



Development of a high performance electrochemical wastewater treatment system

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Abstract

In order to construct a high performance electrochemical system for practical use in industrial and municipal wastewater treatment, laboratory scale electrochemical experiments were performed to select anode materials by applying pulse voltage. Based on the results obtained from laboratory experiments, a pilot plant of electrochemical treatment system ($0.3 \text{ m}^3 \text{ h}^{-1}$) was successfully developed, in which electrocoagulation and electrooxidation processes were used. The performance of the treatment system was evaluated by treating domestic wastewater, pond water containing algae and wastewater from hog raising. As a result, production of hydroxyl radicals detected with *p*-nitrosodimethylaniline (RNO) at Ti/RuO₂–TiO₂ anode was larger than with a platinum anode, and hydroxyl radicals were not detected at Ti anode. Moreover, a significant difference in electrocatalytic properties for ammonia oxidation between platinum and Ti/RuO₂–TiO₂ electrodes was not observed from the cyclic voltammogram. The removal of T-N, T-P, NH₄-N and COD from domestic wastewater and pond water containing algae was approximately 90%, while the removal of chlorophyll-a (chl-a) of algae was approximately 100%. Although the electrochemical treatment system was effective on biologically treated wastewater from hog raising, the treatment of raw wastewater was not remarkable. Therefore, the electrochemical treatment system requires pretreatment when used with wastewater containing high concentrations of suspended solids.

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Nomenclature

BOD	biochemical oxygen demand (mg l^{-1})
chl-a	chlorophyll-a ($\mu\text{g l}^{-1}$)
COD	chemical oxygen demand (mg l^{-1})
N	nitrogen (g)
$\text{NH}_4\text{-N}$	ammonia nitrogen (mg l^{-1})
P	phosphorus (g)
SS	suspended solid (mg l^{-1})
T-N	total nitrogen (mg l^{-1})
T-P	total phosphorus (mg l^{-1})

Subscripts

Cl^-	chlorine ion
Fe	iron
Fe^{2+}	ferrous ion
$\text{Fe}(\text{OH})_2$	ferrous hydroxide
$\text{Fe}(\text{OH})_3$	ferric hydroxide
H^+	hydrogen ion
H_2O_2	hydrogen peroxide
HOCl	hypochlorite
IrO_2	iridium oxide
MO_x	oxide anode
MO_{x+1}	chemisorbed active oxygen
$\text{MO}_x[\bullet\text{OH}]$	adsorbed hydroxyl radical
$\bullet\text{O}$	active oxygen
$\bullet\text{OH}$	hydroxyl radical
OH^-	hydroxyl ion
PbO_2	lead oxide
Pt	platinum
R	organic matter
RNO	<i>p</i> -nitrosodimethylaniline
RO	oxidized organic matter
RuO_2	ruthenium oxide
SnO_2	tin oxide
Ti	titanium
TiO_2	titanium oxide

1. Introduction

The increase in nitrogen and phosphorus from various sources of wastewater has resulted in serious eutrophication of natural bodies of water, and pollution of the water environment has become a serious global problem. In general, methods for treating wastewaters

include biological methods, chemical treatment using ozone, chlorides or coagulants and electrochemical treatment. Although the biological treatment of wastewater is important, it cannot completely remove soluble components, such as endocrine disrupters and pesticides. A large part of nitrogen in domestic wastewater and stock raising wastewater is found as ammonia, which is generally treated by biological nitrification–denitrification. However, the nitrification process requires a larger treatment system and longer treatment time than electrochemical treatment, resulting in a higher treatment cost. Alternatively, chemical treatment involves the addition of high amounts of chemicals resulting in unreacted chemicals being discharged in the treated wastewater [1]. In addition, biological and chemical methods may generate a considerable amount of sludge, which itself requires treatment. As environmental regulations become stringent, new and novel processes for efficient treatment of various kinds of wastewater at relatively low operating cost are needed. In recent years, electrochemical treatment has gained increasing interest because it is relatively economical and has a higher treatment efficiency. The processes can completely convert organic pollutants into gases such as N_2 , CO_2 , etc. Although the electrochemical method for treating a variety of industrial wastewaters has been extensively researched and reported [2–7], almost all the previous work concerning the electrochemical method was on a laboratory scale. There are only a few reports on practical industrial applications. This situation may be due to problems regarding electrode lifetime and energy consumption. On the other hand, a high voltage pulse has a low average current and large instantaneous current. Energy consumption is relatively low because the interval is long. Furthermore, the authors [8] have revealed that high voltage pulse can produce various radical species, which are more effective for the removal of NH_4-N , and the applied voltage influences the RNO bleaching. The authors found that hexavalent chromium was removed by an electrochemical process in the laboratory. As a result, the combination of electrochemical treatment and adsorption onto chitosan provides many advantages, i.e. simplicity, low cost, high ion removal efficiency, and ease of operation [9].

Moreover, Ti/SnO_2 [10] and Ti/PbO_2 [11,12] were effective in removing various organic pollutants from wastewater, and the authors have demonstrated that a Ti/SnO_2 anode can efficiently remove ammonia from wastewater [8]. However, regulations are becoming stricter with respect to the permissible concentrations of metal ions in effluents. In general, noble metal oxides such as RuO_2 have better performance than those of the corresponding noble metals. However, it is difficult to utilize the dimensionally stable anode (DSA) electrodes coated by the oxides in industrial applications because they are expensive, and their service lifetimes are short. However, the high operating lifetimes of oxide coatings can be extended by addition of either conducting oxides such as IrO_2 or non-conducting oxides such as TiO_2 to RuO_2 . TiO_2 is especially attractive because of its lower cost [13]. Houk et al. [14] have shown that quaternary metal oxide films applied to Ti or Pt substrates exhibited high and persistent activity for the electrochemical incineration of benzoquinone. Motheo and Pinhedo [15] reported that the Ti/RuO_2-TiO_2 electrode performs better than Ti/IrO_2-TiO_2 or $Ti/IrO_2-RuO_2-TiO_2$ electrodes when used in the electrochemical degradation of humic acid.

In this present study, to investigate the effect of anode materials on their oxidizability for organic matter, measurement of anode behavior and detection of hydroxyl radicals

formed in the electrochemical process were investigated in the laboratory. A pilot plant scale electrochemical treatment system ($0.3 \text{ m}^3 \text{ h}^{-1}$) using pulse voltage has been successfully developed, and its performance evaluated using domestic wastewater, pond water containing algae and wastewater from hog raising.

2. Theories of electrochemical treatment

Generally, oxidation of organic matter by electrochemical treatment can be classified as direct oxidation at surface of anode and indirect oxidation distant from the anode surface; processes are influenced significantly by the anode material. Recently, oxides anode have been of interest because of higher conductivity and oxidizability. The mechanism of oxidation of organic matter at oxide anode (MO_x) has been suggested by Comminellis [16]. Water is electrolyzed by anodic catalysis to produce adsorbed hydroxyl radicals, given as Eq. (1):



The adsorbed hydroxyl radicals may form chemisorbed active oxygen, as shown in Eq. (2):



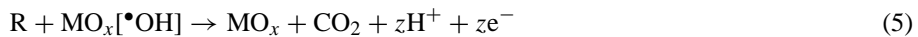
Furthermore, another strong oxidant of hypochlorite may be produced in many wastewaters containing chlorides, as given in Eq. (3) [3,17]:



In addition, high voltage pulse can lead to the formation of a strong electric field and free radicals such as $\bullet\text{OH}$, $\bullet\text{O}$, H^+ and H_2O_2 , etc. [18]:



Organic matter (R) included in wastewater are oxidized by hydroxyl radicals [16], and the reactions are given in Eqs. (5)–(7) [17]:

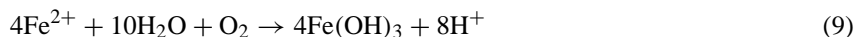


Oxidation of organic matter depends upon the anode material, concentration of NaCl, and current and voltage applied. Although the influence of NaCl and anode material has been investigated in the electrochemical treatment applied dc power supply, the effect of anode material on pulse treatment has not been studied yet.

In addition, electrocoagulation also occurs during electrochemical treatment of wastewater. The electrocoagulation mechanisms has been proposed for the production of $\text{Fe}(\text{OH})_3$ or $\text{Fe}(\text{OH})_2$ [19].

1. Mechanism 1

- Anode:



- Cathode:



2. Mechanism 2

- Anode:



- Cathode:



Removal of various pollutants such as heavy metals [20], nitrate [21] by electrocoagulation has been studied. In the present study, phosphorus included in wastewater was removed by the electrocoagulation mentioned above.

3. Experimental apparatus and methods

3.1. Laboratory experiments

3.1.1. Apparatus

As shown in Fig. 1, the electrochemical apparatus consists of a power supply, flat-plate anode and cathode (4 cm × 12 cm) mounted in a acrylic cell (200 ml), peristaltic pump and reservoir (500 ml). A high voltage pulse generator (YHPG-5K-50MTR, Yamabishi Electric Co. Ltd.) was used as the power supply. Cooling was provided by ice to keep the temperature in the solution below 30 °C.

In this study, the cathode was made from a titanium sheet, and the anodes were a sheet of titanium, platinum and titanium coated with Ti/RuO₂-TiO₂. The ratio of RuO₂ to TiO₂ was 30:70 (v/v). The preparation of Ti/RuO₂-TiO₂ used procedures suggested by Motheo and Pinheiro [15]. That is, the titanium supported oxide layer was coated by thermal decomposition of precursors in isopropyl alcohol. The solvent was evaporated at a low temperature and the dried layer heated at 450 °C for 5 min under a 5 l min⁻¹ O₂ flux. Finally, the electrode was annealed at 450 °C for 1 h. The distance between cathode and anode was set at 4 cm.

3.2. Experimental procedures

3.2.1. Electrocatalytic properties of anodes

In order to investigate the electrocatalytic activities of anodes, cyclic voltammetry measurements were performed in three electrolytes of 100 mM phosphate buffer solution,

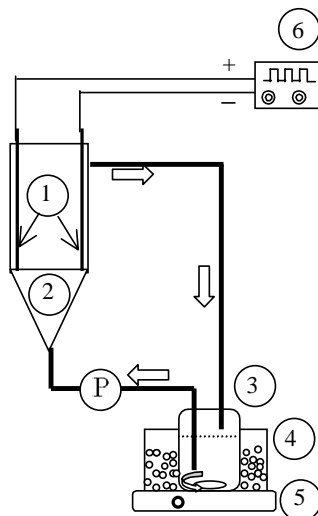


Fig. 1. Schematic diagram of electrochemical apparatus for detecting hydroxyl radicals in laboratory: (1) electrodes; (2) electrochemical cell; (3) beaker; (4) cooling reservoir; (5) stirrer; (6) pulse generator.

100 mM phosphate buffer solution which contained 50 mM NH_4Cl and 50 mM NH_3 , respectively. A platinum wire was used as the counter electrode and a saturated calomel electrode (SCE) was employed as a reference. Working electrodes were a flat-plate made of titanium, $\text{Ti/RuO}_2\text{-TiO}_2$ and platinum; their dimensions were $4\text{ cm} \times 12\text{ cm}$. The geometrical area immersed in the electrolytes was 20 cm^2 . A potential sweep unit (model 1114, BAS Co.) was applied to the potential waveform, and cyclic voltammetry was recorded with a X–Y recorder (MEMORY HiCORDER 8807, HIOKIE. E. Co.). The potential was scanned at 20 mV s^{-1} , starting from 0 V, and the scan range was -2 to 2 V.

3.2.2. Detection of hydroxyl radicals

To measure hydroxyl radicals formed during the electrochemical treatment, a NaCl solution (0.02%, w/w) containing $50\text{ }\mu\text{mol l}^{-1}$ RNO was used because RNO reacts rapidly with hydroxyl radicals selectively. The bleaching of RNO solution by hydroxyl radicals was measured by absorbance changes at 440 nm [12]. RNO solution of 500 ml was poured in the reservoir, and circulated at the flow rate of 87 ml min^{-1} . The applied voltage, peak current and frequency were 600 V, 1.0 A and 1 kHz, respectively. Samples were taken at intervals of 5 min and absorbance of RNO solution was measured by HACH DR/4000 spectrophotometer.

3.3. Pilot plant of electrochemical treatment system

The electrochemical pilot plant consisted of a screen, wastewater tank, and reactor A, reactor B, two sedimentation tanks, dc power supply and pulse generator; its schematic diagram is shown in Fig. 2. Wastewater was pumped through the screen to separate some

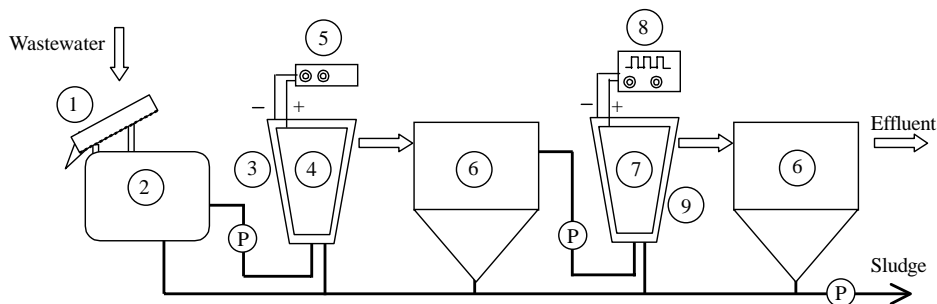


Fig. 2. Schematic diagram of pilot plant electrochemical system ($0.3 \text{ m}^3 \text{ h}^{-1}$): (1) screen; (2) wastewater tank; (3) reactor A (cathode); (4) iron anode; (5) dc power supply; (6) sedimentation tank; (7) Ti/RuO₂ anode; (8) pulse generator; (9) reactor B (cathode).

large solid particles. It then went to the reactor A for treatment for 15 min, and subsequently to the first sedimentation tank for 1 h. The effluent from the first sedimentation tank was transferred to the reactor B for a 15 min treatment. Finally, the treated wastewater was settled in the secondary sedimentation tank for 1 h, and discharged.

The cathodes in reactors A and B were made of stainless steel, the anode in the reactor A was made of iron, and the anode in reactor B was Ti/RuO₂-TiO₂ fabricated by the method mentioned above. The cathodes and anodes were cone-shaped. The dimensions of the anodes were $\varnothing 21 \text{ cm} \times \varnothing 36 \text{ cm} \times \text{H}73 \text{ cm}$, and the distance between the cathode and anode was 2 cm. The cone electrode shape was used to disturb the wastewater flow and promote the pollutant mass transfer between the electrodes and wastewater. Direct current (FX060-100, TAKASAGO Co. Ltd.) was applied the reactor A; the current density was 3 mA cm^{-2} . High voltage pulse (YHPG-0.8K-100A, Yamabishi Electric Co. Ltd.) was applied to the reactor B, the voltage and frequency were 500 V and 25 kHz, respectively.

3.4. Materials

Domestic wastewater and pond water containing algae (7001 in each case) were used in the experiments. To evaluate the treatment efficiency on the wastewater containing high concentration of pollutants, raw wastewater from hog raising and its effluent of biologically treated wastewater were used. The effluent was obtained from raw wastewater treated by screening, coagulation with polyaluminum chloride (PAC), primary aeration and sedimentation, secondary aeration and sedimentation.

3.5. Sampling

Samples were taken from untreated and treated wastewaters. The evolved gas was collected from the reactor B in a TEDLAR pack (1 l) usually used for gas sampling. The TEDLAR packs were purged using argon gas before starting the experiments, and then connected to the reactor B by polyethylene tube.

3.6. Analysis

Concentrations of T-P, T-N, TOC, COD, BOD, chl-a in the wastewater and T-P, T-N, TOC in the sludge were determined according to Japanese sewage test method.

O₂, N₂, CO₂, in the collected gases were identified by gas chromatography (GC-8A, Shimadzu Co., Japan). The detector was TCD, and the columns were Shimalite Q and Porapak Q.

4. Results and discussion

4.1. Electrocatalytic properties of anodes

De Vooy et al. [22] conducted the comparative experiments to discuss the electrocatalytic oxidation of ammonia and the intermediates formed during the reaction using a series of transition metals, and shown that the activity of platinum electrode for ammonium oxidation was larger than others transition metals such as palladium, rhodium, iridium electrodes. In our present study, cyclic voltammograms for titanium, Ti/RuO₂-TiO₂ and platinum electrodes were used, as shown in Figs. 3–5. Titanium was almost no electrochemical activity during all experiments, but the reduction current was largest in phosphate buffer solutions. On the other hand, in the case of Ti/RuO₂-TiO₂, the oxidation current increased gradually from 0 V, and increased sharply from 0.9 V, and reached approximately 1.5 mA at 2 V in phosphate buffer solution. The cyclic voltammogram obtained was similar to the one reported by Pelegrini et al. [23], i.e. the charge was distributed over a wide range of potential, and the band located at 0.9 V was observed corresponding to various solid-state redox transitions of rhodium. However, no oxidation current was observed before 0.9 V, and

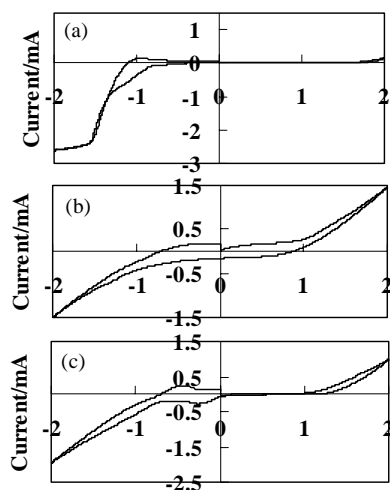


Fig. 3. Cyclic voltammogram obtained in 100 mM phosphate buffer, scan rate: 20 mV s⁻¹; reference: saturated calomel electrode: (a) titanium; (b) Ti/RuO₂-TiO₂; (c) platinum.

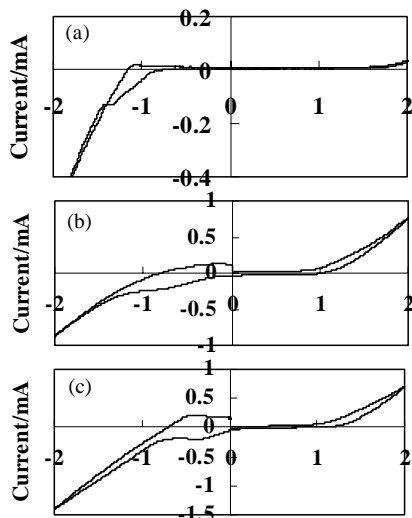


Fig. 4. Cyclic voltammogram obtained in 100 mM phosphate buffer containing 50 mM NH₄Cl, scan rate: 20 mV s⁻¹; reference: saturated calomel electrode: (a) titanium; (b) Ti/RuO₂-TiO₂; (c) platinum.

1 mA at 2 V in the case of platinum. Furthermore, the oxidation current at Ti/RuO₂-TiO₂ was slightly larger than that found using platinum; especially, the oxidation current became smaller and rather low at potentials lower than 0.9 V when added NH₄Cl or NH₃. Therefore, the oxygen-containing products like N₂O and NO may be formed because the selectivity to N₂ is 100% at potentials lower than 0.8 V [22].

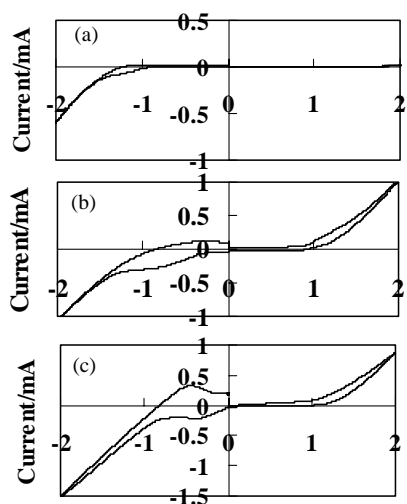


Fig. 5. Cyclic voltammogram obtained in 100 mM phosphate buffer containing 50 mM NH₃, scan rate: 20 mV s⁻¹; reference: saturated calomel electrode: (a) titanium; (b) Ti/RuO₂-TiO₂; (c) platinum.

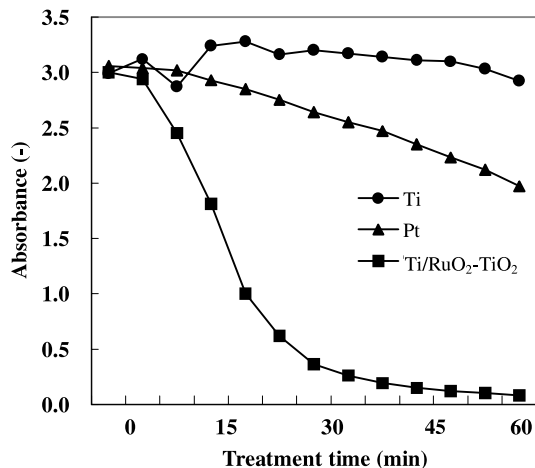


Fig. 6. Electrochemical bleaching of $50 \mu\text{mol l}^{-1}$ in NaCl solution (0.02%, w/w) as a function of treatment time for different anode materials. Pulse voltage: 600 V; peak current: 1.0 A; frequency: 1 kHz.

4.2. Effect of anode materials on radical production

The difference between titanium, platinum and Ti/RuO₂-TiO₂ can be clearly seen in Fig. 6. The absorbance of RNO using Ti/RuO₂-TiO₂ sharply decreased up to the treatment for 30 min, and then decreased slowly. The bleaching ratio was approximately 88% at 30 min and 97% at the end of the experiment. Compared to Ti/RuO₂-TiO₂ anode, absorbance in the case of platinum decreased slowly during all the experiments, and the bleaching ratio reached only 36% at the termination of the experiment. On the other hand, a decrease in absorbance value was not observed for Ti anode, but it rather increased. This result was due to Ti ions electrochemically dissolving and entering into the RNO solution, resulting in increased turbidity of RNO solution. Corrosion of the titanium surface was observed after 1 h. Obviously, radicals such as hydroxyl radicals, which were formed at the Ti/RuO₂-TiO₂ electrode were larger than at the Pt and Ti electrode. Comminellis and Pulgarin [10] reported that hydroxyl radicals formed at platinum anode were almost zero. It was proposed that platinum anode favors selective oxidation to Ti/SnO₂, but not complete combustion. Anodes made of noble metal such as platinum have high oxidative activity for pollutants in wastewater, but the reaction rate is slow, and it is easily inactive [24]. The results obtained in the pulse voltage treatment confirmed the same phenomenon.

4.3. Water quality during pilot plant of electrochemical treatment

The quality of domestic wastewater and pond water containing algae is shown in Table 1. The concentrations of T-N, NH₄-N, T-P, and COD in domestic wastewater after treatment by the electrochemical treatment system were reduced by 73, 81, 99, and 86%, respectively. The concentrations of T-N, T-P, BOD, COD, SS in pond water containing algae reduced by 83, 90, 78, 92, and 97%, respectively, while chl-a removed was almost totally removed.

Table 1
Electrochemical treatment using pilot plant ($0.3 \text{ m}^3 \text{ h}^{-1}$)

Treatment	(a) Domestic wastewater				(b) Pond water containing algae					
	T-N (mg l^{-1})	$\text{NH}_4\text{-N}$ (mg l^{-1})	T-P (mg l^{-1})	COD (mg l^{-1})	T-N (mg l^{-1})	T-P (mg l^{-1})	COD (mg l^{-1})	BOD (mg l^{-1})	SS (mg l^{-1})	chl-a ($\mu\text{g l}^{-1}$)
Untreated ^a	33.03	23.09	4.5	36.5	4.4	0.296	46	10	68	270
Treated ^b	8.86	4.35	0.045	5	0.73	0.03	3.5	2.2	2	0.6

Current density: 3 mA cm^{-2} ; pulse voltage: 500 V; frequency: 25 kHz.

^a Indicates before electrochemical treatment.

^b Indicates after electrochemical treatment.

It can be seen that the treatment system has a high efficiency when treating domestic wastewater and wastewater containing algae. The T-P and algae were removed mainly by coagulation due to the formation of metal ions by electrolysis at the electrodes in reactor A, as shown in Eqs. (8)–(13). Other soluble substances such as $\text{NH}_4\text{-N}$ were decomposed by direct oxidation at the anode and/or indirectly oxidized in reactor B as shown in Eqs. (5)–(7). Although ammonia oxidation at electrode–liquid interfaces occurred [22,25], the removal of ammonia may also through an indirect oxidation route [26] because many radical species such as hydroxyl radicals, hypochlorite might be formed during electrochemical treatment of wastewater containing chlorides. It may be necessary to examine the role of direct and indirect oxidation for ammonia in the future.

Both treated domestic wastewater and pond water became transparent, and the sludge was usable as a fertilizer because no chemicals were used.

4.4. Mass balance

The results for N and P were calculated by N and P concentrations in the wastewater multiplied the volume of wastewater used in the experiments. For domestic wastewater, approximately 91% of P was contained in sludge, while 100% of P was coagulated in sludge when pond water containing algae was treated. The P included in the sludge from the treatment of domestic wastewater treatment was 0.46% (d.b.), and 0.29% (d.b.) for pond water containing algae. On the other hand, approximately 45% of the N from domestic wastewater and 28% from algae wastewater were transferred to sludge, respectively. The N contained in the sludge resulted from domestic wastewater treatment were 1.68% (d.b.) and 1.31% in the sludge from algae wastewater treatment. It can be seen that 38.6% of N from domestic wastewater and 55.2% for algae wastewater were removed as nitrogen gas. Experimentally, 74.2% of N_2 and 0.1% of CO_2 in evolved gas was detected. The production of N_2 and CO_2 follows the reactions (5)–(7).

4.5. Quality of wastewater from hog raising

The removal of T-N, T-P, $\text{NH}_4\text{-N}$, BOD, COD and SS from raw wastewater from hog raising were 15, 87.5, 19.5, 42.5, 46.6, and 69.4%, respectively; while the removal from

Table 2
Electrochemical treatment of wastewater from hog raising using pilot plant ($0.3\text{ m}^3\text{ h}^{-1}$)

Materials	Treatment	T-N (mg l^{-1})	T-P (mg l^{-1})	$\text{NH}_4\text{-N}$ (mg l^{-1})	BOD (mg l^{-1})	COD (mg l^{-1})	SS (mg l^{-1})
Not biologically treated	Untreated ^a	852.0	50.3	807.0	1200.0	730.0	850.0
	Treated ^b	724.2	6.3	650.0	690.0	390.0	260.0
Biologically treated	Untreated ^a	831.8	123.0	94.1	16.0	140.0	19.0
	Treated ^b	272.8	22.1	41.8	13.0	84.0	8.0

Current density: 3 mA cm^{-2} ; pulse voltage: 500 V; frequency: 25 kHz.

^a Indicates before electrochemical treatment.

^b Indicates after electrochemical treatment.

biologically treated wastewater was 67.2, 82.0, 55.6, 18.8, 40, and 57.9%, respectively (Table 2). Obviously, relatively larger removals of T-N and $\text{NH}_4\text{-N}$ were obtained in biologically treated wastewater. This result can be explained by suspended solids in wastewater limiting the electrochemical oxidation of pollutants. For this reason, electrochemical treatment has been proved uneconomical when utilized with raw wastewater containing high concentrations of suspended solids. It is necessary to biologically pretreat if the electrochemical treatment system is to be utilized for wastewater from hog raising.

5. Conclusions

On the basis of laboratory experiments examining the electrochemical catalytic activity of anodes and detection of the production of hydroxyl radicals during pulse voltage treatment, a pilot plant electrochemical treatment system using high voltage pulse has been developed successfully. The treatment performance was evaluated using domestic wastewater, pond water containing algae and wastewater from hog raising. The findings of this study are as follows: (1) no difference in electrocatalytic activity for ammonia oxidation between platinum and $\text{Ti/RuO}_2\text{-TiO}_2$ was observed from the cyclic voltammogram; (2) hydroxyl radicals formed in the electrochemical process were detected using a RNO solution and the production of hydroxyl radicals with $\text{Ti/RuO}_2\text{-TiO}_2$ anode was larger than found using platinum and titanium anode; (3) excellent removal of T-N, $\text{NH}_4\text{-N}$, T-P, and COD from domestic wastewater and pond water containing algae was achieved by the pilot plant of electrochemical treatment system. Furthermore, chl-a was almost completely removed. On the other hand, the electrochemical treatment system was not feasible for treating raw wastewater from hog raising. However, the excellent treatment results were obtained in treating biologically treated wastewater from hog raising. It was suggested that a biological pretreatment might be necessary for treating wastewater containing high concentration of suspended solids.

References

- [1] N. Mohan, N. Balasubramanian, V. Subramanian, Electrochemical treatment of simulated textile effluent, *Chem. Eng. Technol.* 24 (7) (2001) 749–753.
- [2] D.T. Chin, C.Y. Cheng, Oxidation of phenol with ac electrolysis, *J. Electrochem. Soc., Electrochem. Sci. Tech.* 132 (11) (1985) 2605–2611.
- [3] C.J. Israilides, A.G. Vlyssides, V.N. Mourafeti, G. Karvouni, Olive oil wastewater treatment with the use of an electrolysis system, *Bioresource Tech.* 61 (1997) 163–170.
- [4] V. Smith De Sucre, Watkinson, Anodic oxidation of phenol for waste water treatment, *Can. J. Chem. Eng.* 59 (1981) 52–59.
- [5] A.G. Vlyssides, C.J. Israilides, Electrochemical oxidation of a textile dye and finishing wastewater using a Pt/Ti electrode, *J. Environ. Sci. Health A33* (5) (1998) 847–862.
- [6] S.H. Lin, C.L. Wu, Electrochemical removal of nitrite and ammonia for aquaculture, *Water Res.* 30 (3) (1996) 715–721.
- [7] J. Grimm, D. Bessarabov, R. Sanderson, Review of electro-assisted methods for water purification, *Desalination* 115 (1998) 285–294.
- [8] C. Feng, N. Sugiura, M. Takaaki, Study on the electrochemical treatment of wastewater—fundamental experiments for developing the treating equipment, in: *Proceedings of the XIV Memorial CIGR World Congress 2000, Japan, 2000*, pp. 1306–1311.

- [9] K.Y. Chuang, C.P. Norman, N. Sugiura, F. Chuanping, T. Maekawa, Effect of removal of hazardous metals from effluent of biological treatment onto chitosan using electrochemical processing, *J. Soc. Agric. Struct.* 33 (2) (2002) 103–111.
- [10] C. Comninellis, C. Pulgarin, Electrochemical oxidation of phenol for wastewater treatment using SnO₂ anodes, *J. Appl. Electrochem.* 23 (1993) 108–112.
- [11] A.M. Polcaro, S. Palmas, F. Renoldi, M. Mascia, On the performance of Ti/SnO₂ and Ti/PbO₂ anodes in electrochemical degradation of 2-chlorophenol for wastewater treatment, *J. Appl. Electrochem.* 29 (1999) 147–151.
- [12] D. Wabner, C. Grambow, Reactive intermediates during oxidation of water at lead dioxide and platinum electrodes, *J. Electroanal. Chem.* 195 (1985) 95–108.
- [13] C. Comninellis, G.P. Vercesi, Characterization of DSA-type oxygen evolving electrodes: choice of a coating, *J. Appl. Electrochem.* 21 (1991) 335–345.
- [14] L.L. Houk, S.K. Johnson, J. Feng, R.S. Houk, D.C. Johnson, Electrochemical incineration of benzoquinone in aqueous media using a quaternary metal oxide electrode in the absence of a soluble supporting electrolyte, *J. Appl. Electrochem.* 28 (1998) 1167–1177.
- [15] A.J. Motheo, L. Pinhedo, Electrochemical degradation of humic acid, *Sci. Total Environ.* 256 (2000) 67–76.
- [16] C. Comninellis, Electrocatalysis in the electrochemical conversion/combustion of organic pollutants for waste water treatment, *Electrochim. Acta* 39 (1994) 1857–1862.
- [17] L. Szpyrkowicz, G.H. Kelsall, S.N. Kaul, M.De. Faveri, Performance of electrochemical reactor for treatment of tannery wastewaters, *Chem. Eng. Sci.* 56 (2001) 1579–1586.
- [18] B. Sun, M. Sato, J.S. Clements, Oxidative processes occurring when pulsed high voltage discharges degrade phenol in aqueous solution, *Environ. Sci. Tech.* 34 (2000) 509–513.
- [19] M. Yousuf, A. Mollah, R. Schennach, J.R. Parga, D.L. Cocke, Electrocoagulation (EC)—science and applications, *J. Haz. Mater.* B89 (2001) 29–41.
- [20] W. Carl, P.E. Dairymple, Use of electrocoagulation of heavy metals in industrial wastewaters, *Minerals Met. Mater. Soc.* (1995) 103–111.
- [21] A.S. Koparal, U.B. Ogutveren, Removal of nitrate from water by electroreduction and electrocoagulation, *J. Haz. Mater.* B89 (2002) 83–94.
- [22] A.C.A. De Vooy, M.T.M. Koper, R.A. van Santen, J.A.R. van Veen, The role of adsorbates in the electrochemical oxidation of ammonia on noble and transition metal electrodes, *J. Electroanal. Chem.* 506 (2001) 127–137.
- [23] R. Pelegrini, P. Peralta-Zamora, A.R. de Andrade, J. Reyes, N. Duran, Electrochemically assisted photocatalytic degradation of reactive dyes, *Appl. Catal. B: Environ.* 22 (1999) 83–90.
- [24] Y. Takasu, A. Aramata, Y. Hori, *Advance in electrode catalysis*, University of Hokkaido, Sapporo, 2001, pp. 143–159.
- [25] J.F.E. Gootzen, A.H. Wonders, W. Visscher, R.A. van Santen, J.A.R. van Veen, A DEMS and cyclic voltammetry study of NH₃ oxidation on platinumized platinum, *Electrochim. Acta* 43 (12–13) (1998) 1851–1861.
- [26] L. Szpyrkowicz, J. Naumczyk, F. Zilio-Grandi, Electrochemical treatment of tannery wastewater using Ti/Pt and Ti/Pt/Ir electrodes, *Water Res.* 29 (2) (1995) 517–524.