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Article

Facile preparation of a Ti/ α -PbO₂/ β -PbO₂ electrode for the electrochemical degradation of 2-chlorophenol

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ABSTRACT

A Ti/ α -PbO₂/ β -PbO₂ electrode with high stability was prepared and examined toward the electrochemical degradation of 2-chlorophenol. Scanning electron microscopy analysis revealed that Ti/ α -PbO₂/ β -PbO₂ had a cauliflower morphology comprising small β -PbO₂ crystals. The 2-chlorophenol removal rate using the Ti/ α -PbO₂/ β -PbO₂ electrode was 100% after 180 min of electrolysis under optimal conditions, which were selected based on the orthogonal test method, i.e., initial concentration of 2-chlorophenol = 50 mg/L, concentration of Na₂SO₄ = 0.1 mol/L, temperature = 35 °C, and anode current density = 20 mA/cm². Kinetic analyses demonstrated that the electrochemical oxidation of 2-chlorophenol on the Ti/ α -PbO₂/ β -PbO₂ electrode followed pseudo-first order kinetics.

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1. Introduction

2-Chlorophenol is an environmental pollutant presenting in water, soil, etc. It is widely used in industries and in our everyday life as a fungicide, wood preservative, and intermediate in the production of chlorinated pesticides or adhesives [1]. Owing to estrogenic, mutagenic and carcinogenic effects, 2-chlorophenol presents a threat to both the aquatic ecosystem and human health. Accordingly, the decomposition of 2-chlorophenol in wastewater has been studied by many methods such as photodegradation [2,3], chemical oxidation [4–7], and electrochemical degradation [8,9].

Among the above reported methods, electrochemical degradation is an attractive option for the decomposition of 2-chlorophenol because of its high oxidation efficiency, fast reaction rate, amenability to automation, high energy efficiency,

cost effectiveness, and environmentally friendly attributes [10,11]. The electrochemical degradation efficiency is largely dependent on the properties of the anodes. An ideal anode must not only exhibit high efficiencies toward contaminant degradation, but also be electrochemically stable and inexpensive [12]. Recently, studies have mainly focused on “non-active” anodes such as boron-doped diamond (BDD), SnO₂, and PbO₂, which exhibit a high oxygen evolution overpotential and can produce abundant hydroxyl radicals ($\cdot$ OH) [13]. Won's group [8] examined the electrochemical degradation of 2-chlorophenol using a Pt/Ti electrode and a BDD electrode. The BDD electrode displayed a significantly higher efficiency toward the degradation of 2-chlorophenol than the Pt/Ti electrode. Ortiz's group [9] also reported the effective electrochemical degradation of 2-chlorophenol using a BDD anode. However, despite the high chemical stability and outstanding efficiency of BDD

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electrode, its large-scale practical application is limited by its high cost and difficulty in selecting a suitable substrate for the thin diamond layer [14,15].

Alternatively, PbO_2 electrodes have been used as anodes in the chlor-alkali industry for over 70 years because of their high electrical conductivity, which is similar to that of metals, good stability, high overpotential for oxygen evolution, low cost, ease of fabrication, and long service life. In recent decades, PbO_2 anodes have been applied to oxidize organic pollutants [10,16–19]. An SnO_2 – Sb layer between the Ti substrate and PbO_2 has been commonly introduced to enhance the adhesion of the PbO_2 layer [20]. Niu's group has reported several successful studies on the electrochemical mineralization of environment contaminants such as perfluorooctanoic acid, perfluorocarboxylic acid [21,22], and sulfamethoxazole [13] using PbO_2 electrodes.

PbO_2 displays two allotropic forms, orthorhombic and tetragonal (α and β). Compared with α - PbO_2 that features a compact structure, β - PbO_2 is widely used in electrochemical degradation owing to its porous structure that leads to high electrochemical efficiency and large surface area [23,24]. However, direct electrodeposition of β - PbO_2 on a Ti substrate lessens the anode stability and activity because the porous β - PbO_2 structure can easily detach from the Ti substrate.

Some methods have been reported to improve the adhesion of β - PbO_2 on the substrate. For instance, the electrodeposited β - PbO_2 on a platinized Ti (Ti–Pt) substrate was reported to be stable in the electrochemical degradation of real textile wastewater [25,26]. A fluoride-doped Ti/ β - PbO_2 anode showed good performance in the electrochemical degradation of the dimethyl phthalate ester [27]. β - PbO_2 electrode modified by either TiO_2 or Co_3O_4 effectively electrochemically oxidized acid orange 7 [28] and bisphenol A [12], respectively. Additionally, to improve the activity and stability of β - PbO_2 electrode, several layers of SnO_2 – Sb_2O_5 – RuO_2 and α - PbO_2 were introduced between β - PbO_2 and the substrate. Zheng et al. [10] investigated the electrochemical degradation of 4-chlorophenol on Ti/ SnO_2 – Sb_2O_5 – RuO_2 /α- PbO_2 /β- PbO_2 , and Chen et al. [23] investigated the influence of doped nano- CeO_2 on Al/α- PbO_2 /β- PbO_2 electrode for enhancing electro-catalytic activity.

In this study, a Ti/α- PbO_2 /β- PbO_2 electrode was prepared simply by electrodeposition. The layer of α- PbO_2 enhanced the adhesion between the β- PbO_2 layer and Ti substrate. The prepared Ti/α- PbO_2 /β- PbO_2 electrode displayed high catalytic activity and long lifetime toward the degradation of 2-chlorophenol. The degradation of complex compounds, i.e., 2,4-dichlorophenol and bisphenol A, was also investigated to further evaluate the efficiency of the Ti/α- PbO_2 /β- PbO_2 electrode.

2. Experimental

2.1. Materials

2-Chlorophenol, 2,4-dichlorophenol, and bisphenol A were obtained from Sigma-Aldrich. All other chemicals were purchased from Shanghai Sinopharm Chemical Reagent Co., Ltd. All chemicals were of analytical grade. The solutions were pre-

pared with twice-distilled water.

2.2. Electrode preparation

A Ti metal net (2.0 cm × 2.0 cm × 0.1 cm) was used as the substrate. Before deposition, the Ti substrate underwent sand-blasting, ultrasonic cleaning in acetone for 10 min, ultrasonic cleaning in deionized water for 10 min, immersion in 40% NaOH at 80 °C for 2 h, etching in boiling 15% oxalic acid for 2 h, and rinsing with deionized water [29]. After pretreatment, interlayer α- PbO_2 was prepared using the pretreated Ti substrate as an anode and a Cu plate as a cathode in alkaline solution (0.1 mol/L PbO, 3.5 mol/L NaOH) at 40 °C and 10 mA/cm² for 2 h. Finally, top layer β- PbO_2 was electrodeposited on the above prepared substrate in acidic solution at 60 °C using a current density of 20 mA/cm² for 2 h. The acid solution consisted of 50 g/L $\text{Cu}(\text{NO}_3)_2$, 0.5 g/L NaF, and 150 g/L $\text{Pb}(\text{NO}_3)_2$ [23].

2.3. Electrode characterization

Scanning electron microscopy (SEM; HITACHI-4700, Japan) was used to characterize the morphology of the electrode surface. X-ray diffraction (XRD) patterns of the samples were recorded on a D/max-RB X-ray diffractometer (Rigaku, Japan) using Cu K_α radiation (40 kV, 100 mA).

Polarization curves were obtained on the CHI 660C electrochemical workstation (Shanghai ChenHua Instrument Co., Ltd.) using a conventional three-electrode system. A Ti/α- PbO_2 /β- PbO_2 electrode with an effective surface area of 1 cm² was used as the working electrode, a saturated calomel electrode (SCE) was used as the reference electrode, and a platinum electrode was used as the counter electrode. The measurements were conducted at room temperature.

2.4. Procedure of electrochemical degradation

Electrochemical oxidation of 2-chlorophenol was performed in a 150 mL beaker using a Cu plate (8 cm²) as the cathode and Ti/α- PbO_2 /β- PbO_2 (8 cm²) as the anode. The anode and cathode were positioned vertically and parallel to each other with a distance of 1 cm. Na_2SO_4 was chosen as the supporting electrolyte.

During electrochemical degradation, a portion of the reaction solution was withdrawn from the reactor at certain time intervals to determine the concentration of residual 2-chlorophenol in the test solution using a UV spectrophotometer (TU-1901). The removal rate (η) was calculated according to Eq. (1):

$$\eta = (A_0 - A)/A_0 \times 100\% \quad (1)$$

where A_0 and A are the absorbance values of the organic pollutant at time zero and t (s), respectively.

3. Results and discussion

3.1. Electrode characterization

SEM was used to characterize the morphology and surface

structure of the etched Ti substrate, Ti/ α -PbO₂, Ti/ β -PbO₂, and Ti/ α -PbO₂/ β -PbO₂ (Fig. 1). As observed in Fig. 1(a), the etching process in oxalic acid solution generated a Ti surface with a rough texture, which is expected to increase the surface area of the Ti substrate and strengthen the interaction between the deposition layers and Ti substrate [29]. As expected, interlayer α -PbO₂ (Fig. 1(b) and (c)) consisted of uniformly shaped particles in close proximity, i.e., rod-like and fiber-like particles that were smaller than those of the β -PbO₂ layer. Such a structure is expected to facilitate the deposition of β -PbO₂ layer in the subsequent electrode fabrication step. As observed in Fig. 1(d), Ti/ β -PbO₂ comprised typical pyramid-shaped crystals, as consistent with the findings of reported studies [27,28,30]. In contrast, the Ti/ α -PbO₂/ β -PbO₂ electrode (Fig. 1(e)) featured a completely different structure from that of Ti/ β -PbO₂. Specifically, the Ti/ α -PbO₂/ β -PbO₂ electrode featured a cauliflower-type structure comprising clusters of PbO₂ crystals. Furthermore, some pores were visible between the PbO₂ crystals. Such a cauliflower structure is expected to lead to high surface areas for enhancing the adsorption and degradation of pollutants, as demonstrated in these literature studies that reported the synthesis of comparable β -PbO₂ cauliflower-like structures using other methods [31,32]. Accordingly, Ti/ α -PbO₂/ β -PbO₂ is expected to exhibit high activity toward the electrochemical degradation of 2-chlorophenol.

Fig. 1(f) shows the XRD patterns of the intermediate layer

Fig. 1. SEM images of Ti substrate (a), Ti/ α -PbO₂ (b, c), Ti/ β -PbO₂ (d), and Ti/ α -PbO₂/ β -PbO₂ (e). (f) XRD patterns of α -PbO₂ and β -PbO₂.

α -PbO₂ and top layer β -PbO₂ that agree with those of standard references (PDF 01-075-2415, 01-073-0851), thereby indicating the formation of α -PbO₂ and β -PbO₂ crystals in the prepared samples. The α -PbO₂ grains were small as deduced from the relatively weak and wide α -PbO₂ characteristic diffraction peaks. The small α -PbO₂ grains are expected to promote the crystallization of β -PbO₂ as indicated by the strong and sharp β -PbO₂ characteristic diffraction peaks.

3.2. Electrode electrochemical behavior

Polarization curves are typically measured to determine the oxygen evolution overpotential of anode electrodes. More specifically, the onset of oxygen evolution is indicated by a sudden current increase in the linear polarization curve. Anodic oxygen evolution causes a power loss in organic wastewater treatment because oxygen evolution is a side reaction that reduces the current efficiency of organic oxidation [33]. Thus, the use of anodes with a high oxygen evolution overpotential favors the electrochemical oxidation of organics. The mechanism is as follows [34]:

where PbO₂[] represents the electroactive sites of the electrode and RO represents the organic oxidation products. The oxidation of organics is influenced by the amount of adsorbed $\cdot\text{OH}$. Oxygen evolution is an undesirable concomitant reaction.

Furthermore, ozone generates easily when PbO₂ electrodes with high overpotentials are employed, as reported [35]. Ozone is an ideal strong oxidizer for the degradation of organic pollutants with zero toxic residues generation. Ozone can either directly react with organic pollutants or react with H₂O to generate $\cdot\text{OH}$ radicals as follows:

Fig. 2 shows the linear polarization curves obtained in 0.1 mol/L H₂SO₄ using Ti/ β -PbO₂ and Ti/ α -PbO₂/ β -PbO₂ electrodes. As observed, the oxygen evolution potential of the Ti/ α -PbO₂/ β -PbO₂ electrode was 3.1 V, which is much higher than that of Ti/ β -PbO₂ (1.6 V) and some reported electrodes such as β -PbO₂ (1.8 V) [30], Ti/ β -PbO₂ doped with F⁻ (2.0 V)

Fig. 2. Anodic linear sweep voltammograms of the Ti/ β -PbO₂ and Ti/ α -PbO₂/ β -PbO₂ electrodes in 0.1 mol/L H₂SO₄. Scan rate = 100 mV/s.

[27], and $\text{TiO}_2\text{-NTs/SnO}_2\text{-Sb/PbO}_2$ (2.0 V) [34]. As observed in Fig. 1, $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ featured a cauliflower-like structure with few pores, whereas $\text{Ti}/\beta\text{-PbO}_2$ consisted of typical compact pyramid-shaped crystals. Thus, $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ has a larger electroactive surface than $\text{Ti}/\beta\text{-PbO}_2$. Accordingly, the generation of $\cdot\text{OH}$ radicals on $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ is easier and higher than that on $\text{Ti}/\beta\text{-PbO}_2$, and the oxygen evolution potential is considerably higher on the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode.

Electrode stability is an important property in practical application. The stability of PbO_2 electrodes is usually influenced by superficial ruptures and detachment of the PbO_2 film owing to the permeation of solution. Under normal conditions (such as a current density of 20 mA/cm^2), a PbO_2 electrode can remain highly functional for several years. To reduce the testing time, an accelerated life test was used to evaluate the service life of the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes in $1.0 \text{ mol/L H}_2\text{SO}_4$ at 60°C at a current density of 4 A/cm^2 . The electrolysis time when the potential reached 10 V was regarded as the service life of the electrode [14]. As determined herein, the service lives of the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes were 10 and 15 h, respectively. Though the electrode lifetime is strongly dependent on several conditions such as current density, pH, and temperature, the lifetimes of the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes are estimated to be 45.6 and 68.4 years, respectively, at a current density of 20 mA/cm^2 according to Eq. (6) proposed by Hine et al. [12] as follows:

$$t = (A_1/A)^2 t_1 \quad (6)$$

where A_1 is the current density in the accelerated test (4 A/cm^2), A is the current density in practical applications (0.02 A/cm^2), t_1 is the lifetime of the electrode in the accelerated test (h), and t is the electrode lifetime in practical applications (h). The longer lifetime of the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode (compared with that of the $\text{Ti}/\beta\text{-PbO}_2$ electrode) indicates that the $\alpha\text{-PbO}_2$ interlayer greatly enhances the electrochemical stability of top layer $\beta\text{-PbO}_2$ because of the slow formation of an insulating TiO_2 layer owing to the hindered diffusion of O^{2-} ions in water to the Ti substrate in the presence of the compact $\alpha\text{-PbO}_2$ interlayer [34].

3.3. Electrochemical degradation of 2-chlorophenol

The one-factor-at-a-time is a classical methodology adopted for investigating the influence of several factors on a particular parameter. However, such a methodology involves numerous experiments, and some important conclusions on the interaction among factors can be missed. In the present study, an orthogonal test was designed to circumvent the above disadvantages [36]. Four parameters were considered: current density, initial concentration, electrolyte concentration, and reaction temperature. Table 1 lists the experimental conditions, and an orthogonal L_9 (3^4) was considered for the optimization of the experimental conditions. Table 2 shows the orthogonal test results. The K and R values are listed in Table 2. Based on the R values, the influence of the various studied parameters on electrochemical oxidation decreased in the order of current density > reaction temperature > electrolyte concentration > initial concentration. The optimal experimental conditions were cho-

Table 1

Factors and levels of orthogonal test.

Variable	Level 1	Level 2	Level 3
Current density (mA/cm^2)	5	10	20
Initial concentration (mg/L)	50	100	200
Electrolyte concentration (mol/L)	0.05	0.1	0.2
Reaction temperature ($^\circ\text{C}$)	30	40	35

Table 2

Analysis of the L_9 (3^4) test result.

Test No.	Current density (mA/cm^2)	Initial concentration (mg/L)	Electrolyte concentration (mol/L)	Reaction temperature ($^\circ\text{C}$)	Removal rate (%)
1	5	50	0.05	30	85.61
2	5	100	0.1	40	89.31
3	5	200	0.2	35	88.62
4	10	50	0.1	35	95.65
5	10	100	0.2	30	88.35
6	10	200	0.05	40	91.68
7	20	50	0.2	40	97.72
8	20	100	0.05	35	96.90
9	20	200	0.1	30	95.53
K_1	87.84	92.99	91.40	89.83	
K_2	91.89	92.18	93.50	92.80	
K_3	96.72	91.56	91.56	93.72	
R	8.88	1.43	1.94	3.89	

sen according to the results in Table 2 as follows: anode current density 20 mA/cm^2 , reaction temperature 35°C , electrolyte concentration 0.1 mol/L , and 2-chlorophenol initial concentration 50 mg/L . For instance, the average removal rates of 2-chlorophenol at 5, 10, and 20 mA/cm^2 were 87.84%, 91.89%, and 96.72%, respectively. Hence a current density of 20 mA/cm^2 was chosen as the optimal current density.

The variations in the 2-chlorophenol removal rate on the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes under the selected experimental conditions are shown in Fig. 3(a). As observed, both the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes were effective toward the electrochemical degradation of 2-chlorophenol. After 180 min of reaction, the removal rate of 2-chlorophenol on the respective electrodes $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ were 78.4% and 100%, respectively. The higher removal rate of the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode when compared with that of the $\text{Ti}/\beta\text{-PbO}_2$ electrode at the same degradation time supports the fact that using interlayer $\alpha\text{-PbO}_2$ can increase the electrode oxidation activity for 2-chlorophenol.

The calculated voltage of cell $U(t)$ is based on the potential at nil current, the overpotentials of the anode and cathode, and the ohmic drop through the solution of resistance R . The cell voltage can be directly measured during electrolysis reaction. As observed, the cell voltage was mostly stable on both the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes (Fig. 3(b)) during an electrochemical degradation period of 300 min, thus indicating that the prepared electrodes are very stable. The average values of the cell voltage were 4.62 and 4.34 V for the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes, respectively. This finding indicates the onset of a low energy consumption on both electrodes; energy consumption is proportional to the cell

Fig. 3. Removal rate of 2-chlorophenol (a) and variations in cell voltage during electrolysis (b) in the presence of the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anodes. Anode current density 20 mA/cm^2 , reaction temperature 35 $^{\circ}\text{C}$, concentration of Na_2SO_4 0.1 mol/L, and initial concentration of 2-chlorophenol 50 mg/L.

voltage [37]. The cost associated with electrical power usage for 1000 kg of wastewater was calculated as 22 and 20 kWh using the $\text{Ti}/\beta\text{-PbO}_2$ and $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrodes, respectively.

More complex compounds, 2,4-dichlorophenol and bisphenol A, were selected to further investigate the performance of the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode toward electrochemical

Fig. 4. Removal rates of 2,4-dichlorophenol and bisphenol A using a $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anode. The reaction conditions are the same as those stated in Fig. 3.

degradation under the optimum conditions established above. Fig. 4 shows the removal rates of 2,4-dichlorophenol and bisphenol A as a function of degradation time using the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anode. As observed, the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anode also displayed high activity toward the electrochemical degradation of these two complex organic pollutants. As observed from Fig. 3(a) and Fig. 4, the removal rates of 2-chlorophenol and 2,4-dichlorophenol could reach 100% in 180 and 240 min of electrolysis, respectively, whereas the removal rate of bisphenol A could reach 78% after 240 min of electrolysis.

3.4. Kinetic and UV-visible spectroscopy studies

Determining the electrochemical degradation mechanism is of importance for the control of pollutants. Many research studies have focused on the electrochemical oxidation mechanism of chlorophenol. However, the mechanism is not very clear because detection of the transient intermediate is very difficult. To date, the electrochemical degradation mechanism of chlorophenol has been based on the presence of some state intermediates, as identified by high-performance liquid chromatography. Based on resonance Raman spectroscopy, high-performance liquid chromatography, UV-visible spectroscopy, and theoretical calculations, Cong et al. [38] reported that some of the chlorophenols were oxidized to benzoquinone, while others directly degraded into organic acids. However, oxidation to benzoquinone proceeded primarily at the early stages of the degradation process. Other possible intermediates were catechol, phenol, resorcin, hydroquinone, fumaric acid, maleic acid, and oxalic acid. The UV-visible spectrum of 2-chlorophenol shows two absorbance peaks at 217 and 274 nm, which are due to the phenol structure. As observed in Fig. 5, the absorbance peaks changed slightly within 30 min of reaction, which may be due to the influence of intermediates featuring benzene rings such as benzoquinone, catechol, resorcin, phenol, and hydroquinone. The absorbance peaks decreased after 60 min of degradation owing to the degradation of 2-chlorophenol into organic acids such as fumaric acid, maleic acid, and oxalic acid.

Fig. 5. Variations in the UV-visible spectrum of 2-chlorophenol as a function of electrochemical degradation time using a $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode. The reaction conditions are the same as those stated in Fig. 3.

Fig. 6. Linear relationship between $\ln(C_0/C)$ and degradation time using a $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anode. The reaction conditions are the same as those stated in Fig. 3.

Fig. 6 shows the results of the kinetic analysis conducted under optimal conditions over a short electrolysis period of 150 min. As observed, a good linear relationship between $\ln(C_0/C)$ and degradation time was obtained. A regression coefficient of 0.9829 and a pseudo rate constant (k) of 0.013 min^{-1} were obtained when the degradation data of 2-chlorophenol were fitted to a pseudo-first order kinetics model.

4. Conclusions

A $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode with cauliflower-like structure was prepared by electrodeposition. The prepared electrode featured high oxygen evolution overpotential and high electrochemical stability. The efficiency of the $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode was assessed toward the electrochemical degradation of 2-chlorophenol. Under the optimal conditions established herein, the removal rate of 2-chlorophenol attained 100% at 180 min of electrolysis. Furthermore, the removal rates of more complex compounds 2,4-dichlorophenol and bisphenol A were 100% and 78% at 240 min of electrolysis,

respectively. Kinetics analysis revealed that the degradation of 2-chlorophenol followed a pseudo-first order reaction assessed over a short electrolysis time of 150 min, with a regression coefficient of 0.9829 and a pseudo rate constant of 0.013 min^{-1} .

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Graphical Abstract

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Facile preparation of a $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ electrode for the electrochemical degradation of 2-chlorophenol

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A cauliflower-structured $\text{Ti}/\alpha\text{-PbO}_2/\beta\text{-PbO}_2$ anode displays high activity toward the degradation of 2-chlorophenol, with a long active service life of 68.4 years at a current density of 20 mA/cm^2 .

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Ti/ α -PbO₂/ β -PbO₂电极电化学降解2-氯酚

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摘要: 采用电化学沉积法在Ti基底上制备了复合电极Ti/ α -PbO₂/ β -PbO₂, 扫描电镜结果表明电极呈现由 β -PbO₂小晶体组成的菜花状微观形貌。所制电极在电化学降解环境污染物2-氯酚时表现出较高的电催化效率、较好的电极稳定性和较长的电极寿命。用正交实验优化了电化学降解2-氯酚的实验条件。在最优的实验条件(2-氯酚初始浓度50 mg/L, 电解质0.1 mol/L Na₂SO₄, 温度35 °C, 阳极电流密度20 mA/cm²)下电化学降解180 min后, 2-氯酚的去除率达100%。动力学结果表明, Ti/ α -PbO₂/ β -PbO₂电极上2-氯酚的电化学氧化符合准一级动力学过程。

关键词: 电化学降解; 2-氯酚; β -PbO₂电极; α -PbO₂中间层; 动力学

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