

Electrocatalytic oxidative cleavage by electrogenerated periodate

F. Nawaz Khan^a, R. Jayakumar^b, C.N. Pillai^{a,*}

^a Central Electrochemical Research Institute, Chennai Unit, CSIR Madras Complex, Tharamani, Chennai 600113, India

^b Central Leather Research Institute, Bio-Organic Laboratory, Adayar, Chennai 600020, India

Received 6 June 2002; received in revised form 6 June 2002

Abstract

An electrocatalytic method has been developed for the indirect oxidation of vicinal diols and related compounds like hydroxyketones and aminoalcohols. The oxidative cleavage has been performed in a biphasic system containing a phase transfer catalyst by periodate generated from iodate at a Pb–PbO₂ electrode.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Electrocatalysis; Glycol cleavage; Periodate; Electrogenerated reagent; Aminoalcohol cleavage

1. Introduction

Electrogenerated reagents have been used for indirect electrooxidation [1–5]. Periodate is an example of a selective oxidising agent for reaction such as a glycol cleavage [6–8], which can be electrogenerated from iodate. The oxidative cleavage of vicinal diols and related compounds like diketones, hydroxyketones and aminoalcohols can be done with sodium periodate. For water-soluble substrates, an aqueous medium is adequate. For water insoluble substrates, a solvent such as methanol, ethanol, *t*-butanol, dioxan or acetic acid in which the substrate and the oxidising agent have reasonable solubility has to be used. Use of such solvents is not always convenient. The solubility of sodium periodate in such solvents is low, often necessitating the use of large quantity of solvent. The use of phase transfer catalysis that is ideally suited for such situ-

ations has not been extensively studied for periodate oxidations.

The iodate/periodate redox system and other systems has been extensively used for mediated electrooxidation [9–17]. In the reported procedure for the oxidation of 2,3-butanediol to acetaldehyde [10], further anodic oxidation of the aldehyde to acetic acid was encountered. This was circumvented by the use of an ex-cell process in which the electro-generated reagent (periodate) was transferred to another reactor where the organic substrate was added, and after separation of the organic products, the spent reagent was transferred back to the electrolytic cell for regeneration. It was felt that the use of a two phase anolyte where the electrogeneration of the reagent took place in the aqueous phase and the actual oxidation of the organic substrate took place in the organic phase could effectively simulate ex-cell conditions without actually transferring the oxidising agent to another reaction vessel.

A phase transfer catalyst could be used for the aqueous phase-organic phase transfer of reagents. The present study was based on this concept. Though phase transfer catalysis in connection with several electro-

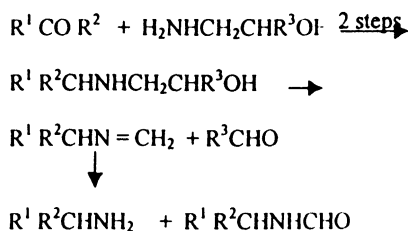
* Corresponding author. Present address: No. 19, Srinivasapuram, I Street, Tiruvanmiyur, Chennai 600041, India.

Fax: +91-44-4911589.

E-mail address: khan.f.nawaz@yahoo.co.in (F. Nawaz Khan).

generated oxidising agents has been reported, it has not been applied to periodate.

Our interest in periodate oxidation arose from a methodology developed in our laboratory for asymmetric synthesis of amines as outlined below [18,19].



It was of interest to see whether such aminoalcohols could be cleaved by the mediated electrooxidation. In the present study, the application of phase transfer catalysis was established by the study of chemical oxidation (by periodate) of selected substrates A–G (Scheme 1). Product analysis was done by gas chromatography and after isolation, by IR and NMR spectroscopy. In a few cases GC-MS was employed.

Electrochemical oxidation of substrate A–J (Scheme 1) were done in an H-type divided cell with Pb–PbO₂ anode and lead cathode. In those experiments involving phase transfer catalysis, the anolyte consisted of, in addition to the aqueous electrolyte, dichloromethane as the lower organic phase. Tetrabutyl-ammonium hydrogen sulphate (TBHS) was used as the phase transfer catalyst. In preliminary experiments, the efficiency of formation of periodate from iodate on the anode was established by doing electrolysis without added substrate and estimating the iodate formed by conventional procedure [7,8].

2. Experimental

The *erythro*-9,10-dihydroxyocta-decanoic acid was prepared [20] from a mixture of 11.28 g (40 mmol) of oleic acid in 100 ml CH₂Cl₂ and 7.25 g (50 mmol) KMnO₄ in 100 ml H₂O under phase transfer conditions using 1 g of TBHS. The reaction mixture was stirred for 8 h and was filtered using suction. The residue of MnO₂ was thoroughly washed with CH₂Cl₂ and filtered again. The filtrate was separated in a separating funnel. The organic layer was washed with distilled water to remove the TBHS. The separated or-

ganic layer was dried over anhydrous Na₂SO₄. The product formed was analysed by IR and NMR.

2.1. General procedure for chemical oxidation

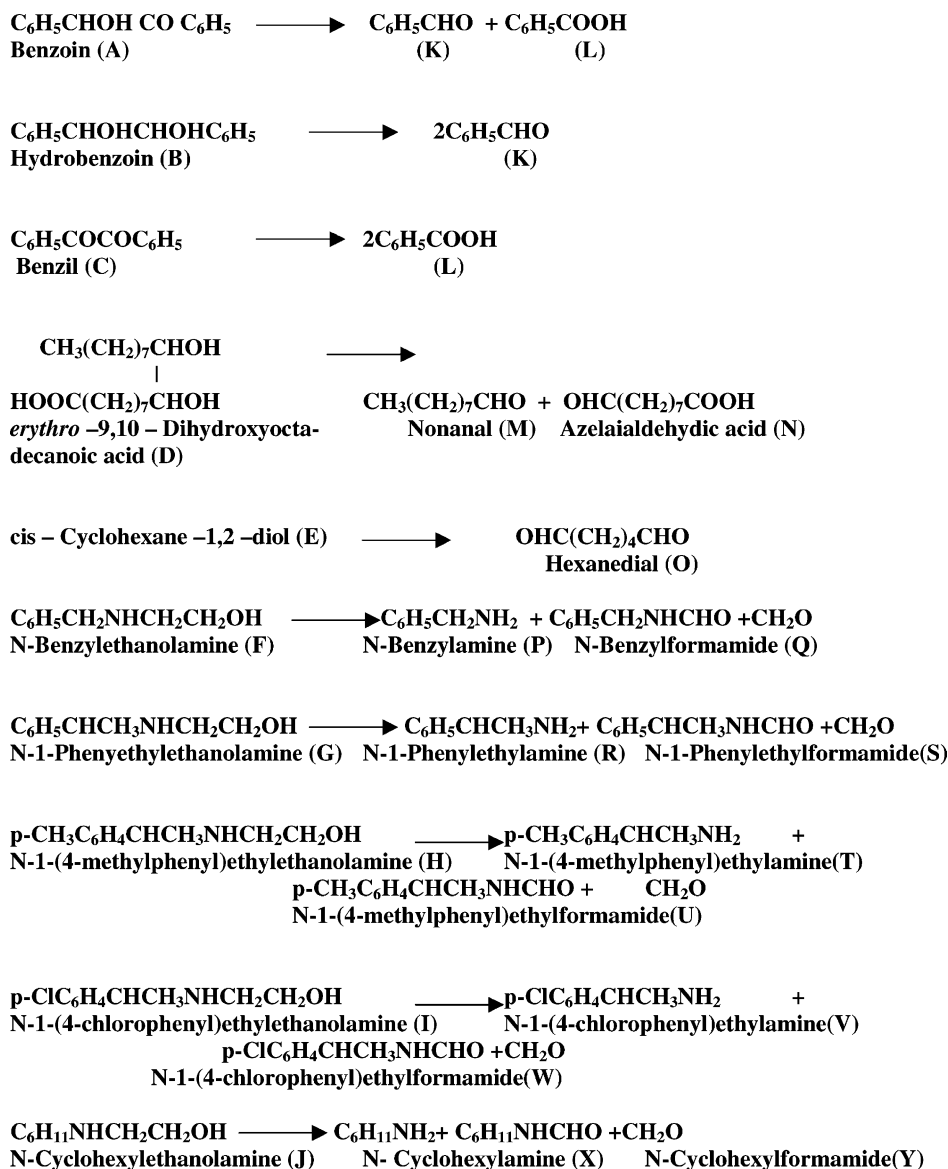
The chemical oxidations were carried out in a RB flask fitted with a stopper. The organic substrates about 1 g were dissolved in dichloromethane, the oxidising reagent dissolve in water was added to it and the mixture was stirred vigorously for about 5 h. After tested for completion of the reaction using TLC, the mixture was transferred into a separating funnel and the two layers were separated and the products were isolated.

2.2. General procedure for electrochemical oxidation

An H-type cell with a sintered glass diaphragm was used for the electrochemical studies with a lead dioxide sheet anode obtained from a lead–acid battery and lead sheet cathode. Reference electrode (SCE) was positioned near the anode. The organic substrates were dissolved in dichloromethane, which formed the lower layer in the anode compartment in the portion of H-type cell below the level of the tube connecting the two limbs, when not stirring. The aqueous layer above CH₂Cl₂ consisted of 0.5 M Na₂SO₄ with added NaIO₃ and TBHS. The current through the solution was maintained at 0.15–0.3 A and potential above 2.0 V. After the electrolysis the dichloromethane layer was separated, washed with water and directly analysed by GC on SE-30 column, temperature programmed at 100–200 °C.

2.3. Electrooxidative cleavage of benzoin

The catholyte was made up of 3.5 g (25 mmol) of Na₂SO₄ in 50 ml H₂O and the anolyte, 10.65 g (75 mmol) of Na₂SO₄, 6.48 g (32.7 mmol) of NaIO₃, 100 ml H₂O, 1 g (5 mmol) of benzoin, 0.5 g (1.5 mmol) TBHS and 50 ml of CH₂Cl₂. The anolyte was agitated by a magnetic stirrer. The current through the solution was 0.15–0.30 A and the anodic potential, 3.91–4.83 V. After the electrolysis, the anolyte was separated from the cell, transferred to a separating funnel, the organic layer separated, and worked up.



Scheme 1. Oxidative cleavage of diols and related compounds.

2.4. Electrooxidative cleavage of erythro-9,10-dihydroxyocta-decanoic acid (D)

The catholyte consisted of 3.5 g (25 mmol) of Na_2SO_4 in 50 ml H_2O and the anolyte was 10.65 g (75 mmol) of Na_2SO_4 , 6.48 g (32.7 mmol) of NaIO_3 , 100 ml H_2O , 1 g (3.5 mmol) of D, 0.5 g (1.5 mmol) TBHS and 50 ml of CH_2Cl_2 . A magnetic stirrer

agitated the anolyte. The current was about 0.15–0.30 A and the anodic potential, 3.91–4.83 V. After the electrolysis, the anolyte was separated from the cell and was transferred to a separating funnel, the organic layer was separated and treated with NaOH , two layers were separated and the aqueous alkali layer was neutralised with acid to obtain the acidic product, $\text{CHO}(\text{CH}_2)_7\text{COOH}$ (N). The organic phase

was washed with water and neutral component, $\text{CH}_3(\text{CH}_2)_7\text{CHO}$ (M) was extracted. The products were analysed using IR and NMR.

2.5. Electrooxidative cleavage of aminoalcohols

The catholyte consisted of 3.5 g (25 mmol) of Na_2SO_4 in 50 ml H_2O and the anolyte was 10.65 g (75 mmol) of Na_2SO_4 , 6.48 g (32.7 mmol) of NaIO_3 , 100 ml H_2O , 1–2 g (10 mmol) of F–J, 0.5 g (1.5 mmol) TBHS and 50 ml of CH_2Cl_2 . The pH of the solution was initially adjusted to 8 by the addition of sodium hydroxide. This was done to prevent the anolyte becoming acidic which was objectionable as discussed below. The anolyte was agitated by a magnetic stirrer. The current was about 0.15–0.30 A and the anodic potential, 3.91–4.83 V. After the electrolysis, the anolyte was separated from the cell and was transferred to a separating funnel, the organic layer was separated and treated with HCl, two layers were separated and the aqueous alkali layer was neutralised with acid to obtain the basic product, amine. The organic phase was washed with water and neutral component formyl derivative was extracted. The products were analysed using IR and NMR.

3. Results and discussions

The results of the periodate oxidation of substrates A–G are presented in Table 1. The oxidation proceeded smoothly in homogeneous medium (methanol). In heterogeneous medium (water–dichloromethane) in the absence of phase transfer agent (compare experiment Nos. 4–7) the conversion was low. Diketone, benzil, C (experiment Nos. 6 and 7) was oxidised at a slower rate than the diols and the hydroxyketone, benzoin. The aminoalcohols, F–G (experiment Nos. 10–13) were oxidised equally efficiently in methanol, as in the biphasic system under phase transfer catalysis. Both the free amine and the formyl derivative, as already reported [19], were formed. There was no significant difference in amine selectivity between the two sets of conditions. The conclusion was that where a mutual solvent like methanol could be used, phase transfer catalysis offered no advantage other than avoiding the need to use large quantity of solvent.

In the case of electrooxidation (Tables 2–5) phase transfer catalysis offered distinct advantages. In the absence of phase transfer catalyst, there was very little oxidation (experiment No. 2 in Tables 2–4). With

Table 1
Chemical oxidation of diols and related compounds

Experiment No.	Substrate ^a (mmol)	Reagent NaIO_4 (mmol)	Solvent	PTC ^b (g)	Reaction time (h)	Yield (%)
1	A (5)	7.5	CH_3OH	None	5	87.72 ^c (80.16) ^d
2	A (5)	5	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	10	80.95 ^c
3	A (5)	5	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.1	10	56 ^c
4	B (4.6)	4.6	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	3	96.75 ^d
5	B (4.6)	4.6	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	None	3	33.47 ^d
6	C (4.6)	4.6	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.1	3	19.8 ^c
7	C (4.6)	4.6	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	None	3	2 ^c
8	D (19)	28.9	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	5	85 (76) ^e
9	E (17.2)	30	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	5	95 ^f
10	F (13)	15	CH_3OH	None	5	(74) ^g 98
11	F (13)	15	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	5	(63) ^g 99
12	G (9)	15	CH_3OH	None	5	(63) ^g 99
13	G (9)	15	$\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$	0.5	5	(51) ^g 98

^a A, benzoin (1 g); B, hydrobenzoin (1 g); C, benzil (1 g); D, *erythro*-9,10-dihydroxyocta-decanoic acid (6.1 g); E, cyclohexanediol (2 g); F, *N*-benzylethanolamine (2 g); G, *N*-phenylethylethanolamine (2 g).

^b Tetrabutyl-ammoniumhydrogen sulphate.

^c Benzoic acid (L).

^d Benzaldehyde (K).

^e Aldehydic acid, $\text{OHC}(\text{CH}_2)\text{COOH}$ (N); and aldehyde, $\text{H}_3\text{C}(\text{CH}_2)\text{CHO}$ (M).

^f Dialdehyde, $\text{OHC}(\text{CH}_2)_4\text{CHO}$ (O).

^g Amine selectivity (P–S).

Table 2
Electrooxidative cleavage of benzoin

Experiment No.	Anolyte composition ^a		Phase transfer catalyst, TBHS	Benzoic acid, yield (%)
	NaIO ₃ (g, mmol) ^b	Na ₂ SO ₄ (g, mmol) ^b		
1	Nil	10.65 (75)	None	0
2	0.212 (1)	10.65 (75)	None	5
3	6.48 (33)	10.65 (75)	0.5 (1.5)	58
4	0.212	10.65 (75)	0.5 (1.5)	48

^a Anode, Pb-PbO₂; cathode, Pb; 2 F/mol water, 100 ml; CH₂Cl₂, 50 ml.

^b 1 g (5 mmol).

Table 3
Electrooxidative cleavage of hydrobenzoin

Experiment No.	Anolyte composition ^a		Phase transfer catalyst, TBHS	Benzaldehyde, yield (%)
	NaIO ₃ (g, mmol) ^b	Na ₂ SO ₄ (g, mmol) ^b		
1	Nil	10.65 (75)	None	0
2	0.212 (1)	10.65 (75)	None	6
3	6.48 (33)	10.65 (75)	0.5 (1.5)	100
4	0.212 (1)	10.65 (75)	0.5 (1.5)	100

^a Anode, Pb-PbO₂; cathode, Pb; 2 F/mol water, 100 ml; CH₂Cl₂, 50 ml.

^b 1 g (4.6 mmol).

Table 4
Electrooxidative cleavage of *erythro*-9,10-dihydroxyocta-decanoic acid

Experiment No.	Anolyte composition ^a		Phase transfer catalyst, TBHS	Conversion ^b (%)
	NaIO ₃ (g, mmol) ^c	Na ₂ SO ₄ (g, mmol) ^c		
1	Nil	10.65 (75)	None	0
2	0.212 (1)	10.65 (75)	None	15
3	6.48 (33)	10.65 (75)	0.5 (1.5)	95
4	0.212	10.65 (75)	0.5 (1.5)	90

^a Anode, Pb-PbO₂; cathode, Pb; 2 F/mol water, 100 ml; CH₂Cl₂, 50 ml.

^b Based on GC analysis.

^c 1 g (4.6 mmol).

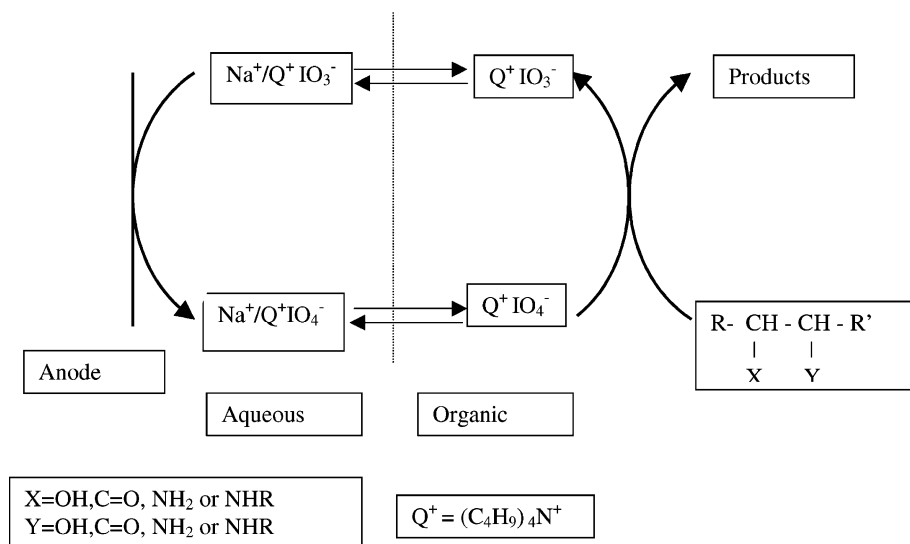
Table 5
Oxidative cleavage of aminoalcohols

Experiment No.	Substrate ^a (mmol)	Anolyte composition ^b		Time (h)	Conversion ^c	Amine selectivity
		NaIO ₃ (mmol)	Na ₂ SO ₄ M			
1	F (10)	28	0.5	10	93	58
2	F (10)	14	0.5	10	98	88
3	G (9)	25	0.5	10	71	65
4	H (10)	25	0.5	10	75	68
5	I (10)	25	0.5	10	74	70
6	J (10)	25	0.5	10	72	66

^a F, *N*-benzylethanolamine; G, *N*-1-phenylethylethanolamine; H, *N*-cyclohexylethanolamine; I, *p*-CH₃C₄H₄CH(NHCH₂CH₂OH)CH₃; J, *p*-ClC₄H₄CH(NHCH₂CH₂OH)CH₃.

^b pH of the solution was adjusted to 8 by the addition of NaOH; PTC, tetrabutyl-ammonium hydrogen sulphate; 0.5 g 2 F/mol water, 100 ml; CH₂Cl₂, 50 ml.

^c Based on GC analysis: includes amine and other products like formyl derivative hydrolysable to amine (P-S).



Scheme 2. Mediated biphasic oxidation.

iodate as the redox reagent and phase transfer catalyst, conversions were quite high (experiment Nos. 3 and 4 in Tables 2–4). Initial experiments were done with excess iodate in the anolyte (experiment No. 3 in Tables 2–4). Subsequent studies with substoichiometric quantity of iodate gave equally satisfactory results (experiment No. 4 in Tables 2–4). Iodate, converted to periodate in the aqueous phase at the anode got extracted into the organic phase as ion pair with tetrabutyl-ammonium cation. After oxidation periodate was regenerated in the aqueous phase, completing the catalytic cycle. Effectively, dichloromethane layer in the anolyte had simulated ex-cell conditions (Scheme 2).

The results of the oxidation of aminoalcohols are presented in Table 5. The situation with aminoalcohols was different from that with the other substrates. During electrolysis, the anode compartment became acidic. Hence, in principle there was no need to use a biphasic system. However aminoalcohols gave intraceivable products in acidic medium. Hence it was necessary to control the pH of the anolyte at neutral or slightly alkaline. This was done by the addition of alkali as required to maintain the pH at about 8. Because of the alkaline pH, tetrabutyl-ammonium ion underwent Hofmann degradation to some extent and tributylamine was detected as a product. Periodate oxidation of aminoalcohols gave, in addition to the amine, the

N-formyl derivative of the amine as already reported [19].

4. Conclusion

The oxidative cleavage of compounds such as ketoalcohol, diol and aminoalcohol by electrogenerated periodate utilising $\text{IO}_4^-/\text{IO}_3^-$ redox mediator in a biphasic system at the PbO_2/Pb electrode was shown to be successful for water insoluble substrates. Under these conditions the IO_4^- generated at the anode was transferred to the organic phase by the phase transfer agent, where the oxidation took place and the iodate formed in this step was transferred back to the aqueous phase where it got reoxidised to periodate at the anode, completing the catalytic cycle. Thus the “ex-cell” methodology was simulated within the cell itself, overcoming the solubility limitations and preventing further oxidation of the product formed.

Acknowledgements

The authors acknowledge the CSIR, Delhi for the funding, Director, CECRI Chennai Unit and Director, CLRI for facilities.

References

- [1] J. Simonet, Organic Electrochemistry, Marcel Dekker, New York, 1991, p. 217.
- [2] E. Steckhan, Top. Curr. Chem. 142 (1987) 1.
- [3] S. Torii, T. Inokuchi, T. Sugiura, J. Org. Chem. 51 (1986) 155.
- [4] S. Torii, T. Inokuchi, K.J. Kondo, Org. Chem. 50 (1985) 4980.
- [5] F. Marken, A.M. Squires, A. Alden, R.G. Compton, J.E.H. Bustan, M.G. Moloney, J. Phys. Chem. B 102 (1998) 1186.
- [6] A.S. Perlin, Oxidation, Marcel Dekker, New York, 1969, p. 189.
- [7] F.J. Welcher, Organic Analytical Reagents, vol. IV, Van Nostrand, Princeton, NJ, 1948, pp. 517–531.
- [8] E. Miller, F. Berger, Ber, 1902, p. 2655.
- [9] A. Yoshiyama, T. Nonaka, M.M. Baizer, T. Chou, Bull. Chem. Soc. Jpn. 58 (1985) 201.
- [10] A. Yoshiyama, T. Chou, T. Fuchigami, T. Nonaka, M.M. Baizer, J. Electrochem. Soc. Jpn. 53 (1985) 989.
- [11] Y. Aiya, S. Fujii, K. Sujino, K. Shirai, J. Electrochem. Soc. 109 (1962) 419.
- [12] T. Shono, Y. Matsumura, T. Hasimoto, K. Hibino, K. Hamaguchi, T. Aoki, J. Am. Chem. Soc. 97 (1975) 2546.
- [13] H. Tanaka, R. Kikuchi, M. Baba, S. Torii, Bull. Chem. Soc. Jpn. 68 (1995) 2989.
- [14] H. Tanaka, M. Kuroboshi, H. Takeda, H. Kanda, S. Torii, J. Electroanal. Chem. 507 (2001) 75.
- [15] S. Torii, T. Inokuchi, Y. Hirata, A simple and improved procedure for the conversion of alkynes to 1,2-diketones by indirect electrooxidation with ruthenium tetroxide as a mediator, Synthesis (1987) 377.
- [16] S. Torii, T. Inokuchi, Y. Araki, Synth. Commun. 17 (1987) 1797.
- [17] S. Torii, T. Inokuchi, S. Matsumoto, T. Saeki, T. Oki, Bull. Chem. Soc. Jpn. 62 (1989) 2108.
- [18] R. Sreekumar, C.N. Pillai, Tetrahedron Asymmetry 4 (1993) 2995.
- [19] R. Sreekumar, R.B.C. Pillai, C.N. Pillai, Ind. J. Chem. 33B (1994) 692.
- [20] M.A. Johnson, P.H. Washecheck, K. Yang, C.M. Starks, US Patent, 3,650,918 (1972).