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Effect of anions on the removal of bisphenol A in wastewater by electro-oxidation process

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ABSTRACT

Bisphenol A (BPA), an endocrine-disrupting chemical, exists widely in natural waters. Advanced oxidation processes, which are based on the generation of hydroxyl radicals (·OH), are one of the promising techniques for the treatment of BPA. The goal of the present study was to investigate the effect of nitrate, bicarbonate, and carbonate in wastewater treatment plant (WWTP) effluent on the removal of bisphenol A (BPA) by bench-scale electro oxidation (EO) process using DSA-Ti electrode. The removal efficiency of BPA against scavenger effect of nitrate and alkalinity was characterized under a variety of reaction time and current densities. In the current density of 3 mA/cm^2, the BPA removal efficiencies showed 40% within 20 min in the presence of nitrate, whereas the BPA removal efficiency was close to 100% in the absence of nitrate. Under the same condition, 42 and 80% of BPA was removed in the presence of bicarbonate and carbonate, respectively. The results indicated that the EO process is a promising technology to remove BPA effectively in WWTPS. However, since the efficiencies of the EO process were remarkably reduced when the concentrations of anions in WWTPs increased, electrochemical technology such as EO process could be used only to oxidize the non-biodegradable compounds during the WWTP process.

Keywords: Bisphenol A; Electrochemical oxidation; Scavenger; Nitrate; Bicarbonate; Carbonate

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1. Introduction

Endocrine-disrupting compounds (EDCs) are exogenous environmental chemicals altering the hormone dynamics as a receptor agonist [1]. Numerous EDCs are ubiquitous in aquatic environments including surface water, ground water supplies, and sewage effluent [2]. Bisphenol A [2,2-bis(4-hydroxyphenyl)propane; BPA] is a well-known endocrine disrupter, and its accumulation can cause harmful

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effects on animal and human health in very low concentrations, particularly at sensitive developmental stages to subsequent generations [3]. This compound is a building block that produces polycarbonate plastic and resin. Thus, BPA is mainly released into the environment either through industrial wastewater treatment plants (WWTPs) or landfill leachates (via hydrolysis of BPA from plastics). BPA is known to quickly biodegrade and to adsorb to suspended solids and sediment in water. Bisphenol A was selected as a trace micropollutant for this study due to its broad abundance in wastewater. There are several reports that BPA was detected at considerably levels ranging from 0.44 to 53 nmol/L in surface water [4] and 5.7 to 75 mmol/L in landfill leachates [5]. Although the potential risk of untreated BPA released from WWTPs was already reported, most of WWTPS are not designed to remove BPA during the treatment process. Thus, the development of an additional treatment process is necessary to reduce BPA release into the environment [6].

The removal process of BPA in WWTPs can be classified into three categories: physical removal, biological treatment, and advanced oxidation processes (AOPs) [7]. AOPs are widely used as potentially powerful methods capable of transforming the pollutants into harmless substances [8]. AOPs are based on the generation of highly reactive non-selective transient oxidizing species such as the hydroxyl radicals which were identified as the dominant oxidizing species [9]. Generation of hydroxyl radicals is commonly accelerated by combining some oxidizing agents such as ozone (O_3), hydrogen peroxide (H_2O_2), UV radiation, ferrous and ferric salts (Fe^{2+} and Fe^{3+}), catalysts such as TiO_2 and electrochemical treatment [10].

Electrochemical treatment is becoming a promising technology for AOPs, because it offers high removal efficiencies in compact reactors with simple equipment for control and operation of the process. During the last few years, electrochemical treatment have been developed and used as alternative options for the remediation of water and wastewater mainly due to their advantages, e.g. environmental compatibility, versatility, high-energy efficiency, amenability of automation and safety, and cost effectiveness. Electrochemical technologies include electro coagulation (EC), electro oxidation (EO), and electro reduction (ER) [11]. Electro-oxidation may occur either by direct oxidation by hydroxyl radicals produced on anodes' surface [12] or by an indirect process where oxidants like chlorine, hypochlorous acid and hypochlorite [13–19], or hydrogen peroxide/ozone [20–23] are formed at electrodes by following reactions (1)–(7):

$$2Cl^- \rightarrow Cl_2 + 2e^- \tag{1}$$

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \tag{2}$$

$$HOCl \rightarrow H^+ + OCl^- \tag{3}$$

$$H_2O \rightarrow {}^{\cdot}OH + H^+ + e^- \tag{4}$$

$$2{}^{\cdot}OH \rightarrow H_2O_2 \tag{5}$$

$$H_2O_2 \rightarrow O_2 + 2H^+ + 2e^- \tag{6}$$

$$O_2 + {}^{\cdot}O \rightarrow O_3 \tag{7}$$

Indirect oxidation occurs when active chlorine species are generated from chloride ions anodically to destroy pollutants. In so-called mediated electro-oxidation, e.g. metal ions are oxidized on an anode from a stable state to a reactive high valence state which in turn attack pollutants directly and may also produce hydroxyl free radicals to promote degradation [24]. In direct electro-oxidation (anodic oxidation), oxidation of pollutants in the electrolytic cell occurs at the electrode surface or by direct electron transfer to the anode [25]. Also, powerful oxidants called reactive oxygen species can be formed from water discharge at the anode. These are hydroxyl radicals and oxygen in the oxide lattice [25]. Anodic oxidation has some benefits over indirect oxidation such as having no need to add chemicals to treated solution and producing less secondary pollution [26]. Electro-oxidation was investigated to treat non-biodegradable wastewater, such as dye wastewater [27], tannery wastewater [28], and landfill leachate [29]. Yue et al. investigated the treatment of dye wastewater by EO process, in the study, about 97% of COD was removed in EO process in the condition of the 70 mA/cm^2 of current density [27]. In the study of Szpyrkowicz et al. [28], the removal efficiency of COD, ammonia, Cr, and sulfides from tannery wastewater was investigated with several kinds of DSA electrodes. And the results were satisfactory with all anodes. Cabeza et al. [29] studied for the removal of ammonium from landfill leachate using the EO process, and 100% of ammonium was removed using boron-doped diamond (BDD) electrode. There are a few studies on the BPA removal using EO process. In the study of Cui et al. [30], electrochemical degradation of BPA by different anodes was studied. Four anode materials, Pt, Ti/RuO_2, Ti/Sb–SnO_2, and Ti/BDD anodes were compared for performance on the removal of BPA, and characterized the chemical properties of the anodes. Boscoletto et al. [31] studied EO treatment for the BPA removal, but focused on the degradation of BPA and formation of intermediates. During the last few decades, research works have been focused on the efficiency in oxidizing various pollutants on different electrodes, improvement in the electro-catalytic activity and electrochemical stability of electrode materials, investigation into factors affecting the process performance, and exploration of the mechanisms and kinetics of pollutant degradation [31,32]. The efficiency of the EO process largely depends on cell configuration, electrode material, electrolyte composition, the microorganism or pollutant, and other experimental parameters, such as current density and the temperature of the treated water [26]. On the other hands, high-energy consumption is the main advantage of this technology. Some recent researchers studied the energy consumption of this process, and provided the model equation of EO process [33–36].

Hydroxyl radicals can oxidize a broad range of organic pollutants quickly and non-selectively [2]. A drawback resulting from such a high degree of reactivity is that the hydroxyl also reacts with "non-target" materials in solution such as nitrate, carbonate, bicarbonate, chloride, and humic substances, all of which are referred to as radical "scavengers." There are many water quality parameters that may impact the effectiveness of any particular AOP. For example, nearly all dissolved organic compounds present in the source water will serve to reduce the removal efficiency of the target compound by consuming ·OH [37].

The goal of the present study was to investigate the effect of nitrate and alkalinity (bicarbonate and carbonate) on the removal of BPA by conducting a bench-scale EO process using DSA-Ti electrode under a variety of reaction time, current density, and initial concentrations of nitrate and alkalinity. The energy consumption of electro-oxidation of BPA with addition of anions was provided also. This study can provide the referable information about the proper application of electrolysis using DSA-Ti electrode for the removal of BPA in aqueous solution containing nitrate and alkalinity.

2. Materials and methods

2.1. Experimental method

The EO system is made up with a reactor, electrodes, and DC power supply (Fig. 1). All tests were conducted using a DC power supply (Unicorn tech., UDP-1501) in a constant current mode. The power range of DC power supply was 0–150 V of voltage and 0–1 A of current. The electrodes with 130 cm^2 of surface area were placed vertically in a 1 L reactor. The DSA (dimensionally stable anode) electrode made with Ti/IrO$_2$ and Ti cathode was used in this study. The plate type electrodes were used in the experiments, and distance between anode and cathode was 1 cm. The tests were carried out at current densities of 3 and 5 mA/m^2. In the preliminary experiment, the tests in the absence of anions were conducted under 1, 3, 5, and 8 mA/cm^2 of current density to define removal tendency of BPA. Current densities of 3, 5 mA/cm^2 were selected to experimental variables in main experiments in that it showed appropriate removal rate to investigate scavenging effect with addition of anions.

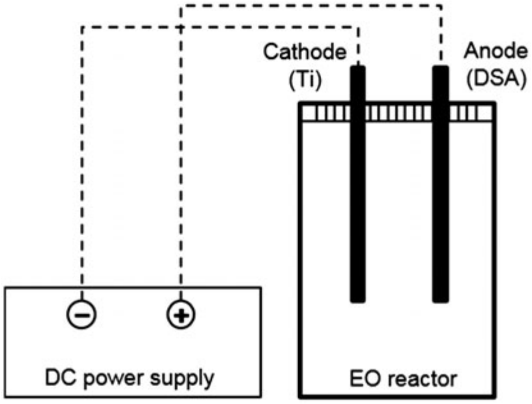

Fig. 1. Schematic diagram of the EO system.

The artificial wastewater contained 10 mg/L BPA followed the procedures from the previous study (2010) [38]. Two kinds of tests were conducted to justify the scavenging effect of anions (Table 1). In the first study, we evaluated the scavenging effect of anions (nitrate, bicarbonate, and carbonate) as mole concentrations. The concentration of nitrate, bicarbonate, and carbonate was 0, 0.1, and 0.35 mmol, respectively. The test on the basis of the composition of WWTP effluent was also conducted. All concentrations of anions are followed as the concentration of WWTP effluent in Korea [39] (Table 2). The concentrations of anions were 5 mg NO_3-N/L and 159 mg as $CaCO_3$/L of HCO_3^-, 169 mg as $CaCO_3$/L of HCO_3^-. In the test with no anions, 500 mg/L NaCl were added in the wastewater as the electrolyte, the initial conductivity was about 1 mS/cm^2. In the test with anions, any electrolyte was not added to the wastewater. In that case, the conductivity was in the range of 0.05–0.1 mS/cm^2. All the solvents and reagents used in this study, including bisphenol A (99%, Sigma-Aldrich, USA), $NaNO_3$ (99%, Samchun, Korea), $NaHCO_3$ (99%, Samchun, Korea), and Na_2CO_3 (99%, Samchun, Korea) were of analytical grade.

Table 1
Experimental conditions

Experiments	Addition of anions	Current density (mA/cm^2)
Test under mole concentration	None	3
	0, 0.1, 0.35 mmol of nitrate	3
	0, 0.1, 0.35 mmol of bicarbonate	3
	0, 0.1, 0.35 mmol of carbonate	3
Test under concentration of WWTP effluent	None	3, 5
	5 mg of NO_3^--N/L of nitrate	3, 5
	159 mg as $CaCO_3$/L of bicarbonate	3, 5
	169 mg as $CaCO_3$/L of carbonate	3, 5

Table 2
Characteristics of the wastewater treatment plant effluent in Korea

Parameter	Value
CODcr (mg/L)	18
BOD_5 (mg/L)	4
TOC (mg/L)	10.5
pH	6.8–7.2
NO_3^--N (mg/L)	5
HCO_3^- (mg $CaCO_3$/L)	159
CO_3^{2-} (mg $CaCO_3$/L)	169

2.2. Analytical method

BPA was analyzed by High-Performance Liquid Chromatography system (Infinity 1290 liquid chromatography, Agilent Technology) with a UV/vis detector. An Eclipse Plus C18 column (2.1 × 100 mm, 1.8 μm particle size, Agilent Technology) was used for the separation of BPA. 40% of deionized water and 60% of acetonitrile were used as a binary mobile phase. The flow rate and the injection volume were 0.3 mL/min and 1 μL, respectively. Under these conditions, the separation time was less than 2 min. The samples were injected directly into the chromatograph, after the filtration by a 0.45-μm syringe filter.

3. Results and discussion

3.1. Effect of nitrate on BPA removal

Variation of BPA removal efficiency vs. time in the presence of nitrate is shown in Fig. 2. The scavenger effect of nitrate on BPA removal efficiency has increased by increasing the concentration of nitrate. In these experiments, BPA was completely removed within 20 min, whereas removal efficiencies were 37.7 and 24.2% in the presence of 0.1 and 0.35 mmol of nitrate, respectively. In the absence of nitrate, the efficiencies of BPA removal have increased by increasing treatment time, and reached 100% in 20 min. In 0.1 mmol of nitrate, BPA removal efficiencies were less than 3% in 5 min, and rapidly increased to 91.6% after 30 min. On the other hand, in the 0.35 mmol of nitrate, about 25% of BPA was removed in first 5 min and slightly increased to 42% in 30 min of treatment. These results show that the scavenger effects of nitrate strongly associated with the concentration of nitrate in artificial wastewater.

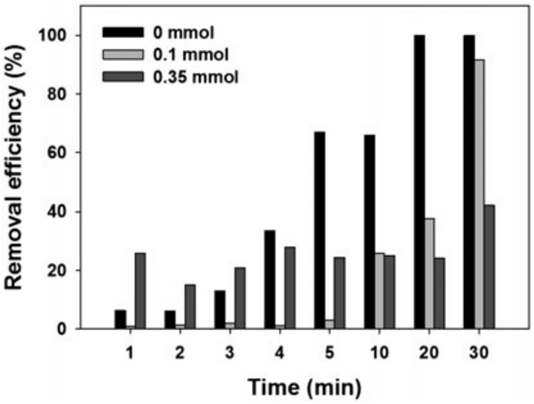

Fig. 2. The removal efficiency (%) of BPA as function of the time in the absence and presence of NO_3^- (initial BPA concentration: 10 mg/L, current density: 3 mA/cm^2).

Drzewicz et al. [40] reported that NO_3^- has no reactivity toward $^{\cdot}OH$. However, it has been reported that NO_3^- could be reduced to NO_2^- when it reacts with the solvated electron (e_{aq}^-) [41], which then could efficiently scavenge $^{\cdot}OH$. In addition to behaving as $^{\cdot}OH$ scavenger, NO_2^- has the ability to scavenge e_{aq}^- and $H^{\cdot}$ as well [42]. Mohamed et al. [43] reported about the reaction equation of nitrite and hydroxyl radicals:

$$NO_3^- + H_2O + 2e^- \rightarrow NO_2^- + 2OH^- \tag{8}$$

$$NO_2^- + {}^{\cdot}OH \rightarrow {}^{\cdot}NO_2 + OH^- \tag{9}$$

3.2. Effect of bicarbonate on BPA removal

Fig. 3 shows BPA removal efficiencies in the presence of 0.1 and 0.35 mmol of bicarbonate. The graph showed that the scavenger effect of bicarbonate is stronger than nitrate in the 0.35 mmol. After 30 min, only 7.5% of BPA was removed in the 0.35 mmol of bicarbonate, while 100% of BPA was removed in the absence of anions, and 88.3% of BPA was removed in 0.1 mmol of bicarbonate. The bicarbonate at 0.1 mmol shows same tendency with nitrate. The concentration of BPA was rapidly decreased after 5 min of treatment and removed 88.3% until 30 min. In the study of Kishimoto et al. [44], the COD removal was strongly inhibited by bicarbonate alkalinity. The HCO_3^- was dissociated into H^+ and CO_3^{2-} ions, which are stronger radical scavengers than HCO_3^-. Bicarbonate reacts readily with the hydroxyl radicals to produce the carbonate radical anion, ${}^{\cdot}CO_3^-$ [45,46], which is also an active species known to participate in aquatic oxidation reactions (Eqs. (10) and (11)):

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \tag{10}$$

$${}^{\cdot}OH + HCO_3^- \rightarrow {}^{\cdot}CO_3^- + H_2O \tag{11}$$

Hoigne and Bader reported that both carbonate and bicarbonate will scavenge hydroxyl radicals to create carbonate radicals which, in turn, react with other organic or inorganic compounds present, albeit at a much slower rate [47].

3.3. Effect of carbonate addition on the BPA removal

To investigate the scavenger effect of carbonate, efficiency of BPA removal in the presence of carbonate was tested. The results are shown in Fig. 4. Generally, BPA removal efficiencies with carbonate show consistent results with addition of bicarbonate.

It is shown that the BPA removal rate has decreased by the addition of carbonate. In 0.1 mmol of carbonate, the removal efficiency was increased after 5 min, whereas 95.6% of BPA was removed after 30 min. The test with carbonate at 0.35 mmol showed a strong scavenger effect and the BPA was removed less than 5% after 30 min of treatment.

In the study of Gultekin and Ince [48], the reaction of ${}^{\cdot}OH$ with CO_3^{2-} generates carbonate radicals (${}^{\cdot}CO_3^-$), which are equally reactive with reducing species in solution (Eq. (12)). Carbonate radicals may react with H_2O_2 to produce other radical species such as peroxy radicals (${}^{\cdot}HO_2$) as shown in Eq. (13), which may contribute to degradation of pollutants by oxidative action, however, at a much slower rate than the reaction of ${}^{\cdot}OH$ [48]:

$${}^{\cdot}OH + CO_3^{2-} \rightarrow OH^- + {}^{\cdot}CO_3^- \tag{12}$$

$$H_2O_2 + {}^{\cdot}CO_3^- \rightarrow HCO_3^- + {}^{\cdot}HO_2 \tag{13}$$

3.4. The comparison of scavenger effect of nitrate and alkalinity on the removal of BPA

Fig. 5 shows the comparison of removal efficiency of BPA after 20 min of treatment with nitrate, bicarbonate, and carbonate. In Figs. 2–4, after 30 min of treatment, the tests under the condition of low

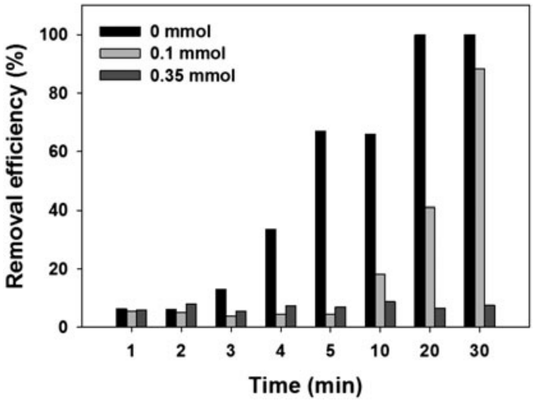

Fig. 3. The removal efficiency (%) of BPA as function of the time in the absence and presence of HCO_3^- (initial BPA concentration: 10 mg/L, current density: 3 mA/cm^2).

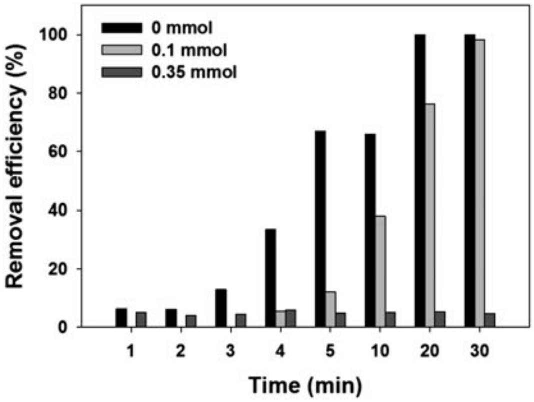

Fig. 4. The removal efficiency (%) of BPA as function of the time in the absence and presence of CO_3^{2-} (initial BPA concentration: 10 mg/L, current density: 3 mA/cm^2).

concentration of anions show about 90% of removal efficiency. The 20-min treatment data were chosen to clearly show scavenging effect of each anion. The graph shows the molecular scavenger effect of the anions. As the concentration of anions increased, the removal efficiencies of each test decreased. It seems that higher concentration of anions caused strong scavenger effect. The previous study shows same tendency. Ghaneian et al. reported that higher concentration of nitrate showed stronger scavenger effect [49]. At the same time, only about 37.7% of BPA was removed in the presence of 0.1 mmol of nitrate, and it was 41.0% of removal efficiency in the presence of 0.1 mmol of bicarbonate. In the case of carbonate, about 91.26% of BPA was removed. In the test with 0.35 mmol of anions, carbonate showed lower BPA removal efficiency than bicarbonate. The difference in scavenging intensity of each anion can be explained by reactivity with OH radical. In the research of Rosenfeldt [50], the carbonate and bicarbonate were classified as inorganic scavengers. They reported that the second-order rate constant with OH radical of bicarbonate and carbonate was 8.5×10^6 and 2.9×10^8 [50]. Reaction rate of carbonate with OH radical is 34 times higher than of bicarbonate under same condition.

3.5. The scavenger effect of nitrate and alkalinity in the WWTP effluent on the removal of BPA

To apply the EO treatment for the BPA removal in the WWTP effluent (WWTP), we applied the exact concentration of municipal WWTP effluent in Wonju, Korea. The tests were performed under various current conditions to maximize field applicability. To investigate the effect of current density on the BPA removal, tests were carried out under 3 and 5 mA/cm^2 of the current density (Fig. 6(a) and (b)). The concentration of each anion follows the characteristics of WWTP effluent in Wonju, Korea. In the test without anions, efficiencies of BPA removal have increased by increasing current density. This finding is consistent with Chen's study [24] that have demonstrate increasing amount of oxidants such as hydroxyl radicals, peroxy radicals, and ozone from electrodes over current density. The higher scavenger effect was obtained in the presence of bicarbonate and carbonate, because the WWTP effluent has a relatively high concentration of bicarbonate and carbonate in comparison with nitrate. Finally, 41.0, 1.6, and 4.4% of BPA was removed in the test with nitrate, bicarbonate, and carbonate in 3 mA/cm^2, respectively. For the case of nitrate, stronger scavenger effect was shown in 5 mA/cm^2 than 3 mA/cm^2 (Fig. 6(b)). The test with no anions showed complete removal of BPA in 4 min of treatment, indicating that the efficiencies of BPA

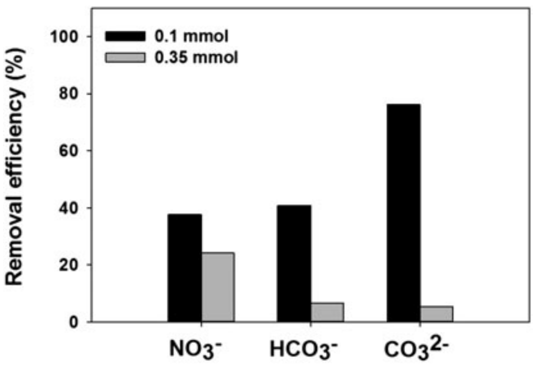

Fig. 5. The comparison of scavenger effect of nitrate, bicarbonate, and carbonate in the same concentration (initial BPA concentration: 10 mg/L, current density: 3 mA/cm^2, treatment time: 20 min, 100% of removal efficiency was obtained in the test without anions at the same time).

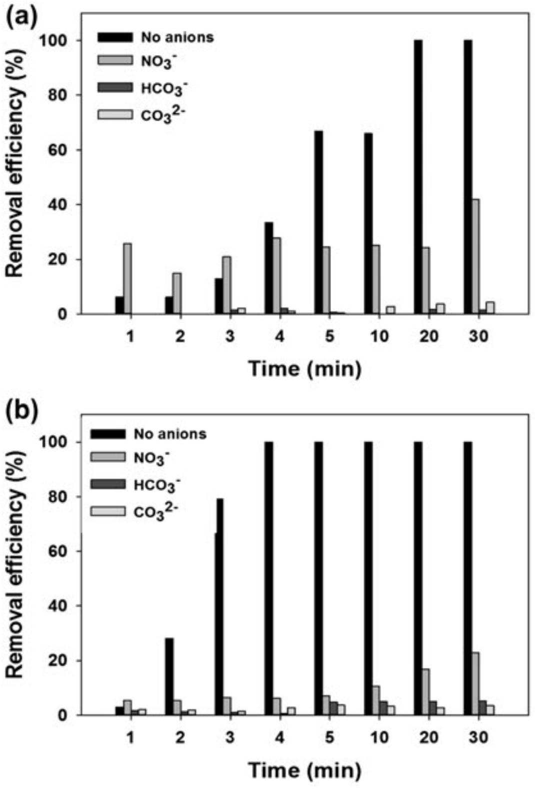

Fig. 6. The removal efficiency of BPA in the presence of nitrate, bicarbonate, and carbonate with the concentration of WWTP effluent ((a) under 3 mA/cm^2 of current density and (b) under 5 mA/cm^2 of current density, initial BPA concentration: 10 mg/L, nitrate: 5 mg NO_3-N/L, bicarbonate: 159 mg/L as $CaCO_3$, carbonate: 169 mg/L as $CaCO_3$).

Table 3
Energy consumptions of EO process

Current density (mA/cm^2)	Anions	U (V)	I (A)	t (h)	V (l)	BPA$_R$ (mg/l)	EC (kWh/g BPA$_R$)	EC (kWh/m^3)
3	None	20.05	0.40	0.20	1	8	0.20	1.60
	Nitrate	30.22	0.40	0.53	1	8	0.80	6.37
	Bicarbonate	28.25	0.40	0.57	1	8	0.80	6.43
	Carbonate	27.22	0.40	0.38	1	8	0.52	4.19
5	None	3.468	0.66	0.06	1	8	0.02	0.14
	Nitrate	85.56	0.66	0.30	1	8	2.15	17.21
	Bicarbonate	50.01	0.66	0.29	1	8	1.21	9.70
	Carbonate	38.09	0.66	0.11	1	8	0.34	2.72

removal have increased by increasing current density. In the previous study also reported that the rate of BPA degradation accelerated as current density increased. For the test with nitrate shows lower BPA removal efficiency in higher current density, it means the scavenger effects of nitrate increased in response to the increased current density. These results show that the reaction of hydroxyl radicals with nitrate, bicarbonate, and carbonate can proceed as fast or faster than their reaction with BPA. As a result, WWTP effluents which contains high bicarbonate and carbonate may require a lowering of alkalinity (e.g. pH adjustment or carbon dioxide stripping) prior to treatment by EO treatment. Complete removal of BPA was obtained in the test without anions. These results are also confirmed in previous study of Boscoletto et al. that the BPA removal was successfully performed through electrochemical oxidation in aqueous solutions. At the end of the treatment, the BPA was break apart to final products consisting of simple short chain aliphatic acids [40]. Cui et al. [30] also reported that the BPA was decomposed, passed through several steps (aromatic compounds, aliphatic acids), and finally mineralized to CO_2. But the study on intermediates was not in the scope of present study [30].

The energy consumption of each experiment was calculated (Table 3). The energy consumption (EC) for the EO process was calculated in kWh per g of removed BPA, according to Eq. (14) [51]. Energy consumption per volume to remove 80% of BPA also calculated as followed Eq. (15) [35]:

$$\mathrm{EC_{BPA}} = \frac{UIt}{V[(\mathrm{BPA})_0 - (\mathrm{BPA})_t]} \tag{14}$$

$$\mathrm{EC_V} = \frac{UIt}{V} \tag{15}$$

In the previous equation, U is the average voltage during EO process (V), I is the current applied during EO process (A), t is the treatment time (h), V is the wastewater volume (L), and BPA_0 and BPA_t are the concentrations of BPA (mg/L) at time 0 and t.

In the test with no anions, 0.20 kWh and 0.02 kWh per g removed BPA was obtained under 3 and 5 mA/cm^2 of current density. In the test with addition of anions, the specific energy consumption was increased remarkably. In both case, the test with the test with nitrate showed highest energy consumption, 0.8, 2.15 kWh/g $\mathrm{BPA_{removal}}$. Except the case of carbonate, the energy consumption was increased under higher current density. In the previous study [35], specific energy consumption of urban wastewater treatment using EO process was 1,066 kWh/kg O_2. It is about 160 times higher than the test with no anion under 5 mA/cm^2 (6.6 kWh/kg O_2 on the basis of COD). But there were some differences of the pollutants, initial concentration, conductivity, and current density. In the study of Domingues-Ramos et al. [36] reported that the initial COD and applied current density were significant parameters in EO process. To investigate accurate energy consumption, the long-term test will be conducted in further study.

4. Conclusions

In this study, the BPA removal using EO process was developed and the scavenger effect of nitrate, bicarbonate, and carbonate in the WWTP effluent on BPA removal was investigated. The results indicated that the EO process is effective method for removing BPA. The BPA was completely removed in EO process. The practical reaction time to remove 100% of BPA was above 20, and 5 min of EO treatment under 3 and 5 mA/cm^2 of current density, respectively. The current density was as a factor that affects removal efficiency. The removal efficiency of BPA was increased as the current density increased regardless of the presence of anions. To investigate the scavenging effect of anions, the BPA removal in EO process with nitrate, bicarbonate, and carbonate was tested in various concentrations. In the test with same mole concentration of anions, nitrate was the strongest scavenger showing 40% of removal efficiency. On the other hand, at higher current density, the scavenger effect was strong as the carbonate > bicarbonate > nitrate. The scavenging effect of bicarbonate and carbonate was more noticeable than nitrate. These findings suggest that the bicarbonate and carbonate could be most influential impact factor in EO treatment for treatment of well-treated municipal WWTP effluent containing BPA. Based on the results, the EO process is capable of significantly reducing BPA, thus representing a promising technology. Further investigations are necessary to find optimal electrolysis conditions, degradation mechanisms, and identification of the intermediates for apply to real WWTP effluents.

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