

Reduction of natural organic matter by an electrolytic process, conventional coagulation and direct descending filtration in a pilot-scale water treatment system

Victor Cochrane Santiago Sampaio, Eliezer Fares Abdala Neto, Ari Clecius Alves de Lima, Isabel Cristina Lima Freitas and Marisete Dantas de Aquino

ABSTRACT

Recently, alternative water treatment systems have been implemented due to the eutrophication of reservoirs, in which high concentrations of organic matter prevent the use of conventional water treatment methods. This paper presents a study on the electrolytic process for water treatment using an alternating current. A reactor with iron and stainless steel electrodes was built and introduced into a water treatment system equipped with conventional coagulation with alum and direct descending filtration. Factors such as pH levels, turbidity, colour, and reductions in the specific UV absorbance were evaluated. The results showed a significant reduction in the specific UV absorbance between raw water and treated water (19.51–26.45%). Furthermore, the reactor did not significantly change the pH of the water. The average turbidity of the treated water was less than or equal to 0.5 NTU, and the average colour reached 2 HU, classifying the treated water as drinking water according to the current ordinance in Brazil. The cost of the electricity used by the reactor was \$0.10 per cubic metre of water produced.

Key words | electrolytic process, natural organic matter, water treatment

Victor Cochrane Santiago Sampaio
(corresponding author)

Eliezer Fares Abdala Neto

Ari Clecius Alves de Lima

Marisete Dantas de Aquino

Departamento de Engenharia Hidráulica e Ambiental,

Universidade Federal do Ceará, Bloco 713, Avenida Humberto Monte S/N, Campus do Pici,

Fortaleza-CE, CEP 60451-970,

Brasil

E-mail: cochrane@ibest.com.br

Isabel Cristina Lima Freitas

Gerência de Desenvolvimento Operacional, Pesquisa e Inovação, Estação de Tratamento de

Água – Gavião,

Companhia de Água e Esgoto do Ceará,

Fortaleza-CE,

Brasil

INTRODUCTION AND OBJECTIVES

The population explosion associated with rapid urbanisation and industrial and technological development in recent years has increased the demand for water. Furthermore, the effluent generated from various urban activities negatively impacts water reserves, leading to a deterioration of the quality of surface and groundwater and often precluding its use. To meet the needs of human consumption and the activities that require high quality water, it is necessary to provide endowed supply systems for water treatment plants that meet potability standards established by the Ordinance enforced in the country (Lima 2011).

In the state of Ceará, Ponte *et al.* (2013) note that high algal content and high colour and turbidity are major problems in reservoirs. Sales (2005) highlights the need to enter a stage of pre-oxidation in a water treatment plant to

remove natural organic matter that originates from humic substances (humic and fulvic acids). These substances form halogens, mainly trihalomethanes.

The electrolytic process has emerged as an efficient technology applied in environmental sanitation. Electrolysis is a non-spontaneous process that requires the use of an electric current, which usually adds oxidation, flotation and coagulation (Atkins & Jones 2001). Electrolysis is based on the use of electrodes (sacrificed or not) with reversible polarity, and coagulant ions can be generated from the anode and hydrogen bubbles at the cathode, which causes the flotation of flakes (Rubio *et al.* 2002). It is a simple, low-cost and versatile automated process, requiring only a small area of the treatment plant. In addition to the benefits to public health from not using potentially toxic chemicals,

it is a particularly clean process because the electron is the main reagent (Gusmão *et al.* 2010; Ribeiro *et al.* 2013).

The electroflotation process acts as a solid/liquid separator based on the suspension of particles by gas bubbles (hydrogen and oxygen) that are generated on the surface of the electrodes (Araya-Farias *et al.* 2008). In conventional flotation processes, the diameter of the bubbles produced varies between 600 and 1,000 micrometres. Because the diameters are too large, these bubbles are not effective for the flotation of particles with diameters less than 20 micrometres. However, electroflotation can produce bubbles with a diameter between 15 and 80 micrometres, which are efficient for the flotation of small particles (Sarkar *et al.* 2011).

Jeong *et al.* (2006) and Curteanu *et al.* (2011) argue that the use of an inert electrode, besides active chlorine, can also be used for the formation of reactive oxygen compounds, such as $\cdot\text{OH}$, O_3 , H_2O_2 and $\cdot\text{O}_2^-$. However, the electrodes may generate an iron coagulant effect and cause increased flakes. According to Phalakornkule *et al.* (2010), the coagulant produced by the electrolytic oxidation of iron in the electrodes may be in the form of hydroxides or highly charged ions, such as $\text{Fe}(\text{H}_2\text{O})_6^{3+}$, $\text{Fe}(\text{H}_2\text{O})_5(\text{OH})^{2+}$, $\text{Fe}(\text{H}_2\text{O})_4(\text{OH})_2^+$, $\text{Fe}_2(\text{H}_2\text{O})_8(\text{OH})_2^{4+}$ and $\text{Fe}_2(\text{H}_2\text{O})_6(\text{OH})_4^{4+}$.

The electrolytic process has been applied in several studies in recent years. Abdala Neto & Aquino (2012) compared a photoreactor (electro-oxidation and heterogeneous photocatalysis) with other pre-oxidants in a water treatment system. The photoreactor reached a higher removal efficiency for turbidity (99.5%), chemical oxygen demand (65.50%) and chlorophyll 'a' (98.97%). In addition, it achieved a greater reduction in the amount of trihalomethanes (77.20 mg L^{-1}) compared with the other pre-oxidants. Qi-yan *et al.* (2007) investigated various process variables in the use of aluminium electrodes to remove humic acid from water. Within 60 minutes, this process removed 97.8% of the humic acid with a current density of 4.76 mA cm^{-2} and a 1.0 cm spacing between the electrodes in a pH acid. Benhadji *et al.* (2011) investigated the application of electrocoagulation with aluminium electrodes in tannery wastewater. With a current density of 7.5 mA cm^{-2} for 45 minutes, there was a reduction of over 90% for biochemical oxygen demand, chemical oxygen demand, turbidity, chromium, iron and nitrate.

Some studies have demonstrated the application of the electrolytic process in the removal of contaminants in drinking water. Kobya *et al.* (2011) obtained an arsenic removal efficiency of 95.7% with aluminum electrodes and 93.5% with iron electrodes. Using aluminum electrodes, Vasudevan *et al.* (2011) removed 98.2% of chromium present in the water.

This process can also remove anions and cations. In addition to removing fluoride ions with the use of aluminum electrodes (Zuo *et al.* 2008; Bennajah *et al.* 2009; Zhao *et al.* 2009; Un *et al.* 2013), Kumar & Goel (2010) removed 84% of nitrate in water with mild steel electrodes. Malakootian *et al.* (2010) removed 98.2 and 97.4% of calcium and total hardness, respectively.

The objective of this research was to investigate the removal of natural organic matter by electrolytic processes (electroflotation, electro-oxidation and electrocoagulation) operating on alternating current and using electrodes made of carbon steel and stainless steel for treating water that is used for human consumption. Furthermore, energy consumption, the parameters of water clarification (turbidity and colour), and the variation of pH in the process were evaluated following the guidelines related to the maximum values established by Ordinance No. 2914 (Brasil 2011), which sets forth procedures for the control and surveillance of water quality for human consumption and its potability standards.

MATERIALS AND METHODS

The experiment was conducted at the Research Center for Companhia de Água e Esgoto do Ceará, located in the annexed area of the Gavião Water Treatment Plant (WTP Gavião), which is in the municipality of Pacatuba.

The reactor was made of acrylic with a thickness of 10 mm and was divided into three chambers, as shown in Figure 1(a). Between each chamber, four holes were made with a diameter of 1.28 cm for possible contact with substances generated in the electrolytic process with water. The dimensions of the working volume were 22.5 cm high, 24.0 cm wide, and 30.0 cm long (giving a useful volume of 16.2 litres). In the first chamber, iron electrodes (carbon steel 1080) were used; in the second and third chambers,

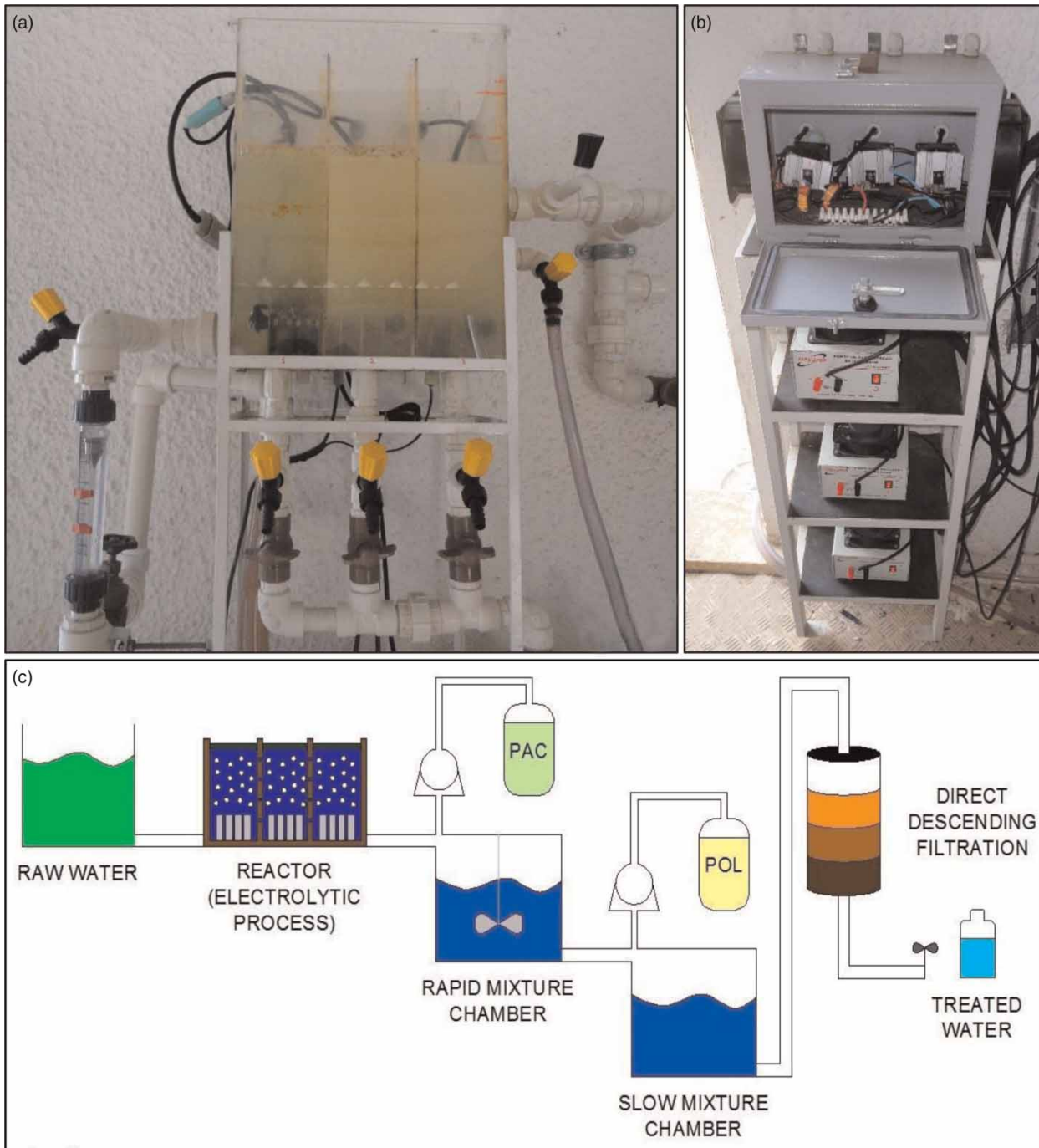


Figure 1 | (a) The electrolytic process reactor, (b) the source of 13.8 V to the alternating current circuits, and (c) a schematic of the water treatment plant on a pilot scale.

electrodes of stainless steel (316L stainless steel) were used. All electrodes measured 20.0 cm long, 5.0 cm tall and 0.2 cm thick. The average current density was 1.83 mA cm^{-2} for the iron electrodes and 4.10 mA cm^{-2} for the stainless steel electrodes.

Three sources of stabilised power (HY1300 Hobby™, Hayama®) were used for operation at 13.8 volts for the alternating current, as shown in Figure 1(b). A cooler was attached to each power supply, and two coolers were coupled to the circuit box to help dissipate heat generated

by electronic components. To evaluate the electrical energy consumed by the process, the power of the system was recorded by a D02A™ power meter (Wanf[®]).

Figure 1(c) shows a sketch of the premises of the pilot WTP. The raw water was pumped from the Gavião Dam to the area used in the experiment, where it was subjected to the electrolytic process, coagulation (addition of coagulant (PAC) in a rapid mixture chamber), flocculation (addition of polymer (POL) in a slow mixture chamber), direct descending filtration and collection of treated water. After the end of filtration career (total operation time from the beginning to passing the filter), the filter was cleaned with the backwash process.

A flow rate of raw water of 10 L min⁻¹, the maximum throughput supported by the pilot WTP, was adopted to produce the maximum amount of water. Thus, the hydraulic detention time in the reactor was 1.62 minutes. The experiment was performed in triplicate (C1, C2 and C3), and for every 0.5 hour, a collection was performed and measurements of the pH, turbidity and colour of the raw water, reactor water and water treated, as well as the pressure drop of the filter, were taken. Every hour, samples were collected to measure the specific ultraviolet absorbance (SUVA) and free residual chlorine from treated water.

The filter used had an internal diameter of 150 mm, a height of 3 m, a sand filter bed thickness of 70 cm, grain sizes ranging from 0.42 to 1.41 mm, a filtration flow of 4 L min⁻¹, and a filtration rate of 326 m³ m⁻² day⁻¹. The coagulant used was polyaluminium chloride (PAC 23™) at a concentration of 6.0 mg L⁻¹, aided by liquid cationic polymer (polyDADMAC™) at 2.0 mg L⁻¹. To measure the pressure drop of the filter, an MPD-79™ differential micro-manometer (Instrutherm[®]) was used.

The analytical methods followed the general guidelines of *Standard Methods for the Examination of Water and Wastewater* (APHA 2012). The pH was determined using a PG 1800™ pH meter (Gehaka[®]), turbidity was determined using a 2100P™ turbidimeter (Hach Company[®]), and apparent colour was determined by visual comparison using DLNH-100™ equipment (Del Lab[®]). The free residual chlorine was determined by titration using DPD (Method 4500 Cl F).

To determine the SUVA (Equation (1)), the samples were filtered on a vacuum filtration system with nylon membranes (Millipore[®]) with a diameter of 47 mm and pores from 0.45 micrometres. Dissolved organic carbon (DOC)

was measured using a TOC-L™ analyser (Shimadzu[®]), and absorbance at 254 nm was measured using a Cary 60 UV-Vis™ spectrophotometer (Agilent[®]).

SUVA (L · mg⁻¹ · M⁻¹)

$$= \frac{\text{Specific ultraviolet absorption at 254 nm (cm}^{-1}\text{)}}{\text{Dissolved organic carbon (mg} \cdot \text{L}^{-1}\text{)}} \times 100 \quad (1)$$

To verify whether there was a significant difference between the raw water, the reactor water and treated water, the Tukey test at a 95% confidence interval was used. The objective of this test was to determine which groups of samples showed differences. The groups were represented by the letters A, B and C. This procedure was performed by the R Project for Statistical Computing[®].

RESULTS AND DISCUSSION

Table 1 shows the values of the pressure drop on the filter along the filtration career and the free residual chlorine in the treated water.

The average time of filtration careers was 3 hours, and the pressure drop was similar for every 0.5 hour. The final pressure drop was approximately 1.30–1.32 mH₂O, at which the filter was overflowing. According to Kuroda (2006), the increased pressure drop may be due to the presence of phytoplankton organisms in the water, causing filter clogging and necessitating an increased frequency of washing.

The samples of treated water showed traces of free residual chlorine (0.04–0.07 mg L⁻¹). The production of

Table 1 | Values of the pressure drop of the filter and the free residual chlorine in the treated water

Time (h)	Pressure drop (mH ₂ O)			Free residual chlorine (mg L ⁻¹)		
	C1	C2	C3	C1	C2	C3
0.5	0.26	0.28	0.27	–	–	–
1.0	0.45	0.45	0.42	0.06	0.05	0.05
1.5	0.67	0.66	0.60	–	–	–
2.0	0.88	0.88	0.85	0.07	0.07	0.04
2.5	1.10	1.09	1.05	–	–	–
3.0	1.32	1.30	1.30	0.05	0.07	0.05

chlorine in the process may have occurred as a result of the oxidation of chloride ions at the anode, as shown in Equation (2)



With the production of free residual chlorine, there is evidence of oxidation caused by the electrolytic process. The presence of chlorine in water can generate hypochlorous acid, which is an efficient disinfectant (Equation (3)) that dissociates and forms the hypochlorite ion (Equation (4)).



The pH, turbidity and colour values are shown in Table 2. For each parameter of each career, a Tukey test with 95% confidence interval was applied.

The average of pH, turbidity and colour of treated water of the filtration careers were compared with the maximum values established by Ordinance No. 2914 (Brasil 2011), which are between 6.0 and 9.0 for pH, 0.5 NTU for turbidity and 15 TCU for colour.

The results show that there was no significant difference between the pH of the raw water and the water that was pre-treated by the reactor (group A). Thus, there was no need to insert a step of pH adjustment during treatment. However, the pH of the treated water was significantly different (group B) from both the untreated water and pre-treated water by the reactor, which was most likely a result of chemical coagulation (clotting and coagulation aid).

Table 2 | pH, turbidity and colour values of the three filtration careers and average

Time (h)	Sample	pH			Turbidity (NTU)			Colour (TCU)		
		C1	C2	C3	C1	C2	C3	C1	C2	C3
0.5	Raw	8.4	8.4	8.4	5.1	4.7	4.2	50	50	50
	Reactor	8.4	8.4	8.3	8.7	12.1	16.5	125	250	400
	Treated	7.7	7.8	7.8	0.6	0.3	0.4	3	2	2
1.0	Raw	8.4	8.4	8.4	4.9	5.3	4.0	50	50	50
	Reactor	8.4	8.4	8.4	9.1	11.2	12.9	125	250	250
	Treated	7.9	7.8	7.9	0.5	0.3	0.3	2	1	2
1.5	Raw	8.4	8.4	8.4	5.4	4.7	4.3	50	50	50
	Reactor	8.4	8.4	8.4	7.1	10.1	10.2	125	250	200
	Treated	7.9	7.9	7.9	0.3	0.3	0.5	2	1	2
2.0	Raw	8.5	8.5	8.4	4.8	4.5	4.8	50	50	50
	Reactor	8.5	8.5	8.3	7.2	9.4	9.2	150	200	150
	Treated	7.9	7.9	8.0	0.3	0.2	0.5	2	1	2
2.5	Raw	8.4	8.4	8.4	4.6	4.5	4.9	50	50	50
	Reactor	8.4	8.4	8.4	7.3	10.2	13.9	125	250	300
	Treated	7.9	7.9	8.0	0.3	0.3	0.5	1	2	1
3.0	Raw	8.4	8.4	8.4	5.3	4.8	4.4	50	50	50
	Reactor	8.4	8.4	8.4	7.8	9.5	9.8	150	200	250
	Treated	8.0	8.0	8.1	0.3	0.5	0.5	2	2	2
Average	Raw	8.4 ^A	8.4 ^A	8.4 ^A	5.0 ^B	4.8 ^B	4.3 ^B	50 ^B	50 ^B	50 ^B
	Treated	7.9 ^B	7.9 ^B	8.0 ^B	0.4 ^C	0.3 ^C	0.5 ^C	2 ^C	2 ^C	2 ^C



Figure 2 | Samples of raw water, pretreated water by the reactor and treated water (left to right).

Regarding the colour and turbidity, there was a significant increase in the water treated by the electrolytic process compared with the raw water. The generation of iron ions at the anode may have caused an increase in the colour of the pretreated water by the reactor, as shown in Equation (5), causing the carbon steel electrodes to be electrically dissolved.



This may be explained by a probable release of iron ions (Fe^{2+}) through the electrodes that have been oxidised (Fe^{3+}) by the electrolytic process, thus exerting a strong attraction towards the surface of colloids, which are negatively charged, and decreasing the forces of electrostatic repulsion. This process allows for particle aggregation, clot formation and flake formation for coagulation in water as shown in Equations (5) and (6):



After filtration, it was observed that water clarification yielded reduced values for turbidity and colour (group C) that met the treated water potability standards established by Ordinance No. 2914 (Brasil 2011), as shown in Figure 2.

Table 3 shows the values of DOC, absorbance of ultraviolet light at 254 nm and SUVA. The Tukey test with a 95% confidence interval for the three parameters was applied.

For all parameters, a significant difference was observed between raw water, which belongs to group A, and treated water, which belongs to group B or C. The results show that the removal efficiency of SUVA was 19.51, 20.47, and 26.45% for filtration careers 1, 2 and 3, respectively. The significant reduction in the presence of organic matter in

Table 3 | DOC values, absorbance (254 nm) and SUVA of the three filtration careers and average

Time (h)	Sample	DOC (mg L ⁻¹)			Absorbance (cm ⁻¹)			SUVA (L · mg ⁻¹ · M ⁻¹)		
		C1	C2	C3	C1	C2	C3	C1	C2	C3
1.0	Raw	11.340	10.520	8.436	0.1391	0.1341	0.1307	1.23	1.27	1.55
	Reactor	10.550	10.280	8.397	0.1138	0.1092	0.1232	1.08	1.06	1.47
	Treated	9.939	9.587	8.134	0.0988	0.0945	0.0895	0.99	0.99	1.10
2.0	Raw	11.340	10.520	8.436	0.1391	0.1341	0.1307	1.23	1.27	1.55
	Reactor	11.040	9.607	8.366	0.1128	0.1199	0.1250	1.02	1.25	1.49
	Treated	9.512	9.591	7.990	0.0922	0.0949	0.0928	0.97	0.99	1.16
3.0	Raw	11.340	10.520	8.436	0.1391	0.1341	0.1307	1.23	1.27	1.55
	Reactor	10.560	9.798	8.380	0.1172	0.1215	0.1209	1.11	1.24	1.44
	Treated	9.605	9.523	7.846	0.0984	0.0992	0.0907	1.02	1.04	1.16
Average	Raw	11.340 ^A	10.520 ^A	8.436 ^A	0.1391 ^A	0.1341 ^A	0.1307 ^A	1.23 ^A	1.27 ^A	1.55 ^A
	Reactor	10.720 ^B	9.895 ^B	8.381 ^A	0.1146 ^B	0.1169 ^B	0.1230 ^B	1.07 ^B	1.18 ^A	1.47 ^B
	Treated	9.685 ^C	9.567 ^C	7.990 ^B	0.0965 ^C	0.0962 ^C	0.0910 ^C	0.99 ^C	1.01 ^B	1.14 ^C

Table 4 | Values of electrical energy consumed per volume of water produced

Information	Average value
Potency (W)	783 ± 53
Average time of filtration career (h)	3
Average volume of treated water produced (m ³)	1.8
Price kW · h (\$)*	0.08
Cost of produced water (\$ · m ⁻³)	0.10

*Amount paid by Gavião WTP, considering 1.00 dollar (\$) = 2.40 reais (R\$).

natural water can decrease the formation of disinfection by-products.

According to Jiang *et al.* (2002), in the electrocoagulation process, iron electrodes are dissolved in electrolysis and form a variety of species of metal hydroxides and coagulants. These species destabilise and aggregate the suspended particles, and the dissolved iron adsorbs contaminants such as dissolved organic matter. Moreover, according to Mohora *et al.* (2012), the hydrogen bubbles produced at the cathode are responsible for the removal of natural organic matter due to the flotation of the particles present in water.

The energy used for the electrolytic pretreatment was monitored based on the power measured in each of the filtration careers. Table 4 shows the data that was used to calculate electricity consumption, which includes the average consumption of electricity (power) of the three filtration careers, average time of each filtration career, average volume of treated water produced, and price of the local electricity per kilowatt-hour. This information can be used to calculate the cost of electricity in step electrolytic pretreatment.

Since the price of electricity per kilowatt-hour is \$0.08, the cost of electricity for the electrolytic pretreatment step was \$0.10 for every m³ of treated water.

CONCLUSION

The results from this study demonstrate that the electrolytic process with the use of an alternating current in conjunction with chemical coagulation and direct filtration significantly removed the natural organic matter in the water. The reduction of the SUVA reached an efficiency

of 19.51–26.45%, with a hydraulic retention time of 1.62 minutes and a current density of 1.83 mA cm⁻² for the iron electrodes and 4.10 mA cm⁻² for the stainless steel electrodes. Furthermore, the electrolytic treatment process resulted in average values of turbidity and colour of the water that were in accordance with the maximum allowable values for Brasil (2011).

The conclusion from this study is that the electrolytic process employed did not significantly alter the pH and that the cost of the energy consumed per m³ of treated water was \$0.10 at this stage of treatment. Thus, the technique of electrocoagulation can be used in water treatment stations to meet the standards established by the applicable Ordinance and to achieve low-cost water production.

REFERENCES

- Abdala Neto, E. F. & Aquino, M. D. 2012 Fotocatálise Heterogênea associada a eletro-oxidação no pré-tratamento de água eutrofizada em uma estação piloto de tratamento de água. *Revista AIDIS de Ingeniería y Ciencias Ambientales: investigación, desarrollo y práctica* 3 (5), 11–19.
- APHA 2012 *Standard Methods for the Examination of Water and Wastewater*. 22nd edn, American Public Health Association/American, Washington, DC, USA.
- Araya-Farias, M., Mondor, M., Lamarche, F., Tajchakavit, S. & Makhlof, J. 2008 Clarification of apple juice by electroflotation. *Innov. Food Sci. Emerg. Technol.* 9, 320–327.
- Atkins, P. & Jones, L. 2001 *Princípios de Química: Questionando a Vida Moderna e o Meio Ambiente*. Bookman, Porto Alegre, 873 pp.
- Benhadji, A., Ahmed, M. T. & Maachi, R. 2011 Electrocoagulation and effect of cathode materials on the removal of pollutants from tannery wastewater of Rouïba. *Desalination* 277, 128–134.
- Bennajah, M., Gourich, B., Essadki, A. H., Vial, C. & Delmas, H. 2009 Defluoridation of Morocco drinking water by electrocoagulation/electroflotation in an electrochemical external-loop airlift reactor. *Chem. Eng. J.* 148 (1), 122–131.
- Brasil 2011 *Portaria MS n° 2914*. Secretaria de Vigilância em Saúde, Brasília, Brasil.
- Curteanu, S., Piuleac, C. G., Godini, K. & Azaryan, G. 2011 Modeling of electrolysis process in wastewater treatment using different types of neural networks. *Chem. Eng. J.* 172, 267–276.
- Gusmão, I. C. C. P., Moraes, P. B. & Bidoia, E. D. 2010 Studies on the electrochemical disinfection of water containing *Escherichia coli* using a dimensionally stable anode. *Brazil. Arch. Biol. Technol.* 5 (53), 1235–1244.

- Jeong, J., Kim, J. Y. & Yoon, J. 2006 The role of reactive oxygen species in the electrochemical inactivation of microorganisms. *Environ. Sci. Technol.* **40**, 6117–6122.
- Jiang, J., Graham, N., André, C., Kelsall, G. H. & Brandon, N. 2002 Laboratory study of electro-coagulation–flotation for water treatment. *Water Res.* **36**, 4064–4078.
- Kobya, M., Gebologlu, U., Ulu, F., Oncel, S. & Demirbas, E. 2011 Removal of arsenic from drinking water by the electrocoagulation using Fe and Al electrodes. *Electrochim. Acta* **56** (14), 5060–5070.
- Kumar, N. S. & Goel, S. 2010 Factors influencing arsenic and nitrate removal from drinking water in a continuous flow electrocoagulation (EC) process. *J. Hazard. Mater.* **173**, 528–533.
- Kuroda, E. K. 2006 Remoção de células e subprodutos de *Microcystis* spp. por dupla filtração, oxidação e adsorção. Thesis, Department of Hydraulic and Sanitation, Universidade de São Paulo, São Carlos, São Paulo, Brazil.
- Lima, J. A. P. 2011 Dupla filtração utilizando filtro de pressão à montante de filtro ascendente em mananciais eutrofizados. Dissertation, Department of Hydraulic and Environmental Engineering, Universidade Federal do Ceará, Fortaleza, Ceará, Brazil.
- Malakootian, M., Mansoorian, H. J. & Moosazadeh, M. 2010 Performance evaluation of electrocoagulation process using iron-rod electrodes for removing hardness from drinking water. *Desalination* **255**, 67–71.
- Mohora, E., Rončević, S., Božo, D., Agbaba, J., Watson, M., Karlović, E. & Dalmacija, M. 2012 Removal of natural organic matter and arsenic from water by electrocoagulation/flotation continuous flow reactor. *J. Hazard. Mater.* **235**, 257–264.
- Phalakornkule, C., Worachai, W. & Satitayut, T. 2010 Characteristics of suspended solids removal by electrocoagulation. *World Acad. Sci. Eng. Technol.* **65**, 233–239.
- Ponte, F. V. G., Moreira, A. M. R., Sales, M. V. & Capelo Neto, J. 2013 Modelo decisório para seleção de tecnologias de tratamento de água em comunidades rurais no semiárido. *Revista Brasil. Recurs. Hídric.* **4** (18), 9–17.
- Qi-yan, F., Xiang-dong, L., Yu-jie, C., Lei, M. & Qing-jun, M. 2007 Removal of humic acid from groundwater by electrocoagulation. *J. China Univ. Mining Technol.* **4** (17), 513–515.
- Ribeiro, F. W. P., Oliveira, S. N., Lima Neto, P., Correia, A. N., Mascaro, L. H., Matos, R., Souza, E. C. P. & Lanza, M. R. V. 2013 Eletrodegradação de ponceau 2R utilizando ânodos dimensionalmente estáveis e Ti/Pt. *Quím. Nova* **1** (36), 85–90.
- Rubio, J., Souza, M. L. & Smith, R. W. 2002 Overview of flotation as a wastewater treatment technique. *Miner. Eng.* **15**, 139–155.
- Sales, M. V. 2005 Tratamento de água eutrofizada através de dupla filtração e oxidação. Thesis Department of Hydraulic and Environmental Engineering, Universidade Federal do Ceará, Fortaleza, Ceará, Brazil.
- Sarkar, M. S. K. A., Donne, S. W. & Evans, G. M. 2011 Utilization of hydrogen in electroflotation of silica. *Adv. Powder Technol.* **22**, 482–492.
- Un, U. T., Koparal, A. S. & Ogutveren, U. B. 2013 Fluoride removal from water and wastewater with a batch cylindrical electrode using electrocoagulation. *Chem. Eng. J.* **223**, 110–115.
- Vasudevan, S., Lakshmi, J. & Sozhan, G. 2011 Studies on the Al–Zn–In-alloy as anode material for the removal of chromium from drinking water in electrocoagulation process. *Desalination* **275**, 260–268.
- Zhao, H., Yang, W., Zhu, J. & Ni, J. 2009 Defluoridation of drinking water by combined electrocoagulation: Effects of the molar ratio of alkalinity and fluoride to Al(III). *Chemosphere* **74** (10), 1391–1395.
- Zuo, Q., Chen, X., Li, W. & Chen, G. 2008 Combined electrocoagulation and electroflotation for removal of fluoride from drinking water. *J. Hazard. Mater.* **159**, 452–457.

First received 9 April 2014; accepted in revised form 16 August 2014. Available online 24 September 2014