rate only four times higher than that of the least active copper phthalocyanine. The various approaches using chemically modified microelectrodes in electrochemical detection of



Scheme 16. Catalytic cycle for the oxidation of NO by [O═M(4-TMPyP)] (M = Mn, Fe).

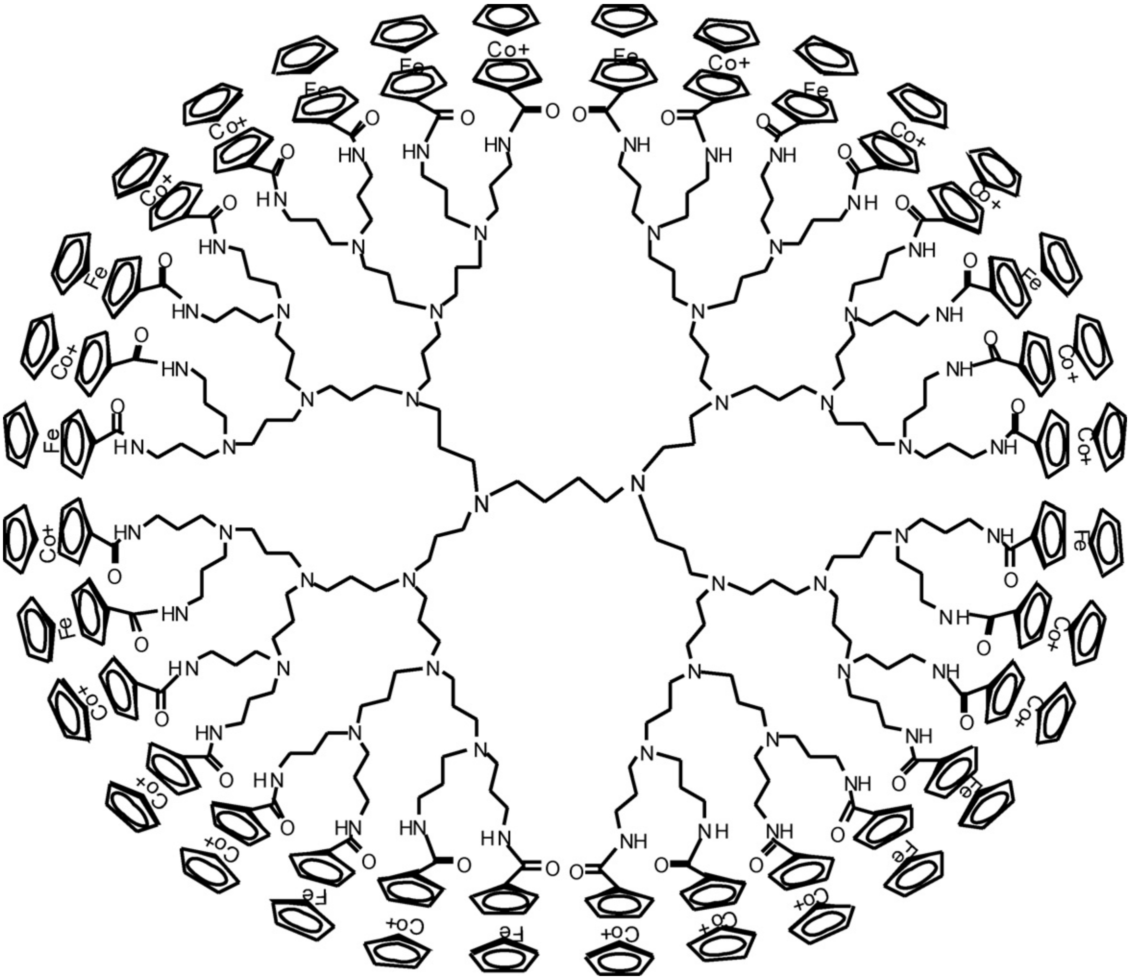
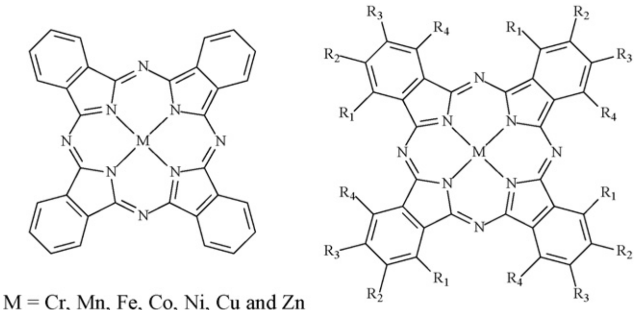


Fig. 17. Structure of ferrocene-cobaltocenium dendrimer [127].



M = Cr, Mn, Fe, Co, Ni, Cu and Zn

M = Ni, Cu

M-Pc: $R_1 = R_2 = R_3 = R_4 = H$

M-TAPc: $R_1 = R_2 = R_4 = H$, $R_3 = NH_2$

M-TNPc:$R_1 = R_2 = R_4 = H$, $R_3 = NO_2$

M-TSPc: $R_1 = R_2 = R_4 = H$, $R_3 = SO_3^-$

Ni-TPhOHPc: $R_1 = R_3 = R_4 = H$, $R_2 = OC_6H_5$

Ni-OBuPc: $R_2 = R_3 = H$, $R_1 = R_4 = O(CH_2)_3CH_3$

Ni-NaPhPc: $R_2 = R_3$ = naphthalocyanine, $R_1 = R_4 = O(CH_2)_3CH_3$

Ni-TkPc: $R_1 = R_3 = R_4 = H$, $R_2 = OC_6H_4C(CH_3)_2C_6H_5$

Cu-F_{16}Pc: $R_1 = R_2 = R_3 = R_4 = F$

Cu-TBuPc: $R_1 = R_2 = R_4 = H$, $R_3 = C(CH_3)_3$

Cu-TazaPc: $R_1 = R_2 = R_4 = H$, carbon atom of R_3 is replaced by nitrogen

Cu-OBuPc: $R_2 = R_3 = H$, $R_1 = R_4 = O(CH_2)_3CH_3$

Fig. 18. Structure of metallophthalocyanines, substituted Ni-Pc and substituted Cu-Pc [165].

$$\mathrm{RSH + PcCo^{II} \longrightarrow PcCo^{II}{-}SR + H^+}$$

$$\mathrm{PcCo^{II}{-}SR \rightleftharpoons PcCo^{III}{-}SR + e^-}$$

$$\mathrm{PcCo^{III}{-}SR \rightleftharpoons PcCo^{III}\cdot + SR\cdot}$$

$$\mathrm{2SR\cdot \rightleftharpoons RSSR}$$

Scheme 17.

NO in biological media have been reviewed by Bedioui and co-workers in 1996, 2000 and 2002, respectively [162,168–170].

7. Electrochemical oxidation of some small molecules

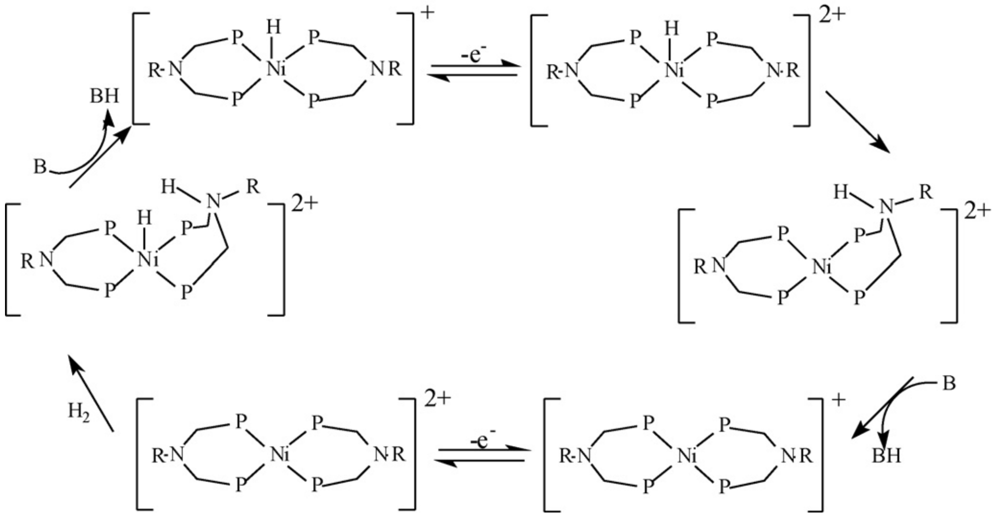
Besides NO, metalloporphyrins and metallophthalocyanines of Fe, Ni, Co are active catalysts for the oxidation of small molecules such as cysteine, thiocyanate, hydrogen and ascorbic acid. Thiol compounds play an important role in biological systems. For example the concentration of cysteine is crucial inside human body and detection of cysteine is therefore clinically important. The electrocatalytic oxidation of cysteine can therefore be developed into an analytical method for cysteine detection. Water-soluble porphyrins of cobalt [171], iron [172] and manganese [172] show catalytic activity for the oxidation of cysteine to cystine. Water-soluble phthalocyanines of cobalt [173–175], manganese and zinc [174] are able to convert cysteine to cystine in good yield in acidic medium. It is believed that the metalloporphyrins and metallophthalocyanines function as redox mediators for cysteine electro-oxidation and the mechanism of cobalt phthalocyanine in acidic medium is shown in Scheme 17 [175].

Other sulfur-containing compounds such as thiocyanate can also be oxidized by metallophthalocyanines. Recently cobalt [176] and iron phthalocyanines [176,177] were immobilized onto gold electrode to act as sensors to detect thiocyanate. The sensors gave a good catalytic activity towards thiocyanate oxidation in pH 4 buffer with a detection limit down to $\sim 10^{-7}\,\mathrm{mol\,dm^{-3}}$. The polymer films are stable and the preparation can be reproduced easily.

Oxidation of small molecules like dihydrogen is of great interest because of its relation to energy research. In biological system the enzyme hydrogenase catalyzes the oxidation of hydrogen or the reduction of proton. The nickel complexes $[\mathrm{Ni(PNP)_2}]^{2+}$ ($\mathrm{PNP = Et_2PCH_2NMeCH_2PEt_2}$) and $[\mathrm{Ni(P_2{}^{Cy}N_2{}^{Bz})_2}]^{2+}$ ($\mathrm{P_2{}^{Cy}N_2{}^{Bz}}$ = 1,3,5,7-tetraphenyl-1,5-diaza-3,7-diphosphacyclooctane) are good catalysts in hydrogen oxidation [178,179]. The complexes incorporate both hydride and proton acceptor sites in a single metal complex. These acceptor sites in the nickel complex are believed to be important in the hydrogen activation and proton transfer process as shown in Scheme 18 [179].

8. Conclusions and outlook

The technological advances involving the use of coordination compounds in electrode modification and catalyst design have been facilitating the development of electrosynthesis, fuel cells and biosensors. The industrial use of electricity as feedstock for oxidation of organic compounds is regarded as an environmentally benign approach to reduce regional pollution and energy consumption. Many organic compounds are kinetically stable towards oxidation at electrode due to the high overpotential of the electrochemical process. The crucial role of metal complexes in this approach is to catalyze the electrode process via an electro-active intermediate in the catalytic cycle. Electrochemical oxidation of alcohols such as benzyl alcohol has been well studied. The electrocatalytic epoxidation or dihydroxylation of alkenes is of high potential in fine chemical industry as epoxides and diols are important intermediates in organic synthesis. It is very encouraging that the asymmetric version of the electrochemical processes have been demonstrated. Further research efforts to improve the catalytic processes may be directed towards increasing the catalyst robustness. Discovery



Scheme 18.

of new reaction media such as ionic liquids is another important research direction to improve the environmental benignity of the processes.

The development of efficient electrodes for water oxidation is the major hurdle in solar energy research. Some metal-oxo species have been shown to be active in the electrocatalytic oxidation of water to dioxygen. However, the instability of these metal species upon repetitive cycling leading to short lifespan of the electrode has impeded the application of the catalysts. Moreover, the mechanistic details have not been thoroughly unraveled and rational design to improve the catalyst stability could therefore be difficult. The design of new catalytic system without the involvement of μ-oxo metal species could result in more robust new catalysts. Driven by the global desire for sustainable and renewable energy resources and also national policy of energy diversification in many countries, a great deal of research effort in the catalyst development for water splitting and fuel cell reaction is foreseeable.

The development of glucose oxidase based biosensors and biofuel cells have been greatly facilitated by the discovery of metal complexes as electron mediators in the redox process. In the development of glucose biofuel cells, the high overpotential commonly encountered in the reduction of O_2 to water at the cathode is yet to be overcome [114,180–183]. To further improve the power density and the durability of the enzyme electrode, nanotechnology has recently been advocated because conductive nano-materials with large surface area can increase the enzyme loading and facilitate reaction kinetics, thus improving the power density of the biofuel cells. In addition, the structure of the nano-materials can be designed through synthesis to improve the stability of the immobilized enzymes [184]. The application of nanotechnology in this aspect will become a new trend to overcome the major obstacles in the development of powerful biofuel cells.

Besides the discovery of new materials and catalysts, mechanistic study is vital in further improving the catalytic process. For example, although metalloporphyrins and metallophthalocyanines are now an important class of catalyst in NO sensor fabrication, the mechanism of NO oxidation and the role of the metal core are still not well understood. To overcome the analytical challenge a thorough understanding of the catalytic process is of utmost importance.

In fact, this review focuses only on a fraction of oxidation processes. Nevertheless, rationally combining coordination chemistry with biotechnology, nanotechnology, electrochemistry and material science on a knowledge-based approach could result in new development of novel catalytic processes which can facilitate energy revolution, alleviate environmental pollution and improve health care, as demonstrated by the aforementioned examples.

Acknowledgments

We acknowledge support from The Hong Kong Polytechnic University and the Research Grants Council (Poly U5014/03P).

References

[1] A. Deronzier, J.C. Moutet, Coord. Chem. Rev. 147 (1996) 339.
[2] A. Deronzier, J.C. Moutet, Comprehensive Coord. Chem. II 9 (2004) 471.
[3] J. Hagen, Industrial Catalysis: a Practical Approach, 2nd ed., Wiley–VCH, Weinheim, 2006.
[4] C.P. Andrieux, J.M. Dumasbouchiat, J.M. Savéant, J. Electroanal. Chem. 87 (1978) 39.
[5] A. Bielânski, J. Haber, Oxygen in Catalysis, Marcel Dekker, New York, 1991.
[6] C.M. Che, V.W.W. Yam, Advances in Transition Metal Coordination Chemistry, JAI Press, Greenwich, 1996.
[7] W.P. Griffith, Coord. Chem. Rev. 5 (1970) 459.
[8] J. Haber, T. Młodnicka, J. Mol. Catal. 74 (1992) 131.
[9] N. Phougat, P. Vasudevan, N.K. Jha, D.K. Bandhopadhyay, Trans. Met. Chem. 28 (2003) 838.
[10] S. Torii, Novel Trends in Electroorganic Synthesis, Springer-Verlag, New York, 1998.
[11] T.J. Meyer, J. Electrochem. Chem. 131 (1984) C221.
[12] B.A. Moyer, M.S. Thompson, T.J. Meyer, J. Am. Chem. Soc. 102 (1980) 2310.
[13] M.S. Thompson, W.F. De Giovani, B.A. Moyer, T.J. Meyer, J. Org. Chem. 49 (1984) 4972.
[14] M.M. Taqui Khan, G. Ramachandraiah, S.H. Mehta, J. Mol. Catal. 50 (1989) 123.
[15] M.M. Taqui Khan, S.H. Mehta, A.P. Rao, K.N. Bhatt, J. Mol. Catal. 75 (1992) 245.
[16] M.M. Taqui Khan, A.P. Rao, S.H. Mehta, J. Mol. Catal. 78 (1993) 263.
[17] C.Y. Chen, S.H. Cheng, Y.O. Su, J. Electroanal. Chem. 487 (2000) 51.
[18] J.T. Groves, JA. Gilbert, Inorg. Chem. 25 (1986) 123.
[19] J.T. Groves, R. Quinn, T.J. McMurry, M. Nakamura, G. Lang, B. Boso, J. Am. Chem. Soc. 107 (1985) 354.
[20] B. Meunier, Chem. Rev. 92 (1992) 1411.
[21] R.A. Sheldon, Metalloporphyrins in Catalytic Oxidations, Marcel Dekker, New York, 1994.
[22] L.I. Simándi, Catalytic Activation of Dioxygen by Metal Complexes, Kluwer Academic Publishers, Dordrecht, 1992.
[23] J.T. Groves, D.V. Subramanian, J. Am. Chem. Soc. 106 (1984) 2177.
[24] D.L. Hickman, A. Nanthakumar, H.M. Goff, J. Am. Chem. Soc. 110 (1988) 6384.
[25] T.S. Lee, Y.O. Su, J. Electroanal. Chem. 414 (1996) 69.
[26] M.H. Liu, Y.O. Su, J. Electroanal. Chem. 452 (1998) 113.
[27] S.E. Creager, R.W. Murray, Inorg. Chem. 26 (1987) 2612.
[28] S.E. Creager, S.A. Raybuck, R.W. Murray, J. Am. Chem. Soc. 108 (1986) 4225.
[29] H. Nishihara, K. Pressprich, R.W. Murray, J.P. Collman, Inorg. Chem. 29 (1990) 1000.
[30] F. Bedioui, J. Devynck, C. BiedCharreton, J. Mol. Catal. A: Chem. 113 (1996) 3.
[31] S. Gutierrezgranados, F. Bedioui, J. Devynck, Electrochim. Acta 38 (1993) 1747.
[32] K.P. Ho, K.Y. Wong, T.H. Chan, Tetrahedron 62 (2006) 6650.
[33] M.C.Y. Tang, K.Y. Wong, T.H. Chan, Chem. Commun. (2005) 1345.
[34] F.C. Chen, S.H. Cheng, C.H. Yu, M.H. Liu, Y.O. Su, J. Electroanal. Chem. 474 (1999) 52.
[35] C.Y. Lin, Y.O. Su, J. Electroanal. Chem. 265 (1989) 305.
[36] M.H. Liu, Y.O. Su, J. Chem. Soc. Chem. Commun. (1994) 971.
[37] C.P. Horwitz, S.E. Creager, R.W. Murray, Inorg. Chem. 29 (1990) 1006.
[38] J.C. Moutet, A. Ourari, Electrochim. Acta 42 (1997) 2525.
[39] P. Guo, K.Y. Wong, Electro. Commun. 1 (1999) 559.
[40] H. Tanaka, M. Kuroboshi, H. Takeda, H. Kanda, S. Torii, J. Electroanal. Chem. 507 (2001) 75.
[41] C. Rong, F.C. Anson, Inorg. Chem. 33 (1994) 1064.
[42] S.E. Creager, R.W. Murray, Inorg. Chem. 24 (1985) 3824.
[43] G.X. He, R.D. Arasasingham, G.H. Zhang, T.C. Bruice, J. Am. Chem. Soc. 113 (1991) 9828.
[44] C.F. Cheng, C.L. Hung, Y.O. Su, S.H. Cheng, J. Electroanal. Chem. 566 (2004) 169.

[45] Y.H. Lu, Y.O. Su, Chem. Commun. (1997) 753.
[46] Y.H. Lu, Y.O. Su, J. Electroanal. Chem. 446 (1998) 25.
[47] R. Criegee, Justus Liebigs Ann. Chem. 522 (1936) 75.
[48] R. Criegee, Angew. Chem. 50 (1937) 153.
[49] R. Criegee, Angew. Chem. 51 (1938) 519.
[50] H.C. Kolb, M.S. Vannieuwenhze, K.B. Sharpless, Chem. Rev. 94 (1994) 2483.
[51] S. Torii, P. Liu, N. Bhuvaneswari, C. Amatore, A. Jutand, J. Org. Chem. 61 (1996) 3055.
[52] S. Torii, P. Liu, H. Tanaka, Chem. Lett. (1995) 319.
[53] N. Chanda, B. Mondal, V.G. Puranik, G.K. Lahiri, Polyhedron 21 (2002) 2033.
[54] V.J. Catalano, R.A. Heck, A. Ohman, M.G. Hill, Polyhedron 19 (2000) 1049.
[55] C. Sens, M. Rodriguez, I. Romero, A. Llobet, T. Parella, J. Benet-Buchholz, Inorg. Chem. 42 (2003) 8385.
[56] M. Rodriguez, I. Romero, A. Llobet, A. Deronzier, M. Biner, T. Parella, H. Stoeckli-Evans, Inorg. Chem. 40 (2001) 4150.
[57] M.Y. Kim, W.K. Seok, Y. Dong, H. Yun, Inorg. Chim. Acta 319 (2001) 194.
[58] X. Sala, A. Poater, I. Romero, M. Rodriguez, A. Llobet, X. Solans, T. Parella, T.M. Santos, Eur. J. Inorg. Chem. (2004) 612.
[59] J.A. Moss, R.M. Leasure, T.J. Meyer, Inorg. Chem. 39 (2000) 1052.
[60] A.R. Guadalupe, X.H. Chen, B.P. Sullivan, T.J. Meyer, Inorg. Chem. 32 (1993) 5502.
[61] M.N. Collomb-Dunand-Sauthier, A. Deronzier, H. LeBozec, M. Navarro, J. Electroanal. Chem. 410 (1996) 21.
[62] A.L.B. Marques, W. Li, E.P. Marques, J. Zhang, Electrochim. Acta 49 (2004) 879.
[63] F. Geneste, C. Moinet, New J. Chem. 28 (2004) 722.
[64] F. Geneste, C. Moinet, G. Jezequel, New J. Chem. 26 (2002) 1539.
[65] H. Sugimoto, H. Tsukube, K. Tanaka, Eur. J. Inorg. Chem. (2004) 4550.
[66] G. Roslonek, J. Taraszewska, J. Electroanal. Chem. 325 (1992) 285.
[67] A. Ciszewski, Electroanalysis 7 (1995) 1132.
[68] A. Ciszewski, G. Milczarek, B. Lewandowska, K. Krutowski, Electroanalysis 15 (2003) 518.
[69] A. Ciszewski, G. Mlczarek, J. Electroanal. Chem. 413 (1996) 137.
[70] S. Trevin, F. Bedioui, M.G.G. Villegas, C. BiedCharreton, J. Mater. Chem. 7 (1997) 923.
[71] S.M. Golabi, A. Nozad, Electroanalysis 16 (2004) 199.
[72] A.N. Golikand, S. Shahrokhian, M. Asgari, M. Ghannadi Maragheh, L. Irannejad, A. Khanchi, J. Power Sources 144 (2005) 21.
[73] A.N. Golikand, M.G. Maragheh, L. Irannejad, M. Asgari, Russ. J. Electrochem. 42 (2006) 167.
[74] M. Fleischmann, K. Korinek, D. Pletcher, J. Electroanal. Chem. 31 (1971) 39.
[75] M.A. Gonzalez-Fuentes, J. Manriquez, S. Gutierrez-Granados, A. Alatorre-Ordaz, L.A. Godinez, Chem. Commun. (2005) 898.
[76] J. Mohan, S. Joshi, R. Prakash, R.C. Srivastava, Electroanalysis 16 (2004) 572.
[77] M. Yagi, M. Kaneko, Chem. Rev. 101 (2001) 21.
[78] S. Mukhopadhyay, S.K. Mandal, S. Bhaduri, W.H. Armstrong, Chem. Rev. 104 (2004) 3981.
[79] W. Rüttinger, G.C. Dismukes, Chem. Rev. 97 (1997) 1.
[80] C. Baffert, S. Romain, A. Richardot, J.C. Lepretre, B. Lefebvre, A. Deronzier, M.N. Collomb, J. Am. Chem. Soc. 127 (2005) 13694.
[81] M. Rodriguez, I. Romero, C. Sens, A. Llobet, J. Mol. Catal. A: Chem. 251 (2006) 215.
[82] R.A. Binstead, C.W. Chronister, J.F. Ni, C.M. Hartshorn, T.J. Meyer, J. Am. Chem. Soc. 122 (2000) 8464.
[83] J.K. Hurst, J.Z. Zhou, Y.B. Lei, Inorg. Chem. 31 (1992) 1010.
[84] H. Yamada, W.F. Siems, T. Koike, J.K. Hurst, J. Am. Chem. Soc. 126 (2004) 9786.
[85] J.K. Hurst, Coord. Chem. Rev. 249 (2005) 313.
[86] Y.K. Lai, K.Y. Wong, J. Electroanal. Chem. 380 (1995) 193.
[87] T. Wada, K. Tsuge, K. Tanaka, Angew. Chem. Int. Ed. 39 (2000) 1479.
[88] T. Wada, K. Tsuge, K. Tanaka, Inorg. Chem. 40 (2001) 329.
[89] C. Sens, I. Romero, M. Rodriguez, A. Llobet, T. Parella, J. Benet-Buchholz, J. Am. Chem. Soc. 126 (2004) 7798.
[90] A.R. Howells, A. Sankarraj, C. Shannon, J. Am. Chem. Soc. 126 (2004) 12258.
[91] K.C. Pillai, A.S. Kumar, J.M. Zen, J. Mol. Catal. A: Chem. 160 (2000) 277.
[92] G.J. Moody, J.D.R. Thomas, Selective Electrode Rev. 13 (1991) 113.
[93] A.E.G. Cass, G. Davis, G.D. Francis, H.A.O. Hill, W.J. Aston, I.J. Higgins, E.V. Plotkin, L.D.L. Scott, A.P.F. Turner, Anal. Chem. 56 (1984) 667.
[94] H.A.O. Hill, G.S. Sanghera, in: A.E.G. Cass (Ed.), Mediated Amperometric Enzyme Electrodes, in Biosensors, A Practical Approach, Oxford University Press, New York, 1990.
[95] A.E.G. Cass, G. Davis, M.J. Green, H.A.O. Hill, J. Electroanal. Chem. 190 (1985) 117.
[96] S.M. Zakeeruddin, D.M. Fraser, M.K. Nazeeruddin, M. Gratzel, J. Electroanal. Chem. 337 (1992) 253.
[97] D.M. Fraser, S.M. Zakeeruddin, M. Gratzel, J. Electroanal. Chem. 359 (1993) 125.
[98] J. Wang, Electroanalysis 13 (2001) 983 (and references therein).
[99] Y. Degani, A. Heller, J. Phys. Chem. 91 (1987) 1285.
[100] Y. Degani, A. Heller, J. Am. Chem. Soc. 110 (1988) 2615.
[101] W. Schuhmann, T.J. Ohara, H.I. Schmidt, A. Heller, J. Am. Chem. Soc. 113 (1991) 1394.
[102] F. Battaglini, P.N. Bartlett, J.H. Wang, Anal. Chem. 72 (2000) 502.
[103] E.S. Ryabova, V.N. Goral, E. Csoregi, B. Mattiasson, A.D. Ryabov, Angew. Chem. Int. Ed. 38 (1999) 804.
[104] H.J. Hecht, H.M. Kalisz, J. Hendle, R.D. Schmid, D. Schomburg, J. Mol. Biol. 229 (1993) 153.
[105] P.M. Allen, H.A.O. Hill, N.J. Walton, J. Electroanal. Chem. 178 (1984) 69.
[106] R. Blonder, E. Katz, Y. Cohen, N. Itzhak, A. Riklin, I. Willner, Anal. Chem. 68 (1996) 3151.
[107] G.L. Tao, E. Katz, I. Willner, Chem. Commun. (1997) 2073.
[108] B.A. Gregg, A. Heller, J. Phys. Chem. 95 (1991) 5970.
[109] B.A. Gregg, A. Heller, J. Phys. Chem. 95 (1991) 5976.
[110] A. Heller, J. Phys. Chem. 96 (1992) 3579.
[111] F. Mao, N. Mano, A. Heller, J. Am. Chem. Soc. 125 (2003) 4951.
[112] M.V. Pishko, A.C. Michael, A. Heller, Anal. Chem. 63 (1991) 2268.
[113] T. Chen, S.C. Barton, G. Binyamin, Z.Q. Gao, Y.C. Zhang, H.E. Kim, A. Heller, J. Am. Chem. Soc. 123 (2001) 8630.
[114] A. Heller, PCCP 6 (2004) 209.
[115] N. Mano, F. Mao, A. Heller, J. Am. Chem. Soc. 125 (2003) 6588.
[116] W. Kutner, T.J. Meyer, R.W. Murray, J. Electroanal. Chem. 195 (1985) 375.
[117] W. Kutner, J.A. Gilbert, A. Tomaszewski, T.J. Meyer, R.W. Murray, J. Electroanal. Chem. 205 (1986) 185.
[118] Y.K. Lai, K.Y. Wong, Electroanalysis 6 (1994) 919.
[119] K. Bamba, J.M. Leger, E. Garnier, C. Bachmann, K. Servat, K.B. Kokoh, Electrochim. Acta 50 (2005) 3341.
[120] L. Angnes, C.M.N. Azevedo, K. Araki, H.E. Toma, Anal. Chim. Acta 329 (1996) 91.
[121] K. Araki, H. Winnischofer, H.E.B. Viana, M.M. Toyama, F.M. Engelmann, I. Mayer, A.L.B. Formiga, H.E. Toma, J. Electroanal. Chem. 562 (2004) 145.
[122] K. Araki, L. Angnes, C.M.N. Azevedo, H.E. Toma, J. Electroanal. Chem. 397 (1995) 205.
[123] M. Quintino, H. Winnischofer, M. Nakamura, K. Araki, H.E. Toma, L. Angnes, Anal. Chim. Acta 539 (2005) 215.
[124] M.S.M. Quintino, K. Araki, H.E. Toma, L. Angnes, Electroanalysis 14 (2002) 1629.
[125] L.M. Santos, R.P. Baldwin, Anal. Chem. 59 (1987) 1766.
[126] F.F. Zhang, Q. Wan, X.L. Wang, Z.D. Sun, Z.Q. Zhu, Y.Z. Xian, L.T. Jin, K. Yamamoto, J. Electroanal. Chem. 571 (2004) 133.
[127] B. Alonso, P.G. Armada, J. Losada, I. Cuadrado, B. Gonzalez, C.M. Casado, Biosens. Bioelectron. 19 (2004) 1617.
[128] T.M. Dawson, V.L. Dawson, Annu. Rev. Med. 47 (1996) 219.
[129] W. Durate, A.K. Sen, F.A. Sunahara, Br. J. Pharmacol. 94 (1988) 463.

[130] S. Monacada, E.A. Higgs, FASEB J. 9 (1995) 219.

[131] S. Monacada, R.M.J. Palmer, E.A. Higgs, Biochem. Pharmacol. 38 (1989) 1709.

[132] D.D. Rees, S. Cellek, R.M.J. Palmer, S. Moncada, Biochem. Biophys. Res. Commun. 173 (1990) 541.

[133] L.J. Ignarro, G.M. Bugga, K.S. Wood, R.E. Byrns, G. Chaudhuri, Proc. Natl. Acad. Sci. 84 (1987) 9265.

[134] R.M.J. Palmer, A.G. Ferrige, S. Moncada, Nature 327 (1987) 524.

[135] J.M. Langrehr, R.A. Hoffman, J.R. Lancaster, R.L. Simmons, Transplantation 55 (1993) 1205.

[136] J. Lincoln, C.H.V. Hoyle, G. Burnstock, Nitric Oxide in Health and Disease, Cambridge University Press, Cambridge, 1997.

[137] S. Murphy, M.L. Simmons, L. Agullo, A. Garcia, D.L. Feinstein, E. Galea, D.J. Reis, D. Minc-Golomb, J.P. Schwartz, Trends Neurosci. 16 (1993) 323.

[138] C.F. Nathan, J.B. Hibbs, Curr. Opin. Immunol. 3 (1991) 65.

[139] A. Ohta, H. Takagi, T. Matsui, Y. Hamai, S. Iida, H. Esumi, Neurosci. Lett. 158 (1993) 33.

[140] D.A. Ruggiero, E.P. Mtui, K. Otake, M. Anwar, J. Comp. Neurol. 364 (1996) 51.

[141] S.H. Snyder, D.S. Bredt, Sci. Am. 266 (1992) 68.

[142] M. Kelm, M. Feelisch, R. Spahr, H.M. Piper, E. Noack, J. Schrader, Biochem. Biophys. Res. Commun. 154 (1988) 236.

[143] T. Malinski, Z. Taha, Nature 358 (1992) 676.

[144] T. Malinski, Z. Taha, S. Grunfeld, A. Burewicz, P. Tomboulian, F. Kiechle, Anal. Chim. Acta 279 (1993) 135.

[145] A. Ciszewski, G. Miczarek, Electroanalysis 10 (1998) 791.

[146] F. Lantoine, S. Trevin, F. Bedioui, J. Devynck, J. Electroanal. Chem. 392 (1995) 85.

[147] K.M. Mitchell, E.K. Michaelis, Electroanalysis 10 (1998) 81.

[148] A. Ciszewski, E. Kubaszewski, M. Lozynski, Electroanalysis 8 (1996) 293.

[149] C.H. Fan, G.X. Li, J.Q. Zhu, D.X. Zhu, Anal. Chim. Acta 423 (2000) 95.

[150] H.P. Lei, N.S. Trofimova, O. Ikeda, Chem. Lett. 32 (2003) 610.

[151] J.P. Lei, H.X. Ju, O. Ikeda, Electrochim. Acta 49 (2004) 2453.

[152] J.P. Lei, H.X. Ju, O. Ikeda, J. Electroanal. Chem. 567 (2004) 331.

[153] J. Hayon, D. Ozer, J. Rishpon, A. Bettelheim, J. Chem. Soc., Chem. Commun. (1994) 619.

[154] F. Bedioui, Y. Bouhier, C. Sorel, J. Devynck, L. Coche-Guerente, A. Deronzier, J.C. Moutet, Electrochim. Acta 38 (1993) 2485.

[155] A.V. Kashevskii, A.Y. Safronov, O. Ikeda, J. Electroanal. Chem. 510 (2001) 86.

[156] S.L. Vilakazi, T. Nyokong, Electrochim. Acta 46 (2000) 453.

[157] N. Diab, J. Oni, A. Schulte, I. Radtke, A. Blochl, W. Schuhmann, Talanta 61 (2003) 43.

[158] N. Diab, W. Schuhmann, Electrochim. Acta 47 (2001) 265.

[159] C.H. Yu, Y.O. Su, J. Electroanal. Chem. 368 (1994) 323.

[160] E. Casero, J. Losada, F. Pariente, E. Lorenzo, Talanta 61 (2003) 61.

[161] T. Nyokong, S. Vilakazi, Talanta 61 (2003) 27.

[162] N.S. Trofimova, A.Y. Satfrontov, O. Ikeda, Electrochim. Acta 50 (2005) 4637.

[163] O. Raveh, N. Peleg, A. Bettelheim, I. Silberman, J. Rishpon, Bioelectrochem. Bioenerg. 43 (1997) 19.

[164] I. Rosen-Margalit, A. Bettelheim, J. Rishpon, Anal. Chim. Acta 281 (1993) 327.

[165] C.A. Caro, J.H. Zagal, F. Bedioui, J. Electrochem. Soc. 150 (2003) E95.

[166] M.C. Miras, A. Badano, M.M. Bruno, C. Barbero, Portugaliae Electrochim. Acta 21 (2003) 235.

[167] J. Obirai, T. Nyokong, J. Electroanal. Chem. 573 (2004) 77.

[168] F. Bedioui, S. Trevin, J. Devynck, Electroanalysis 8 (1996) 1085.

[169] F. Bedioui, N. Villeneuve, Electroanalysis 15 (2003) 5.

[170] M. Pontié, F. Bedioui, Analysis 28 (2000) 465.

[171] D.W. Pang, Z.L. Wang, J. Electroanal. Chem. 358 (1993) 235.

[172] S.M. Chen, Electrochim. Acta 42 (1997) 1663.

[173] G.J. Yang, K. Wang, J.J. Xu, H.Y. Chen, Anal. Lett. 37 (2004) 629.

[174] J. Obirai, T. Nyokong, Electrochim. Acta 50 (2005) 5427.

[175] S. Maree, T. Nyokong, J. Electroanal. Chem. 492 (2000) 120.

[176] K.I. Ozoemena, T. Nyokong, P. Westbroek, Electroanalysis 15 (2003) 1762.

[177] K.I. Ozoemena, T. Nyokong, J. Electroanal. Chem. 579 (2005) 283.

[178] C.J. Curtis, A. Miedaner, R. Ciancanelli, W.W. Ellis, B.C. Noll, M.R. DuBois, D.L. DuBois, Inorg. Chem. 42 (2003) 216.

[179] A.D. Wilson, R.H. Newell, M.J. McNevin, J.T. Muckerman, M. Rakowski DuBois, D.L. DuBois, J. Am. Chem. Soc. 128 (2006) 358.

[180] K. Chan, H. Shin, A. Heller, Bioelectrochemistry 68 (2006) 22.

[181] E. Katz, B. Filanovsky, I. Willner, New J. Chem. 23 (1999) 481.

[182] E. Katz, I. Willner, J. Am. Chem. Soc. 125 (2003) 6803.

[183] E. Katz, I. Willner, A.B. Kotlyar, J. Electroanal. Chem. 479 (1999) 64.

[184] J. Kim, H. Jia, P. Wang, Biotechnol. Adv. 24 (2006) 296.