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Decolorization, mineralization, and toxicity reduction of acid orange 6 by iron-sacrificed plates in the electrocoagulation process

E-E Chang,[1] Hao-Jan Hsing,[2]* Chi-Sean Ko[3] and Pen-Chi Chiang[3]

[1] *Taipei Medical University, Taipei, Taiwan*
[2] *National Science & Technology Center for Disaster Reduction, Taiwan*
[3] *National Taiwan University, Taipei, Taiwan*

Abstract: In this study, electrocoagulation (EC) was used to investigate the decolorization and mineralization of an azo dye solution, as well as biodegradation enhancement and toxicity reduction. Initial pH, flow rate, and acid orange 6 concentration were investigated, and the optimum operational parameters were found to be pH = 4, flow rate (Q) = 0.3 to 0.5 L min^{-1}, and current density = 68.3 A dm^{-2}. With these optimal parameters, total organic carbon and color removal efficiencies of 40% and 98% were achieved, respectively. Biodegradation was evaluated using the ratio of the 5-day biological oxygen demand (BOD_5) and the chemical oxygen demand (COD), which was 0.19 to 0.25 initially and increased to the range 0.25 to 0.4 after EC treatment, indicating that biodegradability was significantly enhanced. The mean effective concentration (EC_{50}) was measured to represent the toxicity of the solution. Initial EC_{50} values ranged from 25 to 6.6%, which represent extremely toxic to very toxic solutions. After EC treatment, the toxicity levels were reduced significantly, suggesting that the EC process could be a promising method for reducing the toxicity of textile wastewater.

Keywords: electrocoagulation; azo dye; decolorization; biodegradation; toxicity reduction

INTRODUCTION

The textile industry is the main consumer of commercial azo dyes. Surplus azo dyes are discharged during dyeing processes and usually contain high levels of dye residues and total suspended solids, a low ratio of 5-day biological oxygen demand to chemical oxygen demand (BOD_5/COD), and color. Without proper treatment, the discharge may increase the environmental burden and may be aesthetically displeasing for the receiving body. The residual dyes and color in wastewater cannot be removed entirely and effectively by conventional wastewater treatment technologies, i.e. sand filtration, chemical coagulation, activated sludge, etc. Some processes, such as activated carbon adsorption and ozonation, may have high removal efficiencies for residuals and color strength,[1,2] but the costs of treatment, operation, and equipment are relatively high compared to those of traditional methods. To overcome the poor treatment efficiency of textile wastewater, various pretreatments, e.g. coagulation with alum or ferric chloride followed by biological processes, are proposed to increase the biodegradability and treatability of textile wastewater.

Electrocoagulation (EC) has proved to be an excellent treatment for various industrial wastewaters[3–5] and has become a popular research topic in recent years because of tightened environmental regulations.[6,7] Usually, the electrodes in an EC reactor can be categorized into three types: monopolar electrodes in parallel connections, monopolar electrodes in series connections, and dipolar electrodes in parallel connections.[8] The EC process uses a sacrificial metal anode to produce metal hydroxides and tiny hydrogen bubbles that coagulate and form flocs, which can be separated from the wastewater effluent.

It has been proven that significant removal efficiencies can be achieved with the use of EC to treat various wastewaters, especially in the removal of fat and grease,[9–11] color and COD in textile wastewater,[3,12] and fluoride in semiconductor wastewater.[13] Some modified EC reactors have been made in recent years, including an upward-flow type used to treat Thames River water, which performed well compared to traditional horizontal-flow reactors.[14]

The target compound used in this research was an acid azo dye, acid orange 6 (AO6) with the chemical name sodium 4-(2,4-dihydroxyphenylazo) benzenesulphonate (C.I. 14 270), a common dye used in textile and food manufacturing. Some of the characteristics of this dye have been studied and reported.[15] In this present study, a sealed, continuous

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* Correspondence to: Hao-Jan Hsing, National Science & Technology Center for Disaster Reduction, 9F, 200, Section 3, Beisin Road, Xindan City, Taipei County, Taiwan 231
E-mail: hjhsing@ncdr.nat.gov.tw

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upward-flow EC reactor was developed to investigate the removal efficiency of pollutants. The objectives of this research focus on selection of control parameters. The effects of the initial stock solution pH, flow rate (*Q*), and initial AO6 concentration were evaluated with respect to color and total organic carbon (TOC) removal efficiencies. In addition, effects on biodegradation enhancement and toxicity reduction were studied.

MATERIALS AND METHODS

Materials

AO6 (structure shown in Fig. 1) was purchased from Sigma-Aldrich (USA). The molecular weight is 316 g $\mathrm{mol^{-1}}$. A stock solution containing AO6 was prepared using deionized water (conductivity = 57 μS $\mathrm{dm^{-1}}$), and NaCl (Thermo Fisher Scientific, Waltham, MA, USA; 99.8%) was added to raise conductivity. The chemicals for TOC, COD, BOD_5, and American Dye Manufacturers Institute (ADMI) tristimulus filter method analyses were purchased from Sigma-Aldrich as well. The stock solution was prepared by dissolving 0.2 g of AO6 into 1 L of deionized water (Millipore, USA) before EC experiments. The initial values of TOC, COD, and ADMI of AO6 stock solution were 32 mg $\mathrm{dm^{-3}}$, 98 mg $\mathrm{dm^{-3}}$, and 28,000, respectively. NaOH (0.2 mol $\mathrm{L^{-1}}$) or HCl (0.1 mol $\mathrm{L^{-1}}$) was used as necessary to adjust the pH of the chemicals purchased from Sigma-Aldrich (USA).

Experimental setup

The experimental apparatus consisted of an EC reactor, a peristaltic pump, and a DC power supply unit. A flow-through, short horizontal plate apparatus designed for the EC experiments, illustrated in Fig. 2, was composed of a set of six rectangular-shaped iron (99.5%) flat plates (length 18 dm, width 18 dm, thickness 0.1 dm, and distance between plates 0.5 dm) as the sacrificial electrodes; these were set apart by acrylic spacers, which formed five parallel cells with a volume of 810 $\mathrm{dm^3}$ liquid holdup. Silicon O-rings were placed between the iron plates and the acrylic spacers to prevent leakage. Cathodes and anodes were connected to the DC power supply unit separately. All parts of the EC apparatus were assembled and screwed together using 316 stainless steel bolts and nuts. Before each experiment, the plates were cleaned manually by abrading with sandpaper. After each experimental run, the iron plates were washed thoroughly with water to remove any solid residues on the surfaces and dried in the oven before being used in the next run.

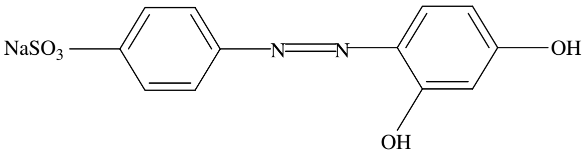

Figure 1. Molecular structure of AO6.

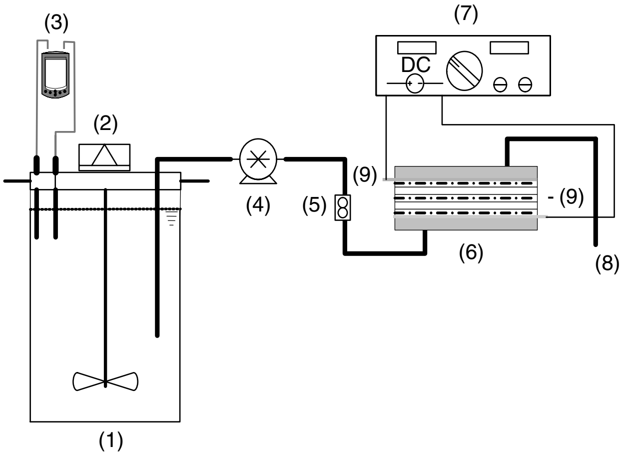

Figure 2. Flow diagram of EC reactor with short horizontal parallel plate electrodes. Component: (1) storage tank, (2) stirrer, (3) pH/conductivity meter, (4) peristaltic pump, (5) flow rate controller, (6) reactor, (7) DC power supplier, (8) exit and sampling port, (9) electrodes.

A peristaltic pump was used to transport stock solution from a storage tank through the EC apparatus, where the solution was pumped to the inlet, located on the bottom of the reactor, and flowed upward so it could pass through all the spaces between the plates, and the treated solution discharged from the exit was collected for further analysis. A variable direct current (DC) power supply (Yang Tong Co., Taiwan) was used to control the applied current output that was connected to the top and bottom iron plates of the EC apparatus.

Procedures and sampling

The pH of the prepared stock solution with AO6 = 200 mg $\mathrm{dm^{-3}}$ was pre-adjusted to 4, 7, and 10, and the conductivity was raised to 200 μS $\mathrm{dm^{-1}}$ for experimental use. The flow rates were designated as 0.3, 0.5, 0.7, and 0.9 $\mathrm{dm^3\ min^{-1}}$ and controlled by a flow controller (Cole-Palmer, USA). The current density was changed from 0 to 152.3 A $\mathrm{dm^{-2}}$ according to the predetermined experimental protocols. Before the experiment was started, the stock solution was pumped into the EC apparatus, and the DC power source was turned on simultaneously. After the flow reached steady state, samples were taken based on predetermined interval times; then, samples were filtered using 0.45 μm filter discs (MillexHV, Millipore, USA). At that point, the filtered samples were ready for further analysis. The temperature of the stock solution was maintained at 25 °C.

Analysis

The pH and conductivity of the solution were measured using a digital pH/conductivity meter (WTW, Germany). Analyses for COD and BOD_5 were performed according to the standard methods[16]. A UV-visible detector (GBC Scientific Equipment, Australia) was used to examine the absorbance of the characteristic wavelength of AO6 at 490 nm ($A_{490\mathrm{nm}}$), which could serve as an indicator of the remaining AO6 species in solution. The ADMI method was employed to evaluate the color extent; absorbance at 590, 540, and 438 nm was also determined to calculate tristimulus values. TOC concentration was measured by a TOC analyzer (O.I Corporation, USA) that utilized the UV-persulfate technique to convert the organic carbon to carbon dioxide, which was subsequently analyzed by an infrared carbon dioxide analyzer calibrated with a potassium hydrogen phthalate standard. The Microtox® test and analyzer (M500, Microbics, USA) were used to measure the acute toxicity of samples collected at various treatment times in this study. The decrease in respiration and subsequent light output of a luminescent bacterium, *Vibrio fischeri*, was measured to determine the level of toxic response. The mean effective concentration (EC_{50}) of the Microtox® analysis is the sample concentration that reduces the reagent light output by 50%,[17] and is used as an indicator of toxicity in this study. The operating procedure detailed by the manufacturer was followed. The effect measured by the Microtox® toxicological bioassay, light loss, is related to the rate of biological activity and was measured after 15 min of sample exposure time in this study.

RESULTS AND DISCUSSION

The effects of selected parameters on the removal of AO6

Initial pH

The effect of initial pH was investigated by adjusting the values of the initial pH in bulk solution to 4, 7, and 10 before transfer into the EC reactor; the results are presented in Fig. 3(a). It was observed that the effluent pH increased and approached 9.5 to 10 for all experimental runs, suggesting that the EC could provide the benefit of effluent pH adjustment. It was found that the AO6 remaining ratio (R_{AO6}), which was defined as AO6 concentration (C_t)/initial AO6 concentration (C_0), decreased as the current density increased under various initial pH conditions. The level of R_{AO6} became stable as the current density increased past 68.3 A dm^{-2}; the difference in R_{AO6} between samples with initial pH conditions of 4 and 10 with the same current density (68.3 A dm^{-2}) was 0.33, and the R_{AO6} value at pH 7 and 10 approached 0.16 as the current density reached 152.3 A dm^{-2}, which is similar to a previous finding.[9] The R_{AO6} values for initial pH conditions of 7 and 10 at current density = 152.3 A dm^{-2} differed by about 15%, suggesting that higher pH may not benefit the target compound removal significantly. Observations showed that the final pH in the effluent was always higher than the initial pH, and the difference between the initial and final pH conditions diminishes for initial pH > 7, suggesting that EC exhibited pH buffering capacity, especially in an alkaline medium.[7]

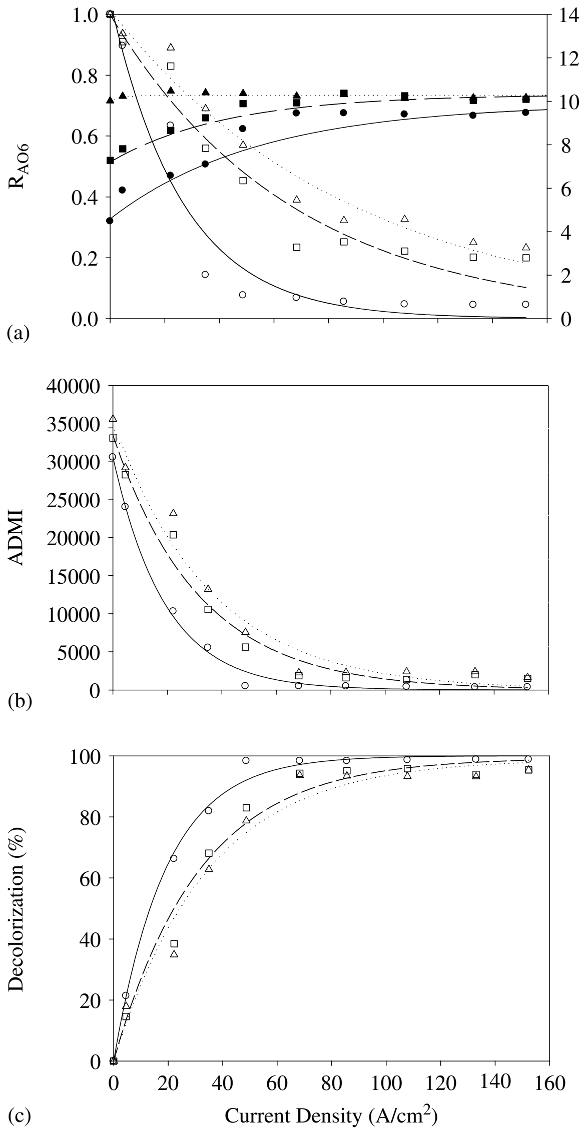

Figure 3. Effect of initial pH on (a) AO6 remaining ratio (R_{AO6}) and pH variation; (b) ADMI reduction; and (c) decolorization. Symbols and lines for R_{AO6}, decolorization, and pH in effluent: ○, ○, ●, and —: pH = 4; □, □, ■, and - - - - : pH = 7, □, □, ▲, and ....: pH = 10.

The sacrificial iron plates released ferrous (Fe^{+2}) ions during electrolysis that could react with the HO^- produced in the cathode to form Fe^{+2} hydroxo complexes with hydroxide ions and polymeric species.[18,19] Thus, two mechanisms were proposed to describe the reaction:[21]

$$\text{Anode} \qquad Fe \longrightarrow Fe^{2+} + 2e^- \qquad (1)$$

$$\text{Cathode} \qquad 2H_2O + 2e^- \longrightarrow 2OH^- + H_2 \qquad (2)$$

Fe^{+2} ions were released into solution which could be examined using an atomic absorption spectrometer. Based on the Pourbaix diagram,[22] complexes of $Fe(OH)_n$ were formed, and the majority were $Fe(OH)_2{}^+$ and $Fe(OH)^{2+}$ for pH conditions ranging between 5 and 10, which was within the operation range in the present experiment and the textile wastewater collected from the equalization tank as reported.[23] A portion of AO6 could coagulate with

Fe^{+2} hydroxo complexes to form flocs and be removed, which could contribute to the AO6 reduction.

The decolorization of treated AO6 solution under three pH conditions was monitored by measuring the ADMI value in effluents; the results are shown in Fig. 3(b). The ADMI reduced rapidly from 35 000–40 000 to below 1600 ADMI as the current density increased to 152.3 A dm^{-2} at $Q = 0.5\,dm^3\,min^{-1}$. As seen in Fig. 3(b), the ADMI decrease rate slows as the current density exceeds 68.3 A dm^{-2}, and the effective reduction was minimal, even as the current density was increased to 152.3 A dm^{-2}, indicating that the best color removal was achieved and an optimal operating voltage range was identified. Furthermore, the decrease rate of ADMI is lower for $pH = 10$ than for $pH = 4$ and 7, suggesting that better decolorization was achieved at lower pH conditions. The decolorization was defined as follows:

$$\text{Decolorization} = (1 - ADMI_t/ADMI_0) \times 100\% \qquad (3)$$

In comparing the voltage needed to reach 90% decolorization for three different initial pH conditions, the $pH = 4$ solution required the lowest current density (about 48.7 A dm^{-2}) to reach 90% decolorization within 5 min of treatment (as shown in Fig. 3(c)), indicating that lowering the initial pH could reduce the current density needed to achieve the same extent of decolorization. As the initial pH rose, it was difficult to reach 96% decolorization, even after raising the current density to 152.3 A dm^{-2}. The decolorization was consistent with AO6 removal, which was due to the coagulation of $Fe(OH)_n$ with AO6 molecules to form flocs, which were removed; this mechanism was similar to the chemical coagulation process applied in wastewater treatment plants.

Flow rate

The effect of flow rates, which were set at 0.3, 0.5, 0.7, and $0.9\,dm^3\,min^{-1}$, on AO6 removal, ADMI reduction, and decolorization were investigated; the corresponding residence times for applied flow rates were 2.7, 1.6, 1.2, and 0.9 min respectively; the results are shown in Fig. 4. The level of R_{AO6} was the lowest at $Q = 0.3\,dm^3\,min^{-1}$ (Fig. 4(a)). The R_{AO6} values at low rates increasing from 0.3 to $0.9\,dm^3\,min^{-1}$ increased from 0.06 to 0.15 at a current density of 68.3 A dm^{-2}, indicating that the AO6 removal efficiencies decreased as flow rates increased but still remained relatively high. It also was noted that the R_{AO6} values approached a steady state (about 0.05 to 0.08) as the current density became greater than 68.3 A dm^{-2} within 5 min of treatment, proving that a current density of 68.3 A dm^{-2} could be a critical factor for the treatment of AO6 solution.

Figure 4(b) illustrates the effect of flow rates on ADMI reduction, similar to that demonstrated for R_{AO6}. The reduction level for both parameters was at least 0.96, provided the initial solution $pH = 4$. When $Q = 0.3\,dm^3\,min^{-1}$, ADMI was reduced to about 500. The ADMI values for the other three flow rates were 550, 770, and 968, respectively.

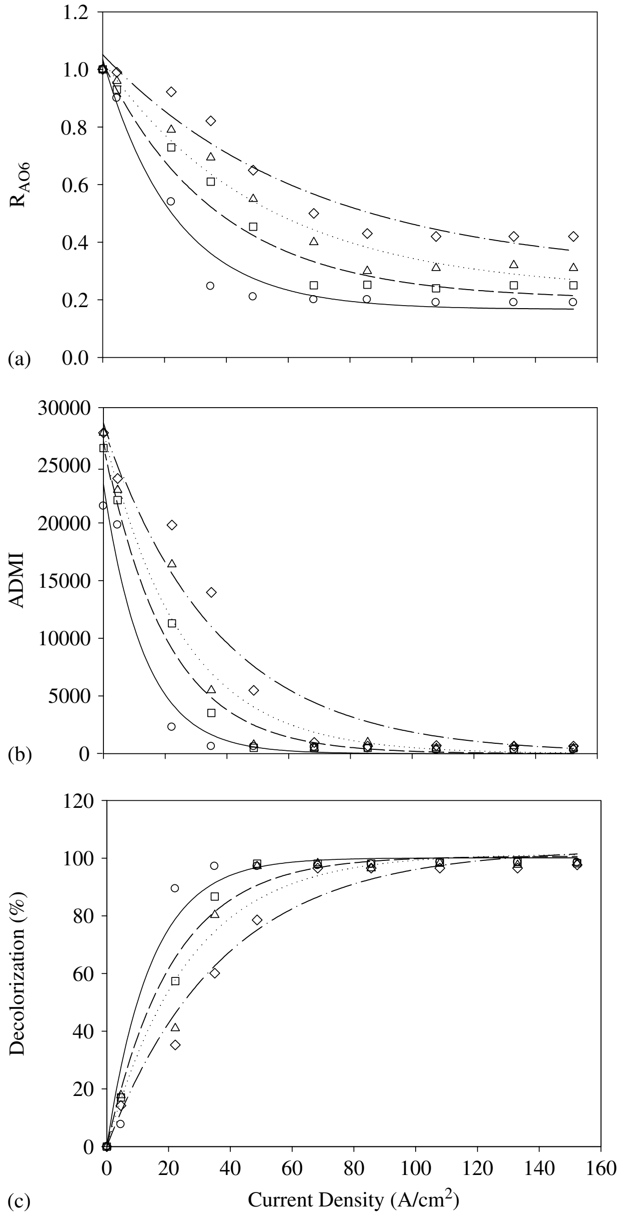

Figure 4. Effect of flow rate on (a) AO6 remaining ratio (R_{AO6}); (b) ADMI reduction; and (c) decolorization. Symbols and lines for R_{AO6} and ADMI: ○ and ——: flow rate = $0.3\,dm^3\,min^{-1}$, □ and - - - - : flow rate = $0.5\,dm^3\,min^{-1}$, □ and .....: flow rate = $0.7\,dm^3\,min^{-1}$, ◇ and –· –: flow rate = $0.9\,dm^3\,min^{-1}$.

Among the experiments performed at the four different flow rates, the lowest current density needed to reach 90% decolorization was required for the case with the lowest flow rate (35.0 A dm^{-2} for $0.3\,dm^3\,min^{-1}$, 48.7 A dm^{-2} for $0.5\,dm^3\,min^{-1}$, 59.8 A dm^{-2} for $0.7\,dm^3\,min^{-1}$, and 85.6 A dm^{-2} for $0.9\,dm^3\,min^{-1}$), as shown in Fig. 4(c). The longer period of time that the solution spent flowing through the reactor at low flow rates allowed for more thorough removal of AO6 and a further extent of decolorization. Moreover, it also was observed that higher ADMI removal was achieved at lower flow rates. For example, the ADMI removal rates for $Q = 0.3$ and $0.9\,\mathrm{dm^3\,min^{-1}}$ were 98 and 41% when the current density was $35.0\,\mathrm{A\,dm^{-2}}$. As a result, it was concluded that lower flow rate conditions could contribute significantly to more effective decolorization. From Fig. 4, the AO6 removal, ADMI reduction, and decolorization were functions of flow rate. The flow rate could reflect the residence time of liquid in the reactor; high flow rate represented a short residence time. Higher residence time meant the solution with AO6 remained in the EC reactor longer, indicating that more $Fe(OH)_n$ generated at the anode could mix thoroughly with AO6 molecules. For the higher flow rates, the residence time would be lower, and a lower coagulation rate would be expected. Thus, the low flow rate could enhance the coagulation effect of AO6 removal in the presented experiments.

Acid orange 6 concentrations

Three concentrations, 50, 100, and $200\,\mathrm{mg\ dm^{-3}}$, were chosen to investigate the concentration effect on the removal of target compounds and color during EC experiments; the results of these experiments are shown Fig. 5. It was observed that the R_{AO6} decreased significantly as solution flowed through the EC reactor and approached a steady state within 5 min of electrolysis, except for the case of AO6 = $200\,\mathrm{mg\,dm^{-3}}$, which reached a steady R_{AO6} value after 10 min, as seen in Fig. 5(a). The R_{AO6} difference for three dye concentrations ranged from 0.17 to 0.05, suggesting that the iron ions generated at the anode were not sufficient to coagulate most AO6 molecules found in the effluent under high concentration conditions by examining the characteristic wavelength of AO6.

The initial ADMI values were 9200, 23 000, and 51 000, corresponding to AO6 = 50, 100, and $200\,\mathrm{mg\ dm^{-3}}$, respectively. After treatment, the values decreased to 210, 830, and 1400, respectively (as shown in Fig. 5(b)). The decrease trend was similar to that of R_{AO6} because of the reduction of AO6 molecules. The important mechanism of decolorization by EC was coagulation; AO6 molecules would be swept off by being adsorbed on iron hydroxide flocs,[13] which would result in a reduction of absorbance in visible wavelengths. It was clear that lower dye concentration could achieve better decolorization efficiency as expected. As the concentration reached $200\,\mathrm{mg\ dm^{-3}}$, the capacity of the iron hydroxide flocs was not sufficient, and the rate of decolorization was considerably slowed (as shown in Fig. 5(c)). Recycling the treated solution will be explored in a further investigation as a potential means to improve the removal efficiency at higher dye concentration.

Removal of COD, TOC, and BOD

Figure 6 illustrated the effects of current density, flow rate, and initial pH on TOC reduction (TOC/TOC_0) as well as the temperature change during electrolysis.

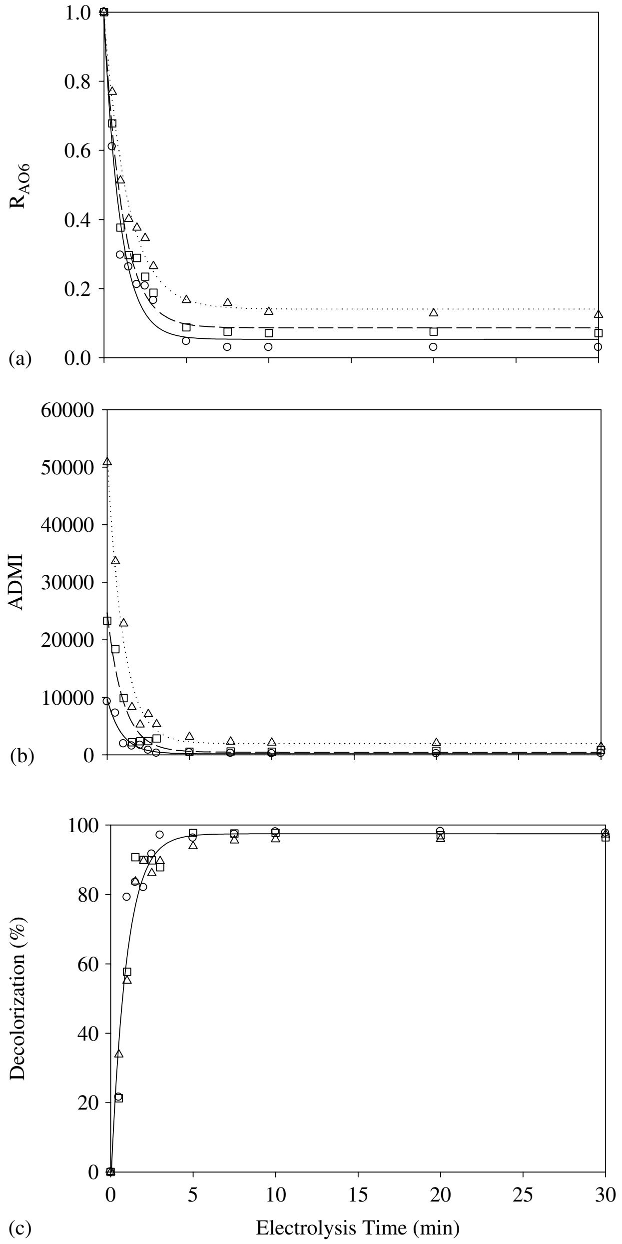

Figure 5. Effect of initial AO6 concentration on (a) AO6 remaining ratio (R_{AO6}); (b) ADMI reduction; and (c) decolorization. Symbols and lines for R_{AO6}, ADMI, and decolorization: ○ and ——: AO6 = $50\,\mathrm{mg\,dm^{-3}}$, □ and - - - - : AO6 = $100\,\mathrm{mg\,dm^{-3}}$, □ and ....: AO6 = $200\,\mathrm{mg\,dm^{-3}}$.

In Fig. 6(a), it was observed that low flow rates resulted in better TOC reduction, which was the same as ADMI reduction. For the case $Q = 0.3\,\mathrm{dm^3\ min^{-1}}$, the extent of TOC reduction was smaller than that for $Q = 0.9\,\mathrm{dm^3\ min^{-1}}$. The difference was about 0.2 at a current density = $68.3\,\mathrm{A\,dm^{-2}}$ within 5 min. As the current density increased from 68.3 to $152.3\,\mathrm{A\ dm^{-2}}$, the difference in TOC reduction for the case $Q = 0.3\,\mathrm{dm^3\ min^{-1}}$ was only 0.03 compared to about 0.1 at $Q = 0.9\,\mathrm{dm^3\ min^{-1}}$, indicating that the effect of higher current density was more remarkable at high flow rates. The observed temperature of the effluent increased from 25 °C to about 50 °C (as shown in Fig. 6(a)), which was due to heat release in the electrolysis process. The temperature increment was significant

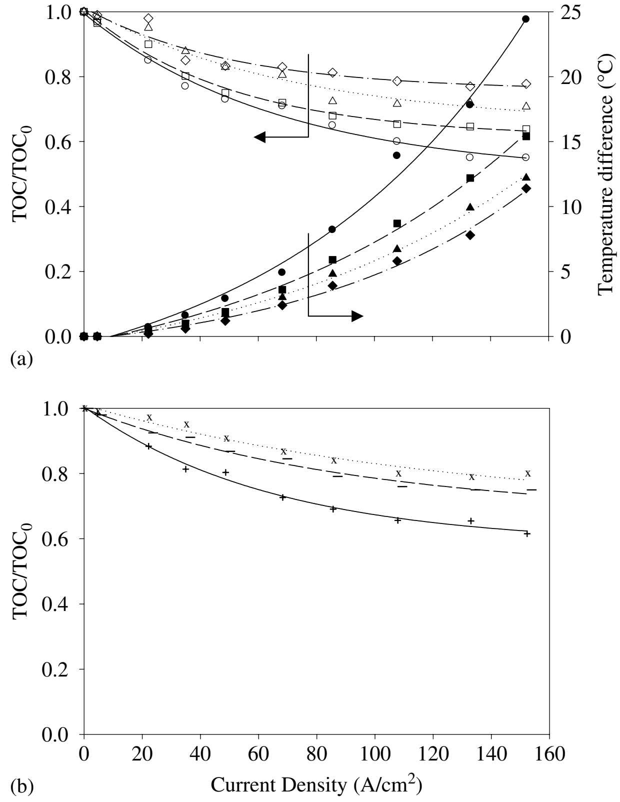

Figure 6. The (a) flow rate and (b) initial pH effect on TOC reduction (TOC/TOC$_0$). Symbols and lines for the effect of flow rate and temperature difference: ○, ● and ——: flow rate = 0.3 dm^3 min^{-1}; □, ■ and - - - - : flow rate = 0.5 dm^3 min^{-1}; △, ▲ and ….: flow rate = 0.7 dm^3 min^{-1}, ◇, ◆ and –· –: flow rate = 0.9 dm^3 min^{-1}. Symbols and lines for the effect of initial pH (pH$_{in}$): + and ——: pH$_{in}$ = 4; —— and - - - - : pH$_{in}$ = 7; × and ….: pH$_{in}$ = 10.

at lower flow rates because of the longer period of time during which the solution flowed through the EC reactor; the time for $Q = 0.3\,dm^3\,min^{-1}$ is 2.7 min compared with 0.9 min for $Q = 0.9\,dm^3\,min^{-1}$. Thus, the solution was heated while flowing through the channel, and it could be taken as a plug flow system.

Under the same flow rate ($Q = 0.5\,dm^3\,min^{-1}$) conditions (Fig. 6(b)), the effect of initial pH was investigated. The best TOC reduction, about 0.38, was observed for the solution with initial pH 4 at current density 68.3 A dm^{-2}, but the difference for initial pH 7 and 10 was not significant. This suggests that a high initial pH and pH increase during the operation would result in lower TOC removal efficiency. For initial pH > 7, TOC removal efficiency was between 0.13 and 0.18, which is less than 50% of that obtained for the pH 4 case. TOC reduction continued as the current density increased and reached 0.62, 0.73, and 0.7 at initial pH 4, 7, and 10, respectively. TOC reduction was consistent with the removal of AO6 by the coagulation of iron hydroxide generated at the anode, which was a physical mechanism to reduce the organic content in solution. Due to the temperature rise in the solution, TOC removal kinetics is not discussed in this present study.

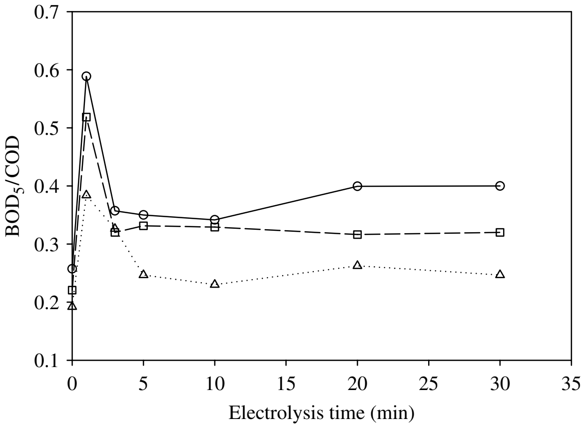

Figure 7. Variation of biodegradability (BOD5/COD) for various AO6 concentrations by EC treatment. Symbols and lines: ○ and ——: AO6 = 50 mg dm^{-3}; □ and - - - - : AO6 = 100 mg dm^{-3}; △ and ….: AO6 = 200 mg dm^{-3}.

Enhancement of biodegradability

BOD$_5$/COD was considered as an indicator of the biodegradability of the AO6 solution after EC treatment and was examined at three different AO6 concentrations (50, 100, 200 mg dm^{-3}). As shown in Fig. 7, the initial BOD$_5$/COD values for three AO6 concentrations ranged from 0.19 to 0.25 at electrolysis time = 0 min, which reflected poor biodegradability and suggested that biodegradation could not be enhanced significantly without further treatment. As AO6 solution was pumped into the EC reactor, samples were taken and analyzed. The BOD$_5$/COD values increased swiftly within 1 min of treatment for all three cases examined. For the case AO6 = 50 mg dm^{-3}, the value increased to about twice its original value (0.24) to about 0.59; then, the value was maintained in a range between 0.35 (10 min) and 0.41 (30 min). Similar trends were observed for the other two AO6 concentrations within the first minute of treatment. That may due to more BOD$_5$ generated under unsteady state which needs further investigation.

The highest BOD$_5$/COD values were obtained at an electrolysis time of 1 min; then, the values decreased to a relatively steady extent for three experimental concentrations. The increase in BOD$_5$/COD was about 145 and 126% of the initial values for AO6 = 100 and 200 mg dm^{-3} at electrolysis time 30 min, respectively, indicating that biodegradation decreased as the target compound concentration increased. Furthermore, the BOD$_5$/COD values were maintained in a similar range for each AO6 concentration as the electrolysis time was lengthened to 30 min; the values were 0.4 (AO6 = 50 mg dm^{-3}), 0.33 (AO6 = 100 mg dm^{-3}), and 0.25 (AO6 = 200 mg dm^{-3}). The explanation for BOD$_5$/COD variation could be that the insoluble form of organic matter was coagulated by iron ions, then removed by sedimentation and floatation processes from the treated solution. The results suggest that (1) the EC process could enhance biodegradation remarkably; (2) biodegradability decreased as

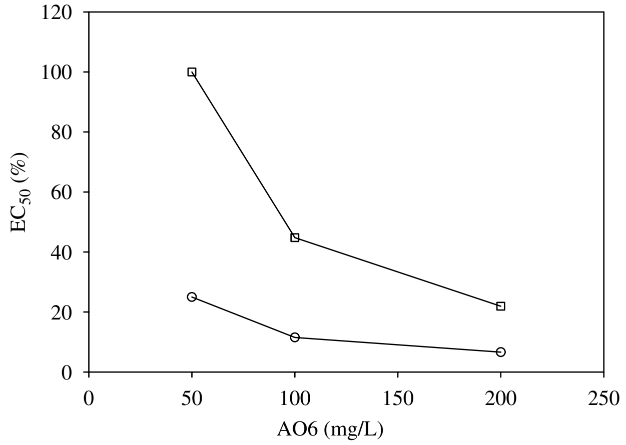

Figure 8. Variation of EC50 for various AO6 concentrations. Symbol: ○: before EC treatment, ◇: after EC treatment.

the target compound concentration increased; and (3) biodegradability enhancement was not strong at high concentrations, which might be due to the constraints of contact area in the reactor, applied current, and electrodes.

Toxicity reduction

The Microtox® test kit was used to evaluate the toxicity, expressed by the EC_{50}, before and after EC treatment by collecting samples at electrolysis time 0 and 30 min. As shown in Fig. 8, the EC_{50} values for the AO6 solution before EC treatment ranged from 25% to 6.6% at AO6 concentrations increasing from 50 to 200 mg dm^{-3}. The EC_{50} values of tested samples were defined as toxic based on a reported scale.[20] After EC treatment, the EC_{50} reached 100% for AO6 = 50 mg dm^{-3}, and decolorization approached 100%, indicating that the byproducts were nontoxic. The EC_{50} values were only about 44 and 22% for AO6 = 100 and 200 mg dm^{-3}, respectively, and the decolorization was not complete for both cases, indicating that a certain amount of AO6 and some toxic byproducts existed. Compared to the initial EC_{50} values, the experimental results revealed that the toxicity for treated samples was reduced, suggesting that EC treatment could reduce toxicity. As a result, it could be concluded that AO6 is inherently toxic and that the toxicity can be reduced by EC treatment. Although the AO6 concentration could affect the level of toxicity, the relationship between the initial AO6 concentration and the toxicity level was nonlinear.

CONCLUSIONS

Controlling factors for the EC process were investigated with regard to the effect on decolorization, mineralization, and toxicity reduction of the AO6 solution. The experimental results and conclusions can be summarized as follows:

- The optimum operational pH to achieve better decolorization and mineralization was found to be 4, compared to 7 and 10.
- The optimum controlling factors were found to be $Q = 0.3$ to $0.5\,\mathrm{dm^3\,min^{-1}}$, current density = $68.3\,\mathrm{A\,dm^{-2}}$, resulting in removal efficiencies for ADMI and TOC of 98 and 40%, respectively.
- Initial BOD_5/COD ratios were 0.19 to 0.25, which suggests poor biodegradability. After the EC process, the average values reached about 0.33, indicating enhanced biodegradability.
- Initial EC_{50} values ranged from 25 to 6.6%, which represent extremely toxic to very toxic solutions. After EC treatment, the EC_{50} increased to 100% for AO6 = 50 mg dm^{-3}, indicating that the toxicity levels were reduced significantly. For the other two experimental cases, the toxicity was reduced from extremely toxic to toxic, suggesting that the EC process could be a promising method to reduce the toxicity of textile wastewater.

The experimental results indicate that the decolorization efficiency was significant, but the desired level of mineralization was not achieved. Thus, some other treatment processes are needed to improve the overall treatment efficiency, such as a combination of biological treatment EC or EC followed by ozonation. In addition, water recycling and reuse in manufacturing processes should be considered.

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