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Original scientific paper

Electrochemical oxidation of textile wastewater combined with 185 nm UV irradiation

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Abstract

The chemical oxygen demand (COD) results obtained after electrochemical oxidation and UV irradiation could hardly meet the strict discharge standard of COD for the textile wastewater after biological treatment. To further treat the textile wastewater after biological treatment, UV light at 185 nm was used in the centre of the commercial PbO_2 mesh cylinder anode with the titanium cylinder cathode in a cylinder electrolyzer. Performances of electrochemical oxidation coupled with 185 nm UV irradiation were investigated at a pilot scale under different oxidation times, current density, initial pH, and electrolyte flow rate without addition of oxidant reagents. The experimental results show that the performance of electrochemical oxidation combined with 185 nm UV irradiation is better than that of either separately applied electrochemical oxidation or 185 nm UV irradiation. 2,4-di-tert-butylphenol, oleamide and octadecanamide could be effectively degraded by electrochemical oxidation combined with 185 nm UV irradiation. Under optimal operating conditions, the electrochemical oxidation with 185 nm UV irradiation could reduce the COD of textile wastewater from 74.0 to 31.0 mg L^{-1} with the electrical consumption of 252.86 kWh per kg of degraded COD, cost of 5.78 CNY per m^3 of textile wastewater, and carbon emissions of 141.10 kg CO_2 per kg of degraded COD. Future research should investigate the interaction effects of variables, as well as the integration of renewable energy and broader contaminant removal capabilities.

Keywords
Wastewater treatment; electrochemical degradation; ultraviolet light; electrical consumption; cost assessment

Introduction

A large amount of the textile wastewater generated in the textile industry can cause severe damage to the ecological environment and human health [1]. The industrial textile wastewater remediation, due to intense colour and high organic load, usually requires certain physico-chemical method(s), followed by biological method(s) [2,3]. It is also necessary to further treat the textile wastewater after biological treatment because of the remaining refractory contaminants [4,5]. To date, electrochemical oxidation, combined with other technologies such as UV irradiation, has gradually garnered interest [6]. Research on the electrochemical degradation of wastewater using UV irradiation has primarily focused on 254 nm UV irradiation [7]. By 185 nm UV irradiation, however, oxygen that is produced by the electrochemical oxidation on the anode can generate ozone, which is beneficial for the oxidation of contaminants in textile wastewater [8]. However, the relevant research on electrochemical oxidation combined with 185 nm UV irradiation for the textile wastewater is still lacking in the literature.

Besides electrochemical oxidation, other physicochemical methods have also been explored for treating textile wastewater; yet each faces its own challenges. Membrane separation is still faced with membrane pollution, and the by-product concentrate solution, although membrane separation has been utilized to treat textile wastewater after biological treatment in industrial applications [9]. Heterogeneous electro-Fenton technology can effectively degrade recalcitrant organic pollutants in wastewater with a wide range of pH values. The addition of H_2O_2 increased the operational cost [10]. The removal of Acid red 283 dye and chemical oxygen demand (COD) could reach 99.5 and 58.5 % at 60 and 120 min of reaction, respectively, by UV/ZnO process [11], but the generation of Zn^{2+} from ZnO could cause metal ion pollution to wastewater. Electrochemical oxidation has been widely investigated in the textile wastewater treatment, mainly focusing on commercial electrodes, such as PbO_2 electrode [12], and electrodes prepared in the laboratory, such as Ti/SnO_2-Nb_2O_5 electrode [13], which face the problem of improving oxidation efficiency. Besides, most of the research on electrochemical oxidation of wastewater was carried out at laboratory scale [14].

On the other side, UV has been employed in the oxidation of contaminants in wastewater, such as UV/H_2O_2 [15], UV/persulfate [16], UV/Fenton and UV/chlorine [17]. The removal of toluene and COD could achieve 97.6 and 65 %, respectively, by peroxydisulfate activated by ferrous ion and ultraviolet (UV) light [18]. The removal of p-nitrotoluene and COD was achieved as 96 and 67 % respectively, by peroxymonosulfate, facilitated by ferrous ion [19]. However, the added chemical reagents in UV technology would increase the costs of the textile wastewater treatment using H_2O_2, persulfate and Fenton reactions. The addition of ferrous ions requires further treatment in the industrial treatment of wastewater.

The already published reports suggest that the removal performance of contaminants by electrochemical oxidation combined with UV irradiation is more efficient than that of electrochemical oxidation or UV irradiation applied separately [20]. Therefore, it would be meaningful to investigate the performance of treating textile wastewater by electrochemical oxidation with 185 nm UV irradiation without the addition of the oxidant reagents, at a pilot scale.

A cost assessment of electrochemical oxidation with 185 nm UV irradiation is essential for its industrial application in textile wastewater treatment. Carbon emissions have been receiving increasing attention in the context of wastewater treatment development, particularly in the context of carbon neutrality [21]. The carbon emissions of textile wastewater treatment should be taken into consideration, which mainly consist of direct greenhouse gas emissions and the indirect carbon emissions, such as electrical consumption and heat consumption [22]. A cost assessment and carbon emission analysis of textile wastewater treatment using electrochemical oxidation combined with 185 nm UV irradiation are also lacking in the current literature [23].

Therefore, in the present study, electrochemical oxidation coupled with 185 nm UV irradiation at a pilot scale is employed to treat textile wastewater following biological treatment. The commercial PbO_2 electrode is used as the anode, without the addition of oxidant reagents, to treat textile wastewater after further biological treatment. The electrochemical performances of electrochemical oxidation combined with 185 mm UV irradiation, electrochemical oxidation alone, and 185 mm UV irradiation alone are compared. COD, electrical consumption, toxicity analysis, cost assessment and carbon emissions are studied in the optimized experimental conditions involving degradation time, current density, initial pH and electrolyte flow rate parameters.

Experimental

Materials and reagents

The commercial PbO_2 cylinder electrode served as the anode, and the cylinder titanium electrode served as the cathode. These electrodes were purchased from Shaanxi Utron Environmental Protection Technology Co., Ltd. PbO2 was electrodeposited onto a titanium cylinder mesh (mesh size 5) with a film thickness of 0.5 mm. The diameter of the PbO_2 cylinder electrode was 40 mm with a height of 680 mm. The diameter of the titanium cylinder electrode was 70 mm, with a thickness of 2 mm. The UV light at 185 nm, equipped with a quartz pipe, was purchased from Suzhou Hemingway Environmental Protection Equipment Co., Ltd. The diameter of the UV light was 25 mm, with a length of 843 mm. Sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH) were used to modify the pH of the solution. The textile wastewater, after biological treatment, was obtained from a textile enterprise in Zhejiang Province.

Experimental apparatus

As shown in Figure 1, the UV light was positioned at the centre of the PbO_2 cylinder anode, with a titanium cylinder serving as the cathode in a cylinder electrolyzer. The interelectrode gap between the PbO_2 anode and the cathode was 15 mm, with the interelectrode gap of 7.5 mm between the UV light and the PbO_2 anode.

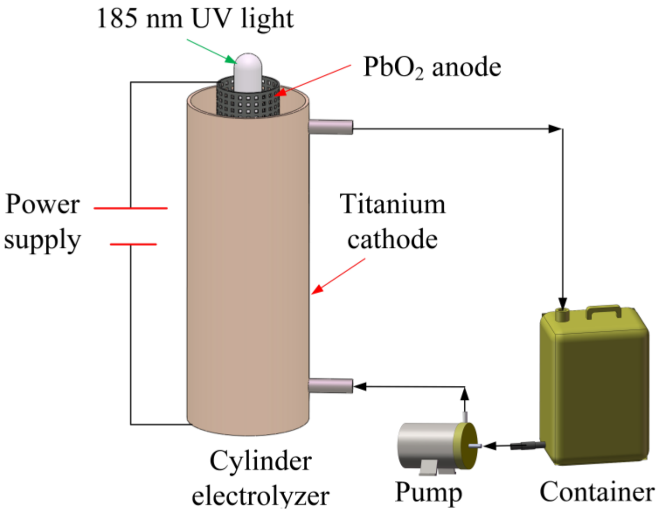

Figure 1. *Diagram of experimental apparatus*

The volume of textile wastewater was 10 L. A magnetic pump (MP-10R) from Baoding Qili Precision Pump Co., Ltd and a DC power supply (JK3060K) from Shenzhen Junke Instrument

Technology Co., Ltd were connected with the cylinder electrolyzer. A magnetic pump exhibits exceptionally low energy consumption due to its specialized, high-efficiency design, featuring an ultra-low-friction magnetic drive system and a motor optimized for minimal energy use in low-flow regimes. These pumps were selected specifically for their ability to meet the experimental requirements with minimal heat generation and energy input.

Experimental design

To evaluate the effectiveness of the electrochemical oxidation with 185 nm UV irradiation for textile wastewater at a pilot scale, the experiments of UV irradiation alone, electrochemical oxidation alone and electrochemical oxidation combined with 185 nm UV irradiation were carried out using 10 L of original textile wastewater. Experiments of electrochemical oxidation with 185 nm UV irradiation were conducted using a constant current density when a DC power supply and UV light were linked to an electrical source. When experiments on electrochemical oxidation were carried out in the cylinder electrolyzer, UV light was cut off. The experiments on UV irradiation were carried out in the cylinder electrolyzer when the DC power supply was cut off. As shown in Figure 1, the textile wastewater continually flowed between the cylinder electrolyzer and the container by a pump. 0.1 mol L^{-1} H_2SO_4 solution and 0.1 mol L^{-1} NaOH solution were used to adjust the pH of the textile wastewater. The experiments were operated at temperatures ranging from 30 to 35 °C. The present study is focused on validating the technical feasibility of the electrochemical oxidation combined with 185 mm UV irradiation at pilot scale, where one-factor-at-a-time (OFAT) is practical for operational troubleshooting. Design of experiments (DOE) will be researched for process intensification in future research, such as the Box-Behnken design [24]. In the present study, the baseline composition of the textile wastewater was used in all experiments, which included COD and toxicants. As for total organic carbon (TOC), Na^+, Cl^- and SO_4^{2-} ions, five batches of textile wastewater were collected at different dates to establish characteristic ranges.

For the sample analysis, the samples were extracted at the electrolyzer outlet to measure the COD by a spectrophotometer (DR3900, Hach, USA). The UV-visible spectra of the samples were measured by an ultraviolet-visible spectrophotometer (UV-2600, Shimadzu, Japan) with distilled water as reference, the scanning wavelength range of 200 to 700 nm, and the scanning interval of 1 nm. The fluorescence spectra of the samples were determined by a fluorescence spectrophotometer (F-7000, Hitachi, Japan) with the excitation wavelength of 200 to 480 nm, the emission wavelength of 220 to 500 nm, the excitation scanning step size of 5 nm, the emission scanning step size of 2 nm, the scanning speed 2400 nm min^{-1}, PMT voltage of 700 V, and the response time of 2 s. The organic compounds in wastewater were analysed using gas chromatography-mass spectrometry (GC-MS) on a GC-MS-Qp2020 NX (Shimadzu, Japan). The TOC of the wastewater was measured by a total organic carbon analyser (TOC-L, Shimadzu, Japan).

Analytical methods

For the electrochemical oxidation, the electrical energy consumption per kilogram of the COD for the textile wastewater (W_e / kWh kg^{-1}) was calculated using Equation (1):

$$W_e = \frac{UIt1000/60}{V\left(\mathrm{COD_o}\text{-}\mathrm{COD_t}\right)} = \frac{50UIt}{3V\left(\mathrm{COD_o}\text{-}\mathrm{COD_t}\right)} \tag{1}$$

where COD_t and COD_o are the COD, mg / L of textile wastewater after treatment and before treatment, respectively, U / V is the cell voltage, I / A is the working current, t / min is the total time of electrochemical oxidation, and V / L is the volume of textile wastewater.

Corresponding to the 185 nm UV irradiation, the electrical energy consumption per kilogram of the COD for the 185 nm UV irradiation (W_u / kWh kg^{-1}) is calculated using Equation (2):

$$W_u = \frac{P_u 1000/60}{V\left(\text{COD}_o\text{-COD}_t\right)} = \frac{50P_u t_u}{3V\left(\text{COD}_o\text{-COD}_t\right)} \tag{2}$$

where P_u / W is the electric power of 185 nm UV irradiation, t_u / min is the total time when the 185 nm UV irradiation is carried out.

Corresponding to the magnetic pump, the electrical energy consumption per kilogram of the COD (W_g / kWh kg^{-1}) is calculated using Equation (3):

$$W_g = \frac{P_g 1000/60}{V\left(\text{COD}_o\text{-COD}_t\right)} = \frac{50P_g t}{3V\left(\text{COD}_o\text{-COD}_t\right)} \tag{3}$$

where P_g / W is the electric power of the magnetic pump.

Based on Equations (1) to (3), the electrical consumption per kilogram of the COD for the electrochemical oxidation combined with 185 nm UV irradiation (W / kWh kg^{-1}) was calculated using Equation (4):

$$W = W_e + W_u + W_g = \frac{50\left(UIt + P_u t_u + P_g t\right)}{3V\left(\text{COD}_o\text{-COD}_t\right)} \tag{4}$$

No heat energy was consumed in the present experiments, apart from the electric power. Therefore, the carbon emissions were attributed to the electrical energy consumption shown in Equation (4). The carbon emissions (CE) per kilogram of the COD for the textile wastewater (kg CO_2 *per* kg COD) were calculated using Equation (5):

$$\text{CE} = Wf_e = \frac{50\left(UIt + P_u t_u\right) f_e}{3V\left(\text{COD}_o\text{-COD}_t\right)} \tag{5}$$

where f_e is the carbon emissions factor of electricity. For China in 2023, f_e is 0.5703 kg CO_2 *per* kWh[1].

For the cost assessment of the electrochemical oxidation with 185 nm UV irradiation, the electric power of 185 nm UV irradiation, electrochemical oxidation, and the pump were the main operation costs with the initial pH of the original textile wastewater. The nominal power of 185 nm UV in the experimental apparatus was 90 W. The nominal power of the magnetic pump in the experimental apparatus was 6 W with a nominal flow rate of 0.3 m^3 h^{-1}. The magnetic pump exhibits exceptionally low electric power because of its specialized high-efficiency design featuring an ultra-low friction magnetic drive system and a motor optimized for minimal energy use in low-flow regimes. The magnetic pump was explicitly selected for its ability to meet the experimental requirements with minimal heat generation and energy consumption.

The electrical energy consumption per cubic meter of the textile wastewater (W_m / kWh m^{-3}) for each experiment was calculated using Equation (6):

$$W_m = W_{em} + W_{um} + W_{mg} = \frac{UIt + P_u t_u + P_g t}{60V} \tag{6}$$

where W_{em} / kWh m^{-3} is the electrical consumption of 185 nm UV irradiation per cubic meter for the textile wastewater, W_{um} / kWh m^{-3} is the electrical consumption of electrochemical oxidation per cubic meter for the textile wastewater and W_{mg} / kWh m^{-3} is the electrical consumption of magnetic pump per cubic meter of the textile wastewater.

The service life of the experimental apparatus is 10 years, with an apparatus depreciation price of 24,000 CNY (approximately 1 CNY = 0.14 US$). A year is set as 365 days, and the depreciation cost

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[1] For Europe in 2023, the carbon emissions factor of electricity is 0.242 kg CO_2 *per* kWh

of the experimental apparatus per cubic meter of the textile wastewater (C_{ea}, CNY m^{-3}) is calculated based on the total operating time required to treat one cubic meter using Equation (7):

$$C_{ea} = \frac{24000t/60}{10\times12\times365\times24\,V/1000} = \frac{250\,t}{657\,V} \tag{7}$$

The cost of electrochemical oxidation with 185 nm UV irradiation per cubic meter of the textile wastewater (C_m / CNY m^{-3}) for each experiment is calculated using Equation (8):

$$C_m = (W_m c_m) + C_{ea} = \frac{\left(UIt + P_u t_u + P_g t\right) c_m}{60V} + \frac{250\,t}{657V} \tag{8}$$

where C_m is the average industrial electricity price in Zhejiang province[2] of 0.625 CNY kWh^{-1}.

Results and discussion

Ultraviolet spectrophotometers of different treatment technologies

The UV-visible spectra of the original textile wastewater and the treated textile wastewater are shown in Figure 2 at an initial pH of 7.3, electrolyte flow rate of 1.5 L min^{-1} and degradation time of 30 min. As shown in Figure 2, all peaks in the treated textile wastewater were reduced.

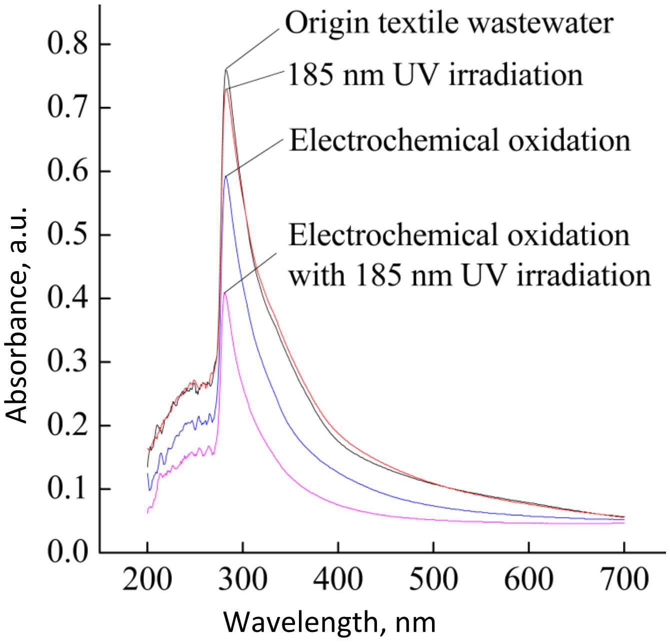

Figure 2. *UV-visible spectra for original textile wastewater and textile wastewater treated by 185 nm UV irradiation, electrochemical oxidation and electrochemical oxidation combined with 185 nm UV irradiation, at the degradation time of 30 min*

The absorbance, with a peak at 285 nm in the visible wavelength range after UV irradiation, was slightly lower than that of the original textile wastewater, which had a peak at 282 nm. The decrease in absorbance, with a peak at 282 nm on the visible wavelength, after electrochemical oxidation at a current density of 10 mA cm^{-2}, was noticeable. The absorbance with the peak at 281 nm on visible wavelength after electrochemical oxidation with 185 nm UV irradiation at a current density of 10 mA cm^{-2} was the lowest. Aromatic structure was characterized by the peaks at 281 to 285 nm [25]. Therefore, the electrochemical oxidation combined with 185 nm UV irradiation had the most effective removal of the aromatic structure in textile wastewater.

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[2] The average industrial electricity price in Europe is about €0.187/kWh in 2024 according to Eurostat / CubeConcepts, Europe's industrial electricity prices 2024, June 2025.

As for fluorescence spectrograms shown in Figure 3, *Ex* (excitation wavelength) refers to the specific wavelength of light used to irradiate the wastewater sample, causing electrons in fluorescent molecules to absorb energy and transition to a higher energy state, and *Em* (emission wavelength) refers to the wavelength of light emitted by the wastewater sample when excited electrons return to a lower energy state, releasing energy in the form of fluorescence. As shown in Figure 3, all peak areas of the treated textile wastewater at the initial pH of 7.3, electrolyte flow rate of 1.5 L min^{-1} and degradation time of 30 min, were reduced compared with those of the original textile wastewater. Compared with Figure 3(a), the peak areas at *Ex* = 310 to 380 nm and *Em* = 360 to 500 nm related to humic acid got smaller in Figure 3(b) [26]. It could be seen from Figure 3(c) that the peak areas at *Ex* = 250 to 310 nm and *Em* = 360 to 500 nm due to fulvic acid got smaller and the peak areas at *Ex* = 310 to 380 nm and *Em* = 360 to 500 nm due to humic acid got smaller dramatically [27]. As shown in Figure 3(d), apart from the smaller peak areas at *Ex* = 310 to 380 nm and *Em* = 360 to -500 nm related to humic acid with the dramatically smaller peak areas at *Ex* = 250 to 310 nm and *Em* = 360 to 500 nm due to fulvic acid, the peak areas at *Ex* = 200 to 250 nm and *Em* = 330 to 360 nm related to low excitation light tryptophan got smaller and the peak areas at *Ex* = 250 to 300 nm and *Em* = 330 to 360 nm related to high excitation light tryptophan got smaller dramatically than those in Figure 3(a). There existed the peak areas at *Ex* = 200 to 250 nm and *Em* = 330 to 360 nm, the peak areas at *Ex* = 200 to 250 nm and *Em* = 200 to 330 nm related to low excitation light tyrosine, the peak areas at *Ex* = 250 to 300 nm and *Em* = 200 to 330 nm related to the high excitation light tyrosine in Figure 3(d).

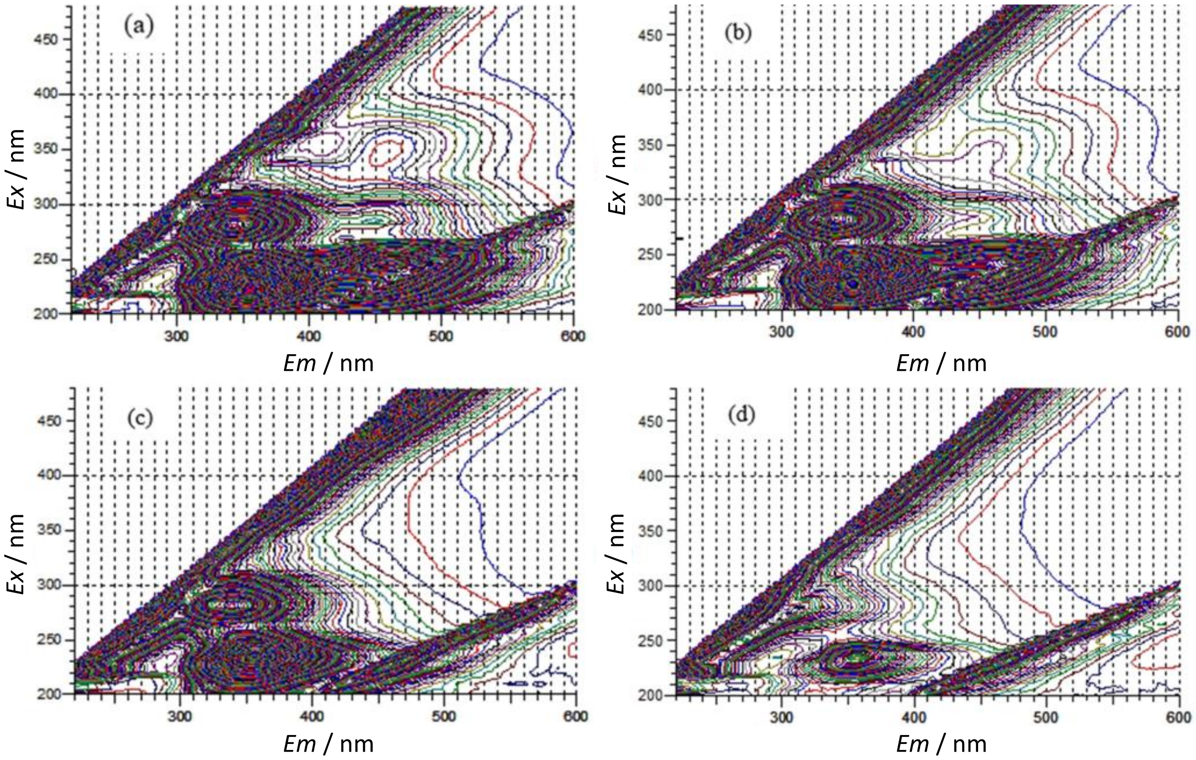

Figure 3. *Fluorescence spectrograms of (a) original textile wastewater, and textile wastewater treated by (b) 185 nm UV irradiation, (c) electrochemical oxidation and (d) electrochemical oxidation combined with 185 nm UV irradiation*

Therefore, the humic acid in textile wastewater can be effectively removed, along with a noticeable removal of fulvic acid, by electrochemical oxidation at a current density of 10 mA cm^{-2}, whereas the peak areas could not be removed by UV irradiation at 185 nm. In addition, the humic acid, the fulvic acid, and the high excitation light tryptophan could be effectively removed by electrochemical oxidation with 185 nm UV irradiation at the current density of 10 mA cm^{-2}. Besides, low excitation light tryptophan, low excitation light tyrosine and high excitation light tyrosine could not be effectively removed by electrochemical oxidation combined with 185 nm UV irradiation.

The electrochemical degradation of textile wastewater with 254 nm UV using a platinum-plated titanium anode has been investigated with the addition of a high concentration of Na_2SO_4, but the fluorescence spectrograms of the textile wastewater are lacking [28]. On the one hand, 185 nm UV irradiation was adopted to combine electrochemical oxidation in this study. On the other hand, a high concentration of Na_2SO_4 was not added to increase the conductivity of the electrolyte solution in the present study, which contributes to the decrease in treatment cost. In addition, the fluorescence spectrograms in this study illustrated that higher efficiency was obtained by electrochemical oxidation with 185 nm UV irradiation using PbO_2 anode than either electrochemical oxidation or 185 nm UV irradiation applied separately.

Toxicity analysis of textile wastewater before and after degradation

Analysis of several high-abundance organic compositions was conducted using gas chromatography-mass spectrometry (GC-MS), shown in Figure 4. As could be seen in Figure 4, oleamide, hexadecanamide and hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester were the main components in the textile wastewater. Organic substances at different residence times in Figure 4 are exhibited in Table 1.

It can be seen from Table 1 that in the original textile wastewater, 2,4-di-tert-butylphenol, hexadecanamide, oleamide, octadecanamide, hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester, cis-11-eicosenamide, monostearin and other substances are present at 2.22, 10.32, 41.14, 5.66, 9.30, 5.98, 5.04 and 20.34 %, respectively. Among the present substances, 2,4-di-tert-butylphenol and oleamide have been extensively studied for their toxicity to various organisms [29,30]. It was also demonstrated that octadecanamide, a widely used surfactant in the textile industry, can pose toxicity to the aquatic environment [31]. Consequently, even 49.02 % of substances (2,4-di-tert-butylphenol, oleamide and octadecanamide) listed in Table 1 have toxic effects on organisms. As shown in Table 1, the percentages of 2,4-Di-tert-butylphenol, oleamide and octadecanamide in the original textile wastewater were reduced, while hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester increased after treatment of 185 nm UV irradiation, electrochemical oxidation and electrochemical oxidation with 185 nm UV irradiation. These suggest that all three toxic substances are degraded, resulting in a drop in their corresponding toxicity.

Table 1. *Content of organic components in textile wastewater before and after degradation*

Organic components	Content, %			
	Original	185 nm UV irradiation	Electrochemical oxidation	Electrochemical oxidation with 185 nm UV irradiation
2,4-Di-tert-butylphenol	2.22	2.19	2.08	1.32
Hexadecanamide	10.32	8.10	8.95	10.28
Oleamide	41.14	38.05	31.75	28.86
Octadecanamide	5.66	5.75	4.85	4.43
Hexadecanoic acid, 2-hydroxy-1--(hydroxymethyl)ethyl ester	9.30	17.13	20.16	20.29
cis-11-Eicosenamide	5.98	6.73	5.33	4.80
Monostearin	5.04	5.36	5.96	9.55
Other substances	20.34	16.69	20.92	20.47

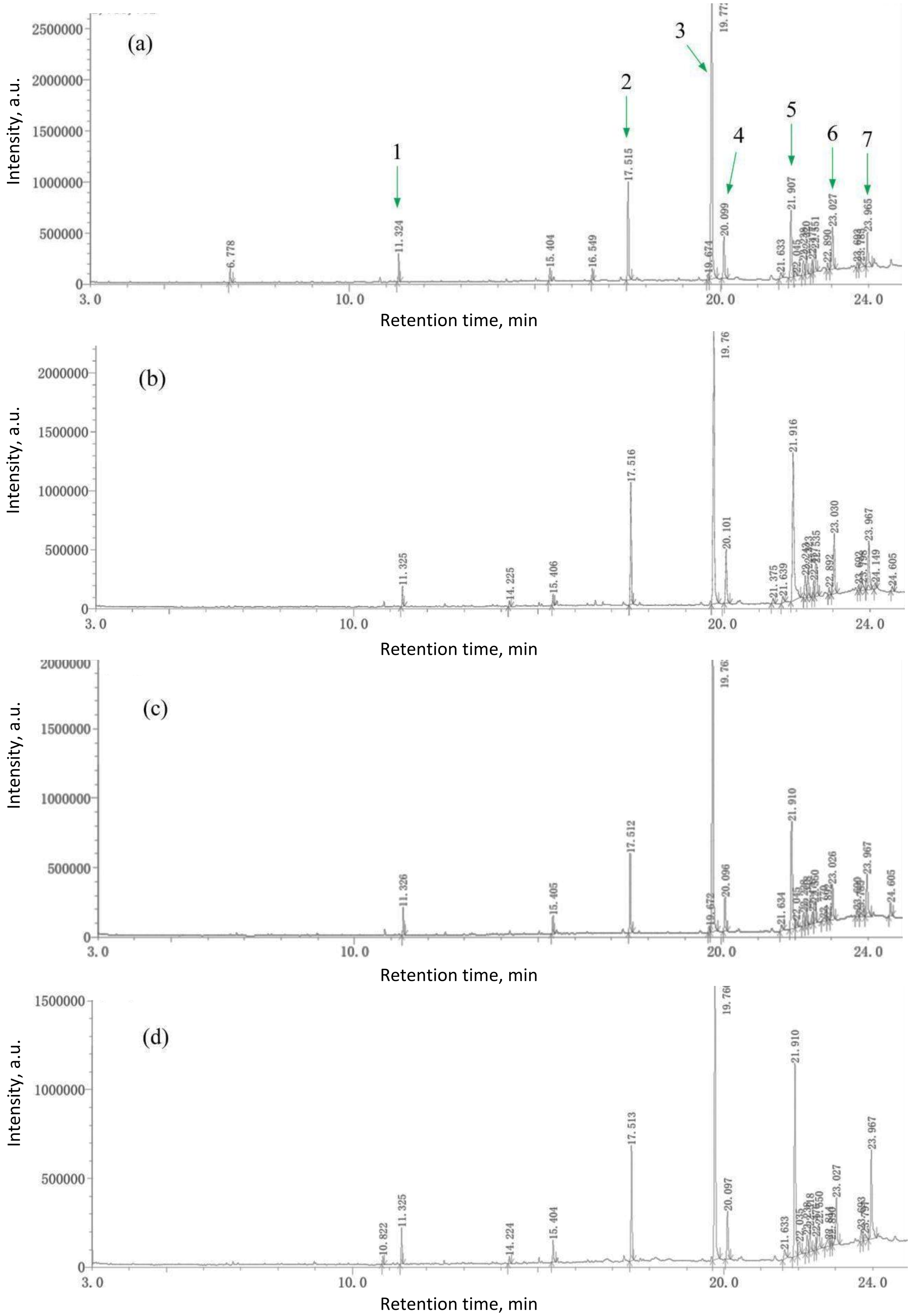

Figure 4. *Total ion chromatograms of GC-MS: (a) original textile wastewater, and textile wastewater treated by (b) 185 nm UV irradiation, (c) electrochemical oxidation and (d) electrochemical oxidation with 185 nm UV irradiation*

The effect of degradation time on COD

As shown in Figure 5, COD of textile wastewater was evaluated at different degradation times during the electrochemical oxidation process at the current density of 10 mA cm^{-2}, initial pH of 7.3 and electrolyte flow rate of 1.5 L min^{-1}. When the textile wastewater was exposed to UV irradiation, a slow COD reduction due to direct UV degradation was observed, with a decrease in COD from 74 to 56 mg L^{-1} at 60 minutes. As for the electrochemical oxidation of textile wastewater by a PbO_2 anode, it can be seen from Figure 5 that the COD at a current density of 10 mA cm^{-2} reached 46 and 28 mg L^{-1} at 30 and 60 min, respectively. The results showed higher COD removal than for UV irradiation. The COD of textile wastewater was reduced by electrochemical oxidation combined with 185 nm UV irradiation at a current density of 10 mA cm^{-2} to 31 and 14 mg L^{-1} at 30 and 60 min, respectively. In addition, Figure 5 shows that the COD by electrochemical oxidation with 185 nm UV irradiation was significantly lower compared to that of UV irradiation or electrochemical oxidation at the same degradation time.

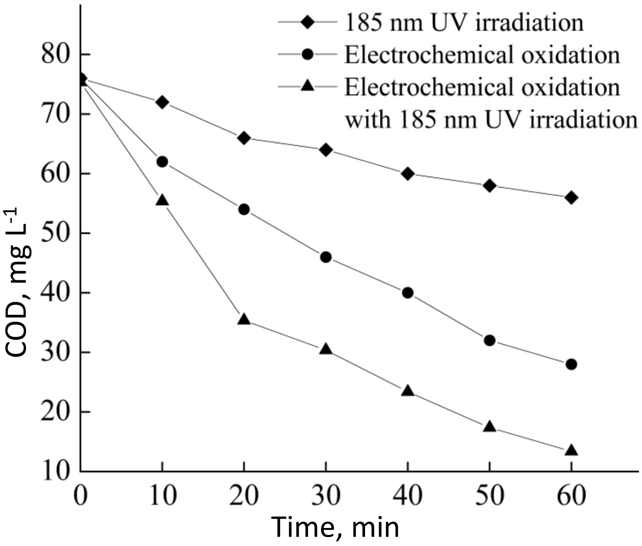

Figure 5. *COD at different degradation times at the current density of 10 mA cm^{-2}, initial pH 7.3 and electrolyte flow rate of 1.5 L min^{-1}*

As for the PbO_2 anode, the hydroxyl radicals (·OH) generated on the anode surface are freely available to degrade organic contaminants during the electrochemical oxidation process [32]. As for the main electrolytes in the original textile wastewater, there existed Na^+, SO_4^{2-} and Cl^- ions with TOC of 13.0 to 13.2 mg L^{-1}, shown in Table 2. TOC of the wastewater after 185 nm UV irradiation, electrochemical oxidation and electrochemical oxidation with 185 nm UV irradiation was reduced to 12.7 to 12.8, 9.9 to 10.3 and 8.1 to 8.3 mg L^{-1}, respectively, which was consistent with the degradation of the compositions in Table 2. Additionally, TOC achieved the largest reduction through electrochemical oxidation with 185 nm UV irradiation.

***Table 2**. Main electrolytes and TOC of the textile wastewater before and after degradation*

Main electrolytes and TOC	Concentration, mg L^{-1}
Original Na^+	612-632
Original Cl^-	243-246
Original SO_4^{2-}	1180-1215
Original TOC	13.0-13.2
TOC after 185 nm UV irradiation	12.7-12.8 (as C)
TOC after electrochemical oxidation	9.9-10.3 (as C)
TOC after electrochemical oxidation with 185 nm UV irradiation	8.1-8.3 (as C)

Due to Cl^- and SO_4^{2-} ions existing in the textile wastewater, Cl_2 and $S_2O_8^{2-}$ ions are generated at the PbO_2 anode as illustrated by Equations (9) and (10) [33], together with oxygen evolution shown as the Equations (11). Furthermore, hypochlorous acid (HClO) could be generated due to the presence of Cl_2 [34], as illustrated by the reaction (12).

$$2Cl^- \rightarrow Cl_2\uparrow + 2e^- \tag{9}$$

$$2SO_4^{2-} \rightarrow S_2O_8^{2-} + 2e^- \tag{10}$$

$$2H_2O \rightarrow O_2\uparrow + 4H^+ + 4e^- \tag{11}$$

$$Cl_2 + H_2O \rightarrow HClO + HCl \tag{12}$$

Several studies have investigated the activation of HClO by UV irradiation. Thus, it was found that different radicals are produced by UV irradiation of activated HClO [35], as shown by Equation (13). Persulfate ions could be activated by UV irradiation, producing the sulphate radicals ($SO_4^{-}\cdot$) [36] as illustrated by Equation (14). Ozone could be generated from O_2 by 185 nm UV irradiation, as shown by Equation (15).

$$HClO + h\nu \rightarrow Cl\cdot + \cdot OH \tag{13}$$

$$S_2O_8^{2-} + h\nu \rightarrow 2SO_4^- \tag{14}$$

$$3O_2 + h\nu \rightarrow 2O_3 \tag{15}$$

Considering the activation of UV irradiation illustrated by reactions (13) to (15) and the COD shown in Figure 5, electrochemical oxidation combined with 185 nm UV irradiation was selected for the following experiments. It can be observed from Figure 5 that after 30 min of degradation, the COD of 31 mg L^{-1} was obtained by electrochemical oxidation combined with 185 nm UV irradiation, which is lower than 50 mg L^{-1}, the first-class standard of COD for the sewage discharge of urban sewage treatment plants in China. Therefore, the degradation time of 30 min for electrochemical oxidation with 185 nm UV irradiation was selected for the following research.

The effect of current density and initial pH on oxidation performance

Figure 6 presents COD and electrical consumption at different initial pH levels at the current density of 10 mA cm^{-2}, the electrolyte flow rate of 1.5 L min^{-1} and the degradation time of 60 min. COD increased from 25 to 33 mg L^{-1} at an initial pH rise from 5 to 7 and then reduced to 27 mg L^{-1} at further initial pH rise from 7 to 9.

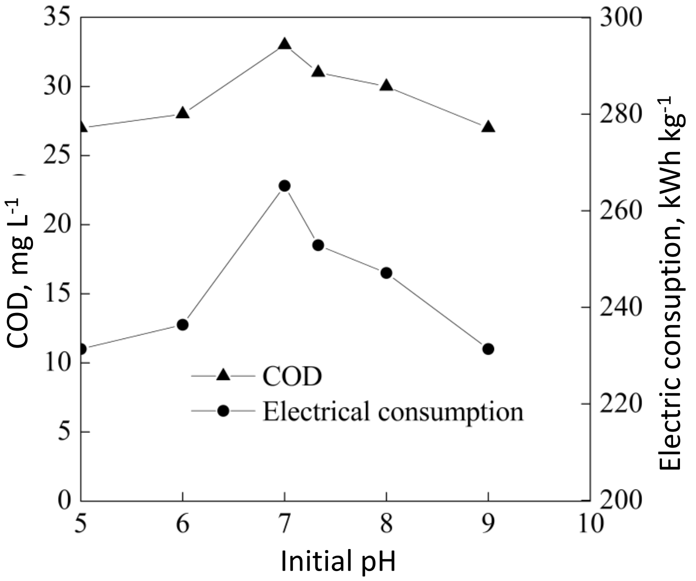

Figure 6. *COD and electrical consumption at different initial pH at current density of 10 mA cm⁻², electrolyte flow rate of 1.5 L min⁻¹ and degradation time of 30 min*

The decrease in electrolyte solution conductivity caused the rise of cell voltage at the same current density when the initial pH increased from 5 to 7, which could enhance the oxygen evolution reaction to some extent. In addition, when the initial pH increased from 7 to 10, the conductivity of the electrolyte solution increased, accompanied by a decrease in cell voltage at the same current density, which could hinder the oxygen evolution reaction to some extent. In addition, the rise in cell voltage could increase electrical consumption, as indicated by Equation (4), which is consistent with the trend in electrical consumption shown in Figure 6. Although the COD at an initial pH of 9 was lower with lower electrical consumption than at an initial pH of 7.3, adjusting the pH required a significant amount of acid or alkaline solution, which increased the cost of textile wastewater treatment. Considering the electrical consumption of 252.86 kWh kg^{-1} at an initial pH of 7.3 was not more than 10 % higher than the electrical consumption of 231.36 kWh kg^{-1} at an initial pH of 9, the original pH of 7.3 was selected as the initial pH of textile wastewater for the following experiments.

Figure 7 shows the COD and the electrical consumption of electrochemical oxidation combined with 185 nm UV irradiation at the current density ranging from 5 to 25 mA cm^{-2} with the initial pH of 7.3, the electrolyte flow rate of 1.5 L min^{-1} and the degradation time of 30 min.

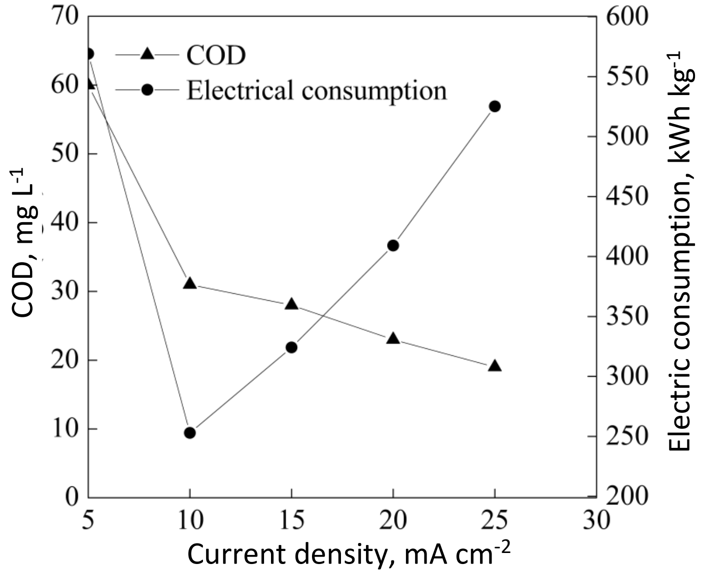

Figure 7. *COD and electrical consumption dependence on current density at initial pH of 7.3, electrolyte flow rate of 1.5 L min^{-1} and degradation time of 30 min*

As shown in Figure 7, the COD is gradually reduced, while the electrical consumption is initially reduced and then gradually increases with the increase in current density. The increase in current density from 5 to 25 mA cm^{-2} enhances the electrochemical oxidation rate of contaminants at the anode surface, thereby lowering the COD of textile wastewater. In addition, the gradual decrease of degradable contaminants caused the reduction rate of COD to be lower from 10 to 25 mA cm^{-2} compared with that from 5 to 10 mA cm^{-2}.

Regarding the rise in current density from 5 to 10 mA cm^{-2}, the electrical consumption decreased from 569.11 to 252.86 kWh kg^{-1}, as a result of the increase in COD removal, as shown in Equation (4). Additionally, the electrical consumption increased with the rise in current density from 10 to 25 mA cm^{-2}. On the one hand, the oxygen evolution reaction was enhanced when the current density increased from 10 to 25 mA cm^{-2}, resulting in a decrease in the COD reduction rate. On the other hand, the gradually increasing current density corresponds to an increase in cell voltage. Therefore, the drop-in COD reduction rate and the high current density increased electrical consumption, as indicated by Equation (4).

The COD at the current density of 10 mA cm^{-2} was 31 mg L^{-1} with the corresponding electrical consumption of 95.88 kWh kg^{-1}, which is lower than 50 mg L^{-1}, which is the first-class standard of COD for the sewage discharge of urban sewage treatment plants in China.

In addition, the electrical consumption at a current density of 10 mA cm^{-2} was the lowest shown in Figure 7 and therefore, the current density of 10 mA cm^{-2} was selected for the following research.

The cost assessment of electrochemical oxidation with 18 nm UV irradiation, calculated according to Equation (8), is shown in Figure 8. As shown in Figure 8, the cost increased from 4.75 to 11.46 CNY m^{-3} when the current density increased from 5 to 25 mA cm^{-2}. In addition, the cost reached 5.78 CNY m^{-3} at the current density of 10 mA cm^{-2}. It was calculated that the costs of the experimental apparatus were 1.14, 0.19 and 4.45 CNY m^{-3}, for the experimental apparatus depreciation, the magnetic pump and electrochemical oxidation with 185 nm UV irradiation, respectively, at the current density of 10 mA cm^{-2} and the degradation time of 30 min.

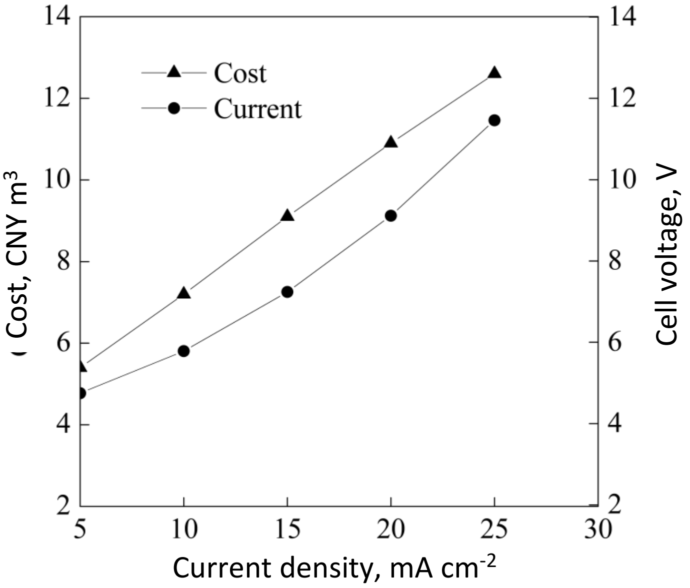

Figure 8. *Cost assessment of electrochemical oxidation under different current densities at initial pH 7.3, electrolyte flow rate of 1.5 L min^{-1} and degradation time of 30 min*

As for the electrochemical oxidation with 185 nm UV irradiation, the costs of electrochemical oxidation and 185 nm UV irradiation were calculated to be 1.64 and 2.81 CNY m^{-3}, respectively. It was demonstrated that the depreciation cost of the experimental apparatus accounted for 19.72 % of the total cost, which was less than that of electrochemical oxidation and 185 nm UV irradiation. Since the electric power of 185 nm UV irradiation was hard to change, the current density was the key parameter to optimize the cost.

As for industrial usages of electrochemical oxidation with 185 nm UV irradiation, the COD of the real textile wastewater obtained from an industrial source in Zhejiang province was reduced from 74.0 to 31.0 mg L^{-1} at a current density of 10 mA cm^{-2}, which could meet China's discharge standards for urban sewage plants. In addition, a commercial PbO_2 anode and Ti cathode were adopted, with a cost analysis conducted at a 10 L volume of real textile wastewater, which provided industrial scalability for the electrochemical oxidation process using 185 nm UV irradiation.

Figure 8 illustrates the relationship between current density, the cost and the corresponding cell voltage. As the current density increased from 5 to 25 mA cm^{-2}, the current increased from 5 to 25 A according to the surface area of the PbO_2 cylinder electrode. In addition, a concomitant rise in cell voltage was observed with the increase in current density. Consequently, the increase in current density and cell voltage directly contributed to higher energy consumption, which caused the higher cost as calculated by Equation (8).

The effect of electrolyte flow rate on oxidation performances

Figure 9 demonstrates the COD and the electrical consumption of the textile wastewater at different electrolyte flow rates at a current density of 10 mA cm^{-2}, initial pH of 7.3 and degradation time of 30 min. It can be observed from Figure 9 that COD after electrochemical oxidation with 185 nm UV irradiation is reduced relatively quickly at first from 45 to 31 mg L^{-1}, and then slowly from 31 to 28 mg L^{-1}. Figure 9 shows that the electrical consumption after electrochemical oxidation with 185 nm UV irradiation is reduced relatively quickly to 252.86 kWh kg-1 at an electrolyte flow rate of 1.5 L min-1 and then decreases slowly. The mass transfer was gradually enhanced with the increase in electrolyte flow rate from 0.5 to 1.5 L min^{-1}, which was beneficial for COD reduction and the reduction of electrical consumption. When the electrolyte flow rate exceeded 1.5 L min^{-1}, the mass transfer in the cylinder electrolyzer was sufficient, resulting in relatively stable COD and electrical consumption values at electrolyte flow rates ranging from 1.5 to 2.5 L min^{-1}.

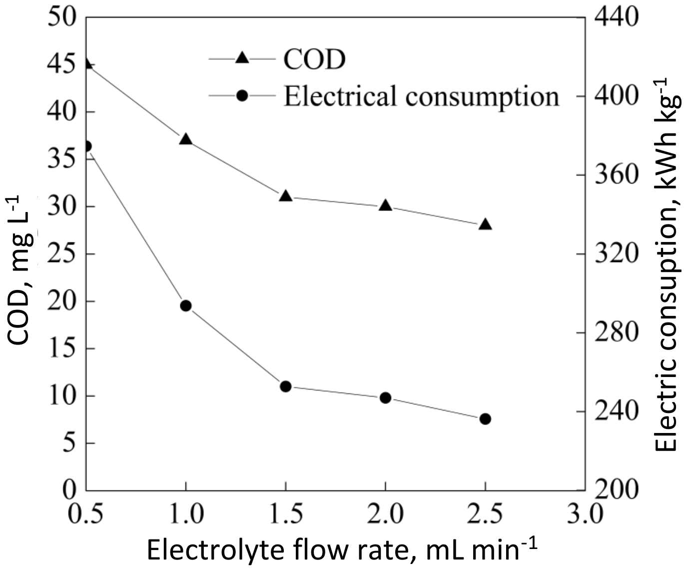

Figure 9. *COD and electrical consumption under different electrolyte flow rates at initial pH of 7.3, current density of 10 mA cm^{-2} and degradation time of 30 min*

Degradation of Acid blue 129 (AB129) could reach 87 % with original dye concentration of 25 mg L^{-1} by UV-activated persulfates for 15 min; however, the composition of real textile wastewater was much more complex than dye wastewater prepared by AB129 [37]. Therefore, the prepared dye wastewater could not accurately reflect the oxidation performance of the textile wastewater in industrial applications. Besides, the carbon emissions were not investigated in the oxidation of AB129.

As shown in Figure 10, the carbon emissions by electrochemical oxidation with 185 nm UV irradiation were gradually reduced from 213.67 to 134.71 kg CO_2 *per* kg of degraded COD with the increase of the electrolyte flow rate from 0.5 to 2.5 L min^{-1} at the current density of 10 mA cm^{-2}, the initial pH 7.3 and the degradation time of 30 min. Carbon emissions reached 144.10 kg CO_2 *per* kg of degraded COD at an electrolyte flow rate of 1.5 L min^{-1} and then remained relatively stable, consistent with the trend in electrical consumption shown in Figure 9. Carbon emissions from electrochemical oxidation with 185 nm UV irradiation, as shown in Figure 10, are a valuable approach for reducing carbon emissions in industrial textile wastewater treatment.

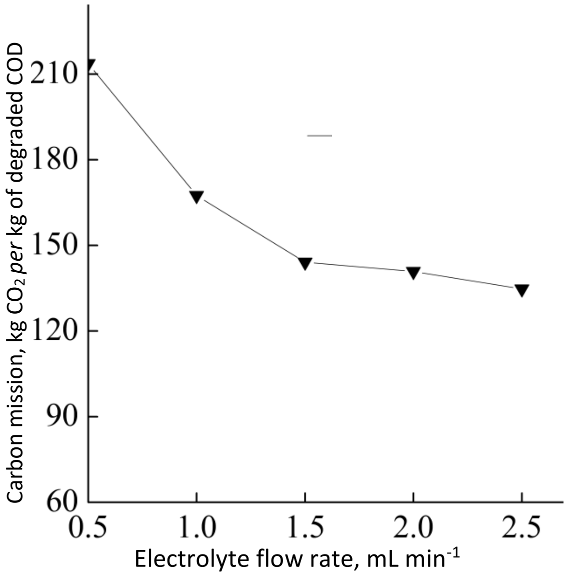

Figure 10. *Carbon emissions under different electrolyte flow rates at initial pH of 7.3, current density of 10 mA cm^{-2} and degradation time of 30 min*

Direct blue 86 dye and real textile wastewater were treated using membrane electrolysis and magnesium coagulation in a lab-scale experiment, which recycled the magnesium coagulant [38]. Although the removal performance of real textile wastewater was investigated, the composition analysis of real textile wastewater was not carried out, and the membrane electrolysis technology still faced the problem of membrane fouling. The composition analysis was conducted by GC-MS without the introduction of the membrane in the treatment process in the present study. The highest decolorization of 85 % and COD removal efficiency of 43.2 % were achieved by the UV/O_3 pressurization process at an O_3 dosage of 200 g t^{-1} and the original COD of 242.0 mg L^{-1} using a 150 W low-pressure mercury lamp (254 nm) [39]. However, the COD after the UV/O_3 pressurization process was still higher than that of China's discharge standards for urban sewage plants required and the addition of O_3 increased the cost of the wastewater treatment with the cost assessment. Ozone was generated by the oxygen dissolved in textile wastewater and the oxygen generated in the anode and the cost assessment was investigated in the present study, which was valuable for the industrial scalability.

The present study provides a practical method for textile industries seeking to comply with stringent discharge standards (COD <50 mg L^{-1}) while minimizing chemical usage and carbon emissions. The modular electrolyzer design shown in Figure 1 allows seamless integration into existing treatment processes, particularly for post-biological oxidation of refractory organics. Since analysis of variance and design of experiments (DOE) were used to investigate the impact of each parameter and their interaction effects, such as the Box-Behnken design [40,41], future research should focus on the DOE for studying the interaction effects of variables such as degradation time, current density, initial pH and electrolyte flow rate. Then, renewable energy integration should be explored to reduce further the energy consumption, carbon emissions and the cost [42]. Last but not least, the removal of emerging pollutants, such as per- and polyfluoroalkyl substances (PFAS) and microplastics, should be investigated to expand the contaminant range through electrochemical oxidation combined with 185 nm UV irradiation [43,44].

Conclusions

The COD of the textile wastewater was reduced from 74.0 to 31.0 mg L^{-1} with the energy consumption of 252.86 kWh *per* kg of degraded COD, a cost of 5.78 CNY *per* m^{-3} of textile wastewater and carbon emissions of 144.10 kg CO_2 *per* kg of degraded COD. A commercial PbO_2 mesh cylinder anode and the titanium cylinder cathode were used, where electrochemical oxidation was combined with 185 nm UV light in the cylinder electrolyzer at the initial pH of 7.3, the current density of 10 mA cm^{-2}, the electrolyte flow rate of 1.5 L min^{-1} and the degradation time of 30 min. The characterization revealed toxic aromatic compounds (2,4-Di-tert-butylphenol, oleamide and octadecanamide) in textile wastewater, which could be effectively degraded by electrochemical oxidation and 185 nm UV irradiation. The COD of the textile wastewater could be reduced to 31.0 mg L^{-1} through electrochemical oxidation with 185 nm UV irradiation, without the addition of oxidant reagents, which met the first-class standard for COD in sewage discharge from urban sewage treatment plants in China. The experimental results at pilot scale indicated that electrochemical oxidation combined with 185 nm UV irradiation had a better effect on COD removal compared with the separate application of electrochemical oxidation and 185 nm UV irradiation. Therefore, electrochemical oxidation with 185 nm UV irradiation using PbO_2 in the cylinder electrolyzer would be an effective method in the industrial application for the treatment of the textile wastewater at a pilot scale. Besides, interaction effects of variables should be investigated, as well as renewable energy integration and broader contaminant removal capabilities in future research.

Conflicts of Interest: *The authors declare no conflict of interest.*

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