Review Article

Recent Developments in Electrochemical Technology for Water and Wastewater Treatments

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ABSTRACT

This paper presents the recent attention in scientific studies and development of electrochemical processes. Electrochemical technology has contributed significantly to the purification of water for better human health and aquatic life forms. In this study, we emphasize the developmental trends of electrochemical technologies, their applications, and recent developments in the context of water and wastewater treatments. Recent studies have made great advances in investigating and optimizing advanced electrochemical oxidation processes in treatment of various organic pollutants, reduction of halogenated contaminants, and disinfection of microorganisms. Besides, electrochemical oxidation processes have been combined with other treatment methods to enable their practical application. Excellent electro-catalytic treatment of contaminant and their by-products was achieved through the application of mixed metal oxides (PbO₂, SnO₂, Ti/RuO₂, etc.), Pt, and boron-doped diamond (BDD) electrodes. Several studies have focused on selective removal of trace pollutants in a complex matrix. These studies have shown the possibility of removing target pollutants with relatively low energy consumption. It can be concluded that enhancement of treatment performance of the present technologies will contribute to a wider application of electrochemical processes in water and wastewater treatment.

Keywords: electrochemical, organic contaminants, anodic oxidation, electropolymerization, reduction, disinfection, sustainable development

INTRODUCTION

In recent years, increasing awareness of the potential risks of contaminants present in water bodies has led to a number of scientific studies and development of industrial processes. Because of the extremely diverse features of industrial wastewater, which usually contains a complex mixture of

organic and inorganic contaminants, the treatment processes are usually chosen based on the nature and concentration of pollutants [1,2]. **Fig. 1** shows a comparison of various treatment processes based on the chemical oxygen demand (COD) reduction capacity. The biological processes show more advantages in terms of long-term treatment with the lowest operating cost; however, the tolerance of microorganisms

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Received: March 31, 2015, Accepted: October 18, 2015, Published online: April 10, 2016

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Fig. 1 Suitability of water treatment technologies based on influent COD concentration (modified from Sires et al. [2] and Andreozzi et al. [59]).

to highly toxic contaminants, limited range of pH for operation, or reappearance of refractory by-products are major drawbacks. Incineration and chemical oxidation are able to eliminate a high load of contaminants, but they pose serious emission problems or generate other toxic compounds [2].

Electrochemical processes involve chemical reactions caused by interactions between electrodes and chemicals. Advanced oxidation processes (AOPs) generally employ strong oxidizing species such as $\text{H}_2\text{O}/\cdot\text{OH}$ (hydroxyl radicals, 2.80 V vs. SHE), O_2/O_3 (ozone, 2.07 V vs. SHE), $\text{SO}_4^{2-}/\text{S}_2\text{O}_8^{2-}$ (peroxodisulfate, 2.01 V vs. SHE) to decompose organic contaminants [3]. Depending on the electrode materials, degradation of organic contaminants can occur in heterogeneous or homogeneous states. In this study, we emphasize the developmental trends of electrochemical technologies, and their applications and recent developments in water purification.

Trends in electrochemical processes

The earliest application of electrochemical technology in water treatment was reported in the United Kingdom in 1889, a century after the first use of electricity to treat water. In 1946, electrocoagulation was first applied to treat drinking water in the US [3]. Electrochemical oxidation of cyanide, phenols, and thiocyanates was introduced in 1971 [4]. **Fig. 2** shows the trends of scientific contributions in electrochemical technology and sustainability concerns in the field of water treatment. The data represent the percentage of annual publications divided by the total acquired data from 1990

to 2013 from the Web of Science™ (www.webofknowledge.com).

Figure 2 shows the development of electrochemical technology and sustainability concept in the field of water treatment during the last 29 years. It is noted that a gradual developmental trend in electrochemical technology had begun from 1995. Previously, a series of studies on electrochemical oxidation of phenol conducted between 1991 and 1995 have been cited a great number of times (427) [5,6]. In the last decade, the number of studies on water treatment, electrochemical processes, and sustainability concerns has increased dramatically. The percentage of annual publications on electrochemical processes has increased by a factor of about two between 2004 and 2012. This indicates the potential for future development of electrochemical processes in water and wastewater treatment.

Sharing attention in the field of water research, public awareness on sustainability has increased remarkably in the last decade. The term “wastewater” was recently redefined as “a used resource” rather than “a waste,” and it can be either reused for other purposes or recycled for the same purpose through proper management to achieve sustainable use and treatment of wastewater [7]. It was reported that the nutrients can be recovered from wastewater electrochemically through phosphorus removal and hydroxyapatite phosphate recovery [8] or through sustainable removal of ammonia by an electrochemically regenerated ion exchange process [9].

As reported in the literature, electrochemical processes were categorized into oxidation, reduction, disinfection,

Fig. 2 Development of electrochemical technologies for water treatment. The data represent percentage of annual publications divided by the total acquired data in each field from 1995 to June 2015, from Web of Science™.

Fig. 3 Trends in electrochemical processes for water treatment.

combined processes, and other electrochemical reactions. The data were acquired with the combined keywords “electrochemical oxidation process” or “electrochemical reduction process,” and so on with “water treatment.” The other electrochemical reactions are those included in electro-Fenton reaction, electrochemical catalysis, electrocoagulation processes, etc. **Fig. 3** shows the trend of annual published papers on electrochemical processes between 1990 and 2012. As shown, electrochemical oxidation and reduction processes are the dominant treatments. The number of annual publications on oxidation processes has increased significantly by about a factor of three in 2012 (232 papers) compared with those in 2004 (76 papers). Recently, the electrochemical disinfection process has been applied for inactivation of

bacteria in water.

The suitability of electrochemical oxidation processes has been examined with wastewaters containing various contaminants/ingredients such as dyes and dye effluent (acid black 194, acid orange 7, gold yellow, indigo carmine, industrial dye effluent, methyl orange, orange II, reactive orange 4, reactive black 8, reactive blue 19/194/221, reactive red 120/195/198), pesticides and herbicides (atrazine, carbaryl, dichlorvos, glyphosate), phenolic compounds (phenol, benzoic acid, chlorinated phenols, nitrophenols), pharmaceuticals and personal care products (PPCPs)/antibiotics (acetaminophen, ketoprofen, metronidazole, ofloxacin, lincomycin, sulfamethoxazole, tetracycline (TC), paracetamol), and endocrine disruptors (estrone (E1), 17 β -estradiol (E2),

Fig. 4 Variables affecting the rate of an electrochemical reaction (adapted from Bard and Faulkner [60]).

17 α -ethinyl estradiol (EE2), estriol (E3), nonylphenol (NP)) [10]. The aims of these studies were to investigate the operating conditions such as supporting electrolytes, current efficiency, pH, and utilization of electrode material for high removal performance.

In addition, electrochemical technology has been applied to evaluate conventional water quality parameters (COD, biochemical oxygen demand (BOD), and suspended solids (SS)), nutrients (nitrogen, phosphorus, and phosphate), resource recovery and recycling. In practice, the application of electrochemical processes for advanced treatment of water has attracted great attention because it is a clean technology, and shows high treatment performance and less by-product accumulation.

ELECTROCHEMICAL PROCESSES

Electrochemical advanced oxidation process (EAOP)

In electrochemistry, the electrolytic cell performance depends on a number of parameters. **Fig. 4** shows the best-studied parameters such as electrode materials, solution characteristics, mass transfer, and electrical variables. Development of electrochemical technology has focused on the configuration of the electrolytic cell through modification of the electrode (i.e., multianode, granular anode, dimensionally stable electrodes, carbon fiber, etc.), and enhancement of removal performance using highly adsorptive material for electrochemical decomposition.

Mechanism of the electrochemical oxidation of organics

Electrochemical oxidation of organic contaminants occurs through two different mechanisms. An indirect electrochemical oxidation generally involves electrogeneration of a strong oxidizing agent on the anode surface that subsequently degrades the pollutants in bulk solution [11]. The most common indirect electrochemical studies focus on the oxidation of chloride ions on anodes because of their availability in wastewater. Other common oxidants that can also be electrogenerated are hydrogen peroxide (H₂O₂) [12] and peroxodisulfuric acid (H₂S₂O₈) [13]. Metal catalytic mediators, such as Co³⁺, Fe²⁺, and Fe³⁺, are employed in electro-Fenton (Fenton-like) reactions. However, this process requires an additional separation step that limits its application in practice [11].

Direct electrochemical oxidation of organic pollutants generally occurs on the anode through the generation of physisorbed “active oxygen” (*OH) or chemisorbed “active oxygen” (oxygen in an oxide lattice, MO_{x+1}) [5,14]. This process is called “anodic oxidation” or “direct oxidation” of organic pollutants. In practice, a number of studies have focused on the use of highly active electrodes such as BDD, graphite carbon or Ebonex. **Fig. 5** shows the fundamental mechanism firstly proposed by Comninellis [5].

In the first step, on the metal oxide anode (MO_x), H₂O (or OH⁻) is discharged to produce *OH that are adsorbed on the anode, as shown in the following equation:

In the second step, the adsorbed *OH interact with the

Fig. 5 Mechanistic scheme of electrochemical mineralization/conversion of organics with simultaneous oxygen evolution. 1) Formation of $\bullet\text{OH}$; 2) transition of O from $\bullet\text{OH}$ to the lattice of the oxide anode; 3) and 4) production of dioxygen in the absence of oxidizable organics; 5) electrochemical mineralization/combustion of organic compounds through $\bullet\text{OH}$, 6) electrochemical conversion of organic compounds (R). (adapted from Comninellis [5]).

oxygen already present in the MO_x to form a so-called higher oxide MO_{x+1} as shown in equation (2):

At any time, the anode surface exhibits two states of “active oxygen”: physisorbed “active oxygen” ($\bullet\text{OH}$) and chemisorbed “active oxygen” MO_{x+1} .

In the absence of oxidizable organics, the physisorbed and chemisorbed “active oxygen” produce dioxygen according to equations (3) and (4):

However, in the presence of oxidizable organics (R), the following reactions can occur:

Hydroxyl radicals can decompose most organic chemicals to carbon dioxide (CO_2). Equation (5) suggests that organic contaminants can be completely decomposed via electron transfer on the anode surface. On the other hand, the organic contaminants (R) can be selectively converted to RO. After the contaminants are degraded/converted, the electrode returns to its original state, MO_x . In the EAOP, electrochemical mineralization and electrochemical polymerization of

organic contaminants have been intensively studied recently.

The following section summarizes recent developments in the EAOP to treat organic contaminants.

Electrochemical oxidation of organic contaminants

Table 1 summarizes the electrochemical oxidation of various toxic contaminants using different anode materials. The most important parameters, such as the initial concentration of pollutants (C_0), current density (I), current efficiency (CE), and removal efficiency (RE), are listed. The initial concentration can be represented as COD, total organic carbon (TOC), or concentration of a certain contaminant. As shown, a wide range of initial concentrations from 0.01 to 100 $\mu\text{g/L}$ of various emergent endocrine disruptors [15] up to 6 g/L of tannic acid (TA) [16] were observed. The range of electrochemical advanced oxidation applications could be further extended because of the selective removal of organic contaminants.

Table 1 shows the complete removal of pollutants on metal oxide anodes. Remarkable development has been achieved in the fabrication of mixed metal oxides for recalcitrant pollutants in wastewater because those chemicals cannot be removed effectively in conventional treatments [10]. The REs of 100% for 10 – 90 mg/L 4-chlorophenol (4-CP) and 1500 mg/L TA were achieved using PbO_2 anodes [17]. Recently, mixed metal oxide materials coated over a titanium substrate have shown significant enhancement in the stability and conductivity of the electrode.

In the final treatment of synthetic tannery wastewater using the Ti/ PbO_2 electrode, Panniza and Cerisola [16] reported that complete removal of 1,500 mg/L TA (and 6,000 mg/L COD) was achieved within 2 h (5 h for COD) at 600 A/m^2 in a solution containing 7 g/L NaCl and 8 g/L Na_2SO_4 as electrolyte. The CE was observed to be in the range of 10% to 31%. The complete removal of TA is a consequence of $\bullet\text{OH}$ formation on the surface of the anode (Eqs. (7) and (8)). The PbO_2 electrode exhibits a high overpotential for oxygen evolution; therefore, TA is also removed by electroactive chloride ions.

The novel non-metal electrodes have received extreme attention due to their active sites and high specific surface area. Nossol et al. [18] reported the effectiveness of carbon nanotube (CNT)/Prussian blue (PB) nanocomposite film for water treatment. The highest CE of 99% was reported for the

Table 1 Electrochemical oxidation of organic contaminants.

Electrode	Pollutant	C ₀ (mg/L)	I (A/m ²)	CE (%)	RE (%)	Highlight & Comments	References
Modified metal oxide electrode, Dimensional stable anode (DSA), Ti substrate							
PbO ₂	Textile wastewater	470 [COD] 0.11 [PhOH]	P. (5.6 V)	–	59 70	Hydraulic retention time (2 and 4 h), pH (6 and 9)	Mukimin et al. [37]
	Real textile wastewater	550 [COD]	750	10–50	95	0.1 M Na ₂ SO ₄ , pH (3, 7, 11), T: (25°C and 45°C)	Aquino et al. [38]
	4-CP	10–90	300	1.0–3.5	100	CNT-modified (CNT–PbO ₂)	Duan et al. [17]
	Methyl Red	220 [COD]	400	2.5	≈100	Flow rate: 180 l/h; pH 3	Panizza and Cerisola [39]
	TA	1500 [TA] 6000 [COD]	600	16–31	100	40 kW h/m ³ [TA], 120 kW h/m ³ [COD]	Panizza and Cerisola [16]
IrO ₂	OTC	100	200	–	83	1000 mg/L Na ₂ SO ₄	Kitazono et al. [20]
	TC	100	200	–	99.4	1000 mg/L Na ₂ SO ₄	Miyata et al. [40]
SnO ₂	EE2	0.5–10	100	0.8–20	96.5	T: 20°C; pH 6.1	Feng et al. [41]
RuO ₂	TA	1500	600	16–31	100	40 kW h/m ³ [TA], 120 kW h/m ³ [COD]	Panizza and Cerisola [16]
SnO ₂ –Sb	Pentachlorophenol	100	100	–	99.8	10 mM Na ₂ SO ₄	Niu et al. [42]
Ru _{0.3} Ti _{0.7} O ₂	Atrazine	20	600	–	100	TOC removal: 5.3 to 46%	Malpass et al. [43]
Sn–Sb–Ni–O	4-CP	1028	31	–	100	TOC removal: 99%	Wang et al. [44]
Graphite carbon, BDD, Ebonex, and Pt anodes							
Graphite carbon	BPA	500	120	–	78.3	0.05 M NaCl, pH 5.0	Govindaraj et al. [45]
	Bovine serum albumin	2500	240	3.0–9.7	91.02	EC: 0.8–2.0 kW h/kg COD	Sundarapandiyan et al. [46]
BDD (Boron-doped diamond)	Oxalic/oxamic acid	2.08 mM	333	12–27	≈100	0.05 M Na ₂ SO ₄ , 0.5 mM Fe ²⁺ , pH 3.0	Garcia-Segura and Brillas [47]
	Tannery wastewater	2370 [COD] 756 [TOC]	250– 1000	99	70–90 78– 100	0.1 M Na ₂ SO ₄ , pH 2.4	Costa et al. [19]
	Chlorobenzene (CB)	50	170	–	94.3	0.05 M Na ₂ SO ₄ as electrolyte	Liu et al. [48]
	E2	0.5 [E2]	500		100	E2 and BPA were completely removed within 0.5 h and 5 h, respectively.	Yoshihara and Murugananthan [49]
	BPA	20 [BPA]	357		100		
	E2	0.25	250	1–2	100	0.1 M Na ₂ SO ₄ ; pH 6; T: 25°C	Murugananthan et al. [50]
CNT/PB	Methyl Orange	2.5×10 ^{−7} M	P. mode		96–98	0.1 M KCl and 1.0 M H ₂ O ₂ .	Nossol et al. [18]
Ebonex (Ti ₄ O ₇)	p-Substituted Phenol	25 mM p-nitrophenol	35	11.8	30.2	Operation in LSV mode	Zaky and Chaplin [51]
Pt	CB	50	170	–	85.2	0.05 M Na ₂ SO ₄ as electrolyte	Liu et al. [48]
	DCP, BPA, NP, E2	0.08–0.14	0.0002	90–96	96	10 mM Na ₂ SO ₄ as electrolyte	Sakakibara et al. [52]
	Reactive Orange 91/ Red 184/Blue 182/ Black 5	5 × 10 ^{−4} M [each dye]	P. (12 V)	–	94.4	0.02 M NaCl and 0.02 M Na ₂ SO ₄ as electrolyte	Sakalis et al. [53]

Table 1 Electrochemical oxidation of organic contaminants. (*cont.* -polymerization)

Electrode	Pollutant	C ₀ (mmol/L)	Oxidative potential (V)	Highlight & Comments	References
Glassy carbon	E1	0.01	0.45–0.8 (Ag/AgCl)	0.01 M Na ₂ SO ₄ ; Scan rate: 100 mV/s, removal: 93%	Cong et al. [21]
	Allylamine	10	≈1.6 (Ag/AgCl)	Scan rate: 10 mV/s; 0.1 M Bu ₄ NBF ₄ as electrolyte	Bardini et al. [54]
304 stainless steel	Phenol	2.0	1.1–1.3 (SCE)	0.1 M Na ₂ SO ₄ ; Scan rate: 50 mV/s; oxygen evolution 1.3 V	Zhang et al. [55]
	o-toluidine	100	≈1.2 (SCE)	0.1 M sodium salicylate, oxygen evolution: 1.8 V (SCE), the thickness on SS: 4–21 μm (at 5–25 cycles)	Shinde and Patil [56]
Ta/PbO ₂	Phenol	0.5–100	1.041 (SCE)	1 M H ₂ SO ₄ ; T: 25°C; scan rate: 200 mV/s	Tahar and Savall [57]
Carbon fiber	BPA, Bisphenol S (BPS) or Diphenolic acid (DPA)	1.0	0.65–0.97 (Ag/AgCl)	0.1 M Na ₂ SO ₄ ; pH 5.8; scan rate: 15 mV/s	Kuramitz et al. [58]

Table 2 Electrochemical reduction of pollutants or organic and inorganic contaminants.

Electrode	Pollutant	C ₀ (mg/L)	I (A/m ²)	CE (%)	RE (%)	Highlight & Comments	References
Glassy carbon	Methyl triclosan	1515	P (–2.17 V) –		43	In DMF solvent	Peverly et al. [26]
	Methyl (2-Bromo-methyl) benzoate	559	P (–1.85V) (SCE)			In DMF solvent	Allen et al. [27]
Pd	Haloacetic acids (HAAS)	0.12–0.6	3.0		50	At 6 A/m ² , HAAS diffusion became the primary rate-limiting step	Zhao et al. [25]
	2,4-DCP	100	0.8–66		93.2	Electrodeposition current (37.5 A/m ²), Conc. of Pd ²⁺ (22.5 mM)	Sun et al. [24]
Carbon felt	BrO ₃ [–]	0.1 mM	40	0.09–0.17	100	High removal was achieved within 15 min at pH 2.2	Kishimoto and Matsuda [28]
Metals*	BrO ₃ [–]	0.77 μM	0.18	0.11		BrO ₃ [–] removal (40%) was achieved with 1.7 min contact time.	Kishimoto et al. [29]

* Ni, Cu, Al, Ti, Fe, Pb, Zn, Ti/Pt, brass, stainless steel, and BDD were used. In case of Cu electrode, the CE achieved 8.5% without pH control.

treatment of tannery wastewater containing 73 mg/L phenol, 2370 mg/L COD, and 756 mg/L TOC with 0.1 M Na₂SO₄ using Si/BDD anode [19]. In chloride ion-free solution, the BDD anode was found to exhibit high removal performance with excellent CE. The BDD electrode exhibits very low adsorption affinity for •OH, resulting in a very high chemical reactivity of the •OH for the oxidation of organic compounds

[19]. The complete removal of oxalic/oxamic acid, E2, and bisphenol A (BPA) was achieved using BDD anodes in 0.05 to 0.1 M Na₂SO₄ as electrolyte.

Selective removal of toxic chemicals has shown a potential development. Kitazono et al. [20] reported a selective electrochemical degradation of TC antibiotics in the raw milk of cows using Ti/IrO₂ or Ti/PbO₂ anodes. When using

the NaCl electrolyte, oxytetracycline (OTC) was degraded selectively because the rate constant k_{OTC} was 11.6 times higher than k_{COD} . This study demonstrated the applicability of this method for the removal of antibiotic residues in raw milk on the laboratory scale. Recently, Sakakibara et al. [15] have demonstrated selective removal of phenolic compounds at a high removal rate with extremely low energy consumption using a packed-bed granular Pt electrode reactor. Cong et al. [21] have further developed the electrolytic reactor consisting of a granular glassy carbon electrode for removal of natural and synthetic estrogen in wastewater through electropolymerization. The mechanism of selective oxidation of various phenolic compounds was proposed. Cong and Sakakibara [22] reported that endocrine disruptors such as E1, E2, EE2, were oxidized in the range of 0.4 – 0.8 V vs Ag/AgCl and confirmed that EE2 was selectively removed in the presence of co-substances. Similar approaches are shown in **Table 1**. These studies focus on the conversion of phenolic compounds to a less harmful product or accumulation before final deposition.

Electrochemical advanced reduction processes

Advanced reduction processes usually involve different conventional activation methods, such as ultraviolet (UV), electron beam (E-beam), microwave energy, or reducing agents such as sulfur dioxide radical anions (SO_2^-). These methods have shown good ability to eliminate nitrate ions, perchlorate ions, dichlorophenol (DCP), and perfluorooctanoic acid (PFOA) [23]. The electrochemical reduction process is based on electrocatalytic hydrogenolysis, in which chemisorbed hydrogen atoms generated on the cathode by electrolysis of water remove the halogen atoms of the contaminants. The dehalogenation mechanism can be explained by the following equations (9) – (12) [24]:

The first step in the dehalogenation process involves 1) the chemisorption of H_{ads} and halogenated compounds (R-X) onto the metal surface (M) (Eqs. (9) and (10)) and 2) the exchange between H_{ads} and halogen atoms. It was reported that very high RE was achieved on palladium cathodes because of their good chemisorption capacity for H_{ads} [24,25].

Recent studies have been performed on the possibility for electrochemical reduction of methyl triclosan and methyl (2-bromomethyl) benzoate using glassy carbon cathodes in dimethylformamide (DMF) solvent [26,27] (**Table 2**). The study shows that the direct reduction of selected organic halides involving carbanion intermediates could lead to the formation of cyclic products via the addition-elimination reaction at carbonyl group [27]. Therefore, the toxicity of the original compound is eliminated.

As a disinfection by-product in water supplies, bromate (BrO_3^-) was recognized as potentially toxic for human health [28,29]. Electrochemical treatment of BrO_3^- in contaminated tap water was conducted in flow mode at different contact times. It was reported that higher terminal potential and longer contact time resulted in higher BrO_3^- removal rate. A decrease in BrO_3^- concentration was from 100 $\mu\text{g/L}$ to 48 $\mu\text{g/L}$ at a terminal potential of 7.0 V and contact time of 9.2 s, corresponding to about 9.6 to 5.1 kWh for the removal of 1.0 g of BrO_3^- . Therefore, electrochemical reduction of BrO_3^- has the potential for application to water and wastewater treatment because of its rapid reduction rate [28,29].

Disinfection process

Electrochemical disinfection has been applied to secondary wastewater treatment plant effluent [30], paper mill bacteria [31], bacteria and bacteriophages [32]. At the current development stage, electrochemical disinfection process employs two approaches that are (1) water electrolysed separately is added to water containing microorganisms and (2) water containing microorganisms is pumped through the oxidation cell and is electrolysed there [33]. To date, the inactivation of *Escherichia coli* or *Pseudomonas aeruginosa* has been investigated using BDD or Pt electrodes [33–35]. Griessler et al. [33] reported that current supply mode significantly affects the disinfection of microorganisms. For example, a direct current (DC) showed a stronger microbicidal effect than alternating current (AC), corresponding to reductions between 0.9 log and 4.0 log compared to 0.4 log and 2.9 log, respectively. Perez et al. [30] reported that 99.5% removal of *E. coli* was achieved within 60 min at a current density of 800 A/m^2 in the presence of 60 mg/L of chloride ion (Cl^-) using a BDD electrode. In general, the mechanisms proposed include oxidative stress, electrochemical generation of oxidants, irreversible permeabilization of cell membranes, and electrochemical oxidation of vital cellular constituents [32]. These studies showed effective inactivation of microorganisms after exposure to an electric current or electric field.

Fig. 6 Combination of electro-oxidation treatment with other processes (adapted from Anglada et al. [11]).

Combined processes

In order to enhance the treatment performance, electrochemical oxidation has been successfully applied in combination with other processes. Anglada et al. [11] summarized the main combinations as shown in **Fig. 6**. The most common combined electrochemical process is an integration of electro-oxidation with biological processes and vice versa (1 and 2). In flow 1, at the first stage, electrochemical oxidation degrades pollutants or converts them to biodegradable substances, and then biological processes subsequently degrade them to the desired level. The system has the advantages of both reduced operating cost and shorter retention time [11]. This combined process is usually applied in the treatment of refractory pollutants or landfill wastewater that contains a high COD level.

In contrast, electro-oxidation was applied as a polishing step (2) for achieving complete mineralization of pollutants in the effluent from a biological treatment. Panizza et al. [36] reported that integration of a BDD electrode reactor with a biofilm airlift suspension reactor could reduce the power consumption by about 61 – 80 kWh/m³. Similarly, the electrochemical process was used as a polishing step in cases of post-treatments of membrane bioreactors (MBRs) (3), MBR-reverse osmosis (RO) (4), chemical coagulation followed by electro-oxidation, MBR (5), and electroenzymatic treatment (6) [11].

CONCLUSIONS

This study highlights the recent developments of electrochemical technologies in water and wastewater treatment.

Recent studies have made great advances in the investigation and optimization of EAOPs in the treatment of various organic pollutants, reduction of halogenated contaminants, and disinfection of microorganisms. In addition, electrochemical oxidation processes have been combined with other treatment methods to enable their practical application. It was observed that excellent electro-catalytic electrodes, such as mixed metal oxides (PbO₂, SnO₂, Ti/RuO₂, etc.), Pt, and BDD electrodes achieved almost complete removal of contaminants, as well as their by-products. In addition, some studies have focused on the concept of selective removal of trace pollutants in a complex matrix. These studies have shown the possibility of removing the target pollutants with relatively low energy consumption. Although many new findings in electrochemical technology have been reported as reviewed in this paper, it is considered that electrodes are still expensive and their long-term performances have not been clearly understood. Therefore, further studies on low-cost electrodes with long-term stability are needed to be a feasible alternative to conventional water and wastewater treatment technologies.

ACKNOWLEDGMENTS

This study was supported by a fund from Research Committee on Electrochemical Technology, Japan Society on Water Environment (JSWE).

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