

Electrochemically activated water as an alternative to chlorine for decentralized disinfection

K. Ghebremichael, E. Muchelemba, B. Petrusovski and G. Amy

ABSTRACT

Electrochemically activated (ECA) water is being extensively studied and considered as an alternative to chlorine for disinfection. Some researchers claim that ECA is by and large a chlorine solution, while others claim the presence of reactive oxygen species such as ozone and hydroxyl radicals in addition to chlorine. This study compares sodium hypochlorite (NaOCl) and ECA in terms of disinfection efficacy, trihalomethanes (THMs) formation, stability and composition. The studies were carried out under different process conditions (pH 5, 7 and 9, disinfectant concentrations of 2–5 mg/L and dissolved organic carbon (DOC) concentration of 2–4 mg/L). The results indicated that in the presence of low DOC (<2 mg/L) ECA showed better disinfection efficacy for *Escherichia coli* inactivation, formed lower THM and had better stability compared with NaOCl at both pH 5 and 7. Stability studies of stock solutions showed that over a period of 30 days, ECA decayed by only 5% while NaOCl decayed by 37.5% at temperatures of 4 °C. In a fresh ECA of 200 mg/L chlorine, about 5.3 mg/L ozone and 36.9 mg/L ClO₂ were detected. The study demonstrates that ECA could be a suitable alternative to NaOCl where decentralized production and use are required.

Key words | anolyte, disinfection, ECA, *E. coli*, sodium hypochlorite, THM

K. Ghebremichael (corresponding author)
E. Muchelemba
B. Petrusovski
Department of Urban Water and Sanitation,
UNESCO-IHE,
Westvest 7, PO Box 3015,
2601 DA Delft,
The Netherlands
E-mail: k.ghebremichael@unesco-ihe.org

G. Amy
Water Desalination and Reuse Center,
Kaust,
Saudi Arabia

INTRODUCTION

Chlorine has long been recognised as an effective disinfectant; however, its impacts in terms of the formation of undesirable disinfection by-products and risks of transport/storage have led to the re-evaluation of its use and the search for alternative disinfectants. One of the alternative disinfectants is electrochemically activated water (ECA). In the last decade, electrochemical disinfection has been considered for use in water treatment and more recently in sanitization of industrial production facilities. ECA is considered a more environmentally friendly disinfectant that has higher disinfection efficacy compared with chlorine because of the presence of a mixture of oxidants (Martínez-Huitle & Brillas 2008). There is, however, some controversy over the possible presence of oxidants other than chlorine in ECA and some researchers describe it as another form of chlorine solution.

ECA water is produced by passing a dilute salt solution through an electrolytic cell where the anode and cathode

are separated by a membrane. Two types of ECA water are produced at the anode and cathode, which are referred to as the anolyte and catholyte, respectively. The anolyte has low pH (2.3–2.7), high dissolved oxygen, high oxidation-reduction potential (ORP greater than 1,000 mV), chlorine species and oxygen species such as ozone, hydrogen peroxide and hydroxyl radicals (Kunigk *et al.* 2008; Martínez-Huitle & Brillas 2008). Of these, chlorine species have been recognised as the main oxidants (Len *et al.* 2002). The catholyte on the other hand has high pH (10–11.5) and low ORP of –800 to –900 mV (Hsu 2005). Electrochemical disinfection can be applied either under direct current where both antimicrobial agents and electric current are said to act synergistically (Kerwick *et al.* 2005) or by dosing separately generated anolyte solution to the water to be disinfected.

ECA is reported to be effective for microbial inactivation. Venkitanarayanan *et al.* (1999) reported that ECA

achieved 7 log inactivation of *Escherichia coli* 0157H:H7, *Salmonella enteritis* (*S. enteritis*) and *Listeria monocytogenes* (*L. monocytogenes*) after 5 min exposure, while chlorine, with the same concentration, had similar efficacy only for *E. coli* 0157H:H7 and *L. monocytogenes*. Gonzalez (2002) also reported that ECA had superior inactivation of biofilms, long-lasting residual chlorine and 50% reduction in trihalomethanes (THMs) and haloacetic acids (HAAs) formation compared with NaOCl. This improvement was attributed to the presence of chloro-oxygen species, despite their short life.

Martínez-Huitle & Brillas (2008) claim that better disinfection efficacy of ECA was attributed to the presence of oxygen species such as hydroxyl radicals, which have very high oxidation potential. However, Martínez-Huitle & Brillas (2008) hypothesized that, owing to their short lifetime, their likely role can only be considered under direct current. By using chloride-free electrolyte (sodium sulphate), Kerwick *et al.* (2005) observed inactivation of microorganisms and attributed it to the presence of hydroxyl radicals. Jeong *et al.* (2007) also observed inactivation of microorganisms using chloride-free phosphate buffer. On the other hand, Gauw *et al.* (1999) disputed the presence of oxidants other than free chlorine in freshly generated ECA solutions.

ECA is typically generated on site and can either be used immediately or stored for up to one week. If ozone and hydroxyl radicals are generated in ECA systems and stored, their contribution can be ruled out because of their transitory nature, therefore their possible contribution is limited to electrochemical disinfection under direct current. One of the drawbacks of the direct current systems can be the formation of bromate due to the presence of ozone. Studies of the effect of storage on the efficacy of anolyte solution provide important information on whether there is a need for onsite production or not. Len *et al.* (2002) studied the effects of storage on chlorine loss from ECA under different conditions of light, agitation, temperature, pH and exposure to open air. The study showed that in open containers, at pH 2.5 and temperature of 25 °C chlorine was completely lost after 100 h from an ECA solution. With agitation the chlorine loss was almost five times faster. Under closed conditions, on the other hand, the effect of volatilization was eliminated and self-decomposition was the only means of chlorine loss. Under illumination, 60% of chlorine was lost after 1,400 h in

comparison to 40% under dark conditions. Increase in pH from 2.5 to 9.0 decreased chlorine loss. Kunigk *et al.* (2008) demonstrated that the effect of temperature (between 25 °C and 40 °C) on the loss of chlorine in both ECA and NaOCl solutions was very small. However, chlorine concentration in both ECA and NaOCl decreased with time in open conditions and followed the first-order kinetics for the observed time of 500 h. The rate constant for chlorine loss was higher in the case of NaOCl solution ($5.28 \times 10^{-3}/\text{h}$) compared with ECA ($2.45 \times 10^{-3}/\text{h}$).

Previous disinfection studies with ECA have typically used freshly generated solutions or have been conducted under direct current. There is limited knowledge on the stability of ECA with storage time and the effect of dissolved organic carbon (DOC) on disinfection performance. Disinfection by-product (DBP) formation of NaOCl is well documented, but information on DBP formation by ECA is limited. The main objective of this study was to assess the disinfection efficacy of ECA and to assess the DBP formation potential in comparison with NaOCl. The paper will address the following specific objectives: (i) compare efficacy of ECA and NaOCl for *E. coli* inactivation; (ii) assess the possible presence of other oxidants such as chlorine dioxide and ozone in ECA solutions; (iii) compare THM formation potential of ECA and NaOCl; and (iv) investigate the stability of ECA and NaOCl stock solutions in storage.

MATERIALS AND METHODS

Chlorine stock solutions

Disinfectant solutions were prepared from NaOCl stock solution and ECA units. Two ECA solutions were used: (i) from a commercial generator (Biostel[®]); and (ii) from a hand held MIOX[®] purifier. The ECA from Biostel[®] was produced using twin cells separated by an electro-diaphragm membrane exposed to a current of about 12.5 A. The disinfectant solution from the MIOX[®] purifier was produced using food grade quality NaCl according to procedures outlined by MIOX[®] corporation (www.miox.com [accessed 14 March 2011]). The solution was produced by adding 5 g of food grade NaCl and 2 mL demineralized water to the MIOX[®] unit followed by four button clicks. The solution

was diluted to about 100 mL to make about 200 mg/L chlorine stock solution. MIOX[®] and ECA concentrations were expressed as mg chlorine/L.

Model buffer water

Buffer solutions of pH 5, 7 and 9 were prepared in accordance with the procedure of CRC (1998). Buffer pH 5 was prepared by adding 50 mL of 0.1 M potassium phthalate with 22.6 mL of 0.1 M NaOH. Buffer pH 7 was prepared by adding 50 mL of 0.1 M potassium dihydrogen phosphate to 29.1 mL of 0.1 M NaOH. Buffer pH 9 was prepared by adding 50 mL of 0.025 M borax to 4.6 mL of 0.1 M nitric acid. The buffered model waters were prepared by mixing demineralized water with the desired pH buffer solutions to maintain the final pH within a range of ± 0.3 .

Chromo cult nutrient agar and bacterial culture (*E. coli*)

Chromo cult nutrient agar (Merck, Germany) was prepared by dissolving 26.5 g of chromo cult in 1,000 mL demineralized water. This was thoroughly mixed and placed in a water bath at 99 °C for 30–45 min. The media was then cooled in an oven to about 50 °C after which it was poured into Petri dishes. *E. coli* culture (ATCC strain 25922, Netherlands) was grown in tryptic soy broth for 24 h at 37 °C. About 10^7 CFU/mL of the cultured *E. coli* was diluted in the ratio of 1:10 and 1:100 for the experiments. The spread plate technique was used to quantify the *E. coli*.

DOC source

The source of DOC used was Suwannee River Humic Acid (SRHA) Standard II 2S10H. SRHA was dissolved in Milli-Q water and its DOC concentration was determined using a Shimadzu TOC-VCPN TOC analyser.

EXPERIMENTAL METHODS

Disinfection efficacy

The disinfection efficacies of ECA and NaOCl for *E. coli* were evaluated under varying chlorine doses (2–5 mg/L

and pH (5, 7 and 9). About 1 mL of 10^7 of *E. coli* was diluted (1:10 and 1:100) and directly spiked into 100 mL flasks containing disinfectants in buffered solution. The contents were thoroughly mixed by inverting the flask several times for about 3 min. A non-neutralized sample volume of 0.1 mL was taken from the mixed solution and inoculated on chromo cult nutrient agar. The plates were inverted and incubated for 24 h at 37 °C and CFU values per mL were determined. In each test three plates were inoculated from each sample. A detection limit of 1 CFU/mL was adopted in calculating the log inactivation units.

In order to study the effect of DOC on disinfection efficacy, tests were performed by adding SRHA (with DOC of 2–5 mg/L) and *E. coli* (10^7 per mL and dilutions of 1:10 and 1:100). Disinfection experiments in demineralized buffered water (no DOC) and Delft tap water were also carried out. Delft tap water had a pH of 8.1, DOC of 1.9 mg/L and no chlorine residual.

THM formation

Two approaches were used to assess THM formation: the purge and trap method and mathematical modelling. The THMs species that were measured or estimated include trichloromethane (chloroform CHCl_3), bromodichloromethane (CHBrCl_2), chlorodibromomethane (CHBr_2Cl) and tribromomethane (bromoform CHBr_3). In the purge and trap method THM concentrations were determined according to the procedure of Roccaro *et al.* (2008). A known concentration of disinfectant was added to a 500 mL volumetric flask containing a known DOC concentration. At predetermined times, 100 mL samples were collected in glass bottles with PTFE tops into which 8 mg of $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ had been added prior to collection in order to quench the residual chlorine. The bottles were filled to the top with sample in order to exclude any air before closing the bottles. Dilutions were prepared to make sure that maximum concentration did not exceed 50 $\mu\text{g/L}$. Concentrations below 2 $\mu\text{g/L}$ were reported as <2 $\mu\text{g/L}$. In all cases duplicates samples were analysed and average values are reported.

THMs (total and four species) were also estimated using the Amy *et al.* (1998) model, which is based on lower chlorine doses (Equation (1)) and is applicable to either raw

water or chemically coagulated waters. The chemical DBP models are established based on chlorine disinfection (NaOCl) and it would be important to check if the models also fit the THM formation by ECA/MIOX. This paper will discuss any limitations of the model to predict the DBP formation of MIOX/ECA.

$$\text{TTHM} = 10^{-1.385}(\text{DOC})^{1.098}(\text{Cl}_2)^{0.152}(\text{Br}^-)^{0.068} \times (\text{temp})^{0.609}(\text{pH})^{1.601}(\text{time})^{0.263} \quad (1)$$

where, time is in hours; DOC, Cl₂ and Br⁻ in mg/L, and temperature in °C.

Stability (disinfectant decay)

Stability of the disinfectant was monitored by measuring the total available chlorine of the stock solutions of ECA and NaOCl. Bottles without head spaces were stored at a temperature of 4 °C and samples were collected every day for more than a month. For the ECA, effect of storage on the disinfection efficacy of *E. coli* was studied. Samples of 'new' ECA (solution stored for 1 week) and 'old' ECA (solution stored for two months) were used in the study.

ANALYTICAL METHODS

Mixed oxidants

Chlorine was measured according to the *N,N*-diethyl-phenylenediamine (DPD) colorimetric method (APHA 1998).

Ozone was analysed using a low range program of the Indigo spectrophotometric method (Bader & Hoigne 1981) using Accu Vac Ampuls with a HACH DR/890 spectrophotometer with ozone concentration in the range 0–0.25 mg/L and detection limit of 0.02 mg/L.

Chlorine dioxide was measured using a modified DPD colorimetric method (APHA 1998) by suppressing free chlorine using glycine. A buffer reagent and DPD indicator solution were thoroughly mixed to which EDTA disodium salt was added. The glycine treated sample was then added to the solution and mixed thoroughly. This was followed by

rapid titration with standard ferrous ammonium sulphate until the red colour disappeared.

RESULTS AND DISCUSSION

Comparison of the disinfection efficacy of NaOCl as well as ECA and/or MIOX[®] was conducted for different water quality conditions. The main parameters that were investigated in this study include variations in pH, type of water source, DOC concentration and effect of storage on disinfection. Stability of the stock solutions and THM formation potentials of the disinfectants were also investigated.

Comparing disinfection efficacy

Effect of pH

Figure 1(a) shows results of *E. coli* disinfection efficacy of ECA and NaOCl at 2.0 mg/L, pH 5, 7, 9 and the presence and absence of DOC (demineralized water). Both disinfectants were more effective at pH 5 compared with higher pH (pH 7 and 9). At pH 9 both disinfectants had negligible disinfection efficacy. This agrees with the work of Park *et al.* (2004), who observed increased disinfection efficacy at lower pH. As the pH increases, the concentration of hypochlorous acid (HOCl) decreases while the concentration of hypochlorite ion (OCl⁻) increases. The percentage of HOCl at pH values of 5, 7 and 9 are about 100%, 50% and 10%, respectively (Kortvelyesi 2004).

Figure 1(a) also shows that at pH 5, ECA achieved about 2 log higher inactivation than NaOCl under the same experimental conditions. And at pH 7, ECA was still more effective than NaOCl but inactivation efficacy was only 0.3 log units higher.

Effect of water quality

Figure 1(b) shows that at pH 5 the disinfection efficacies of both ECA and NaOCl were lower in Delft tap water compared with that in demineralized water. The efficacy of ECA for *E. coli* inactivation in demineralized water and Delft tap water was 5.2 and 3 log units, respectively. In the case of NaOCl, the corresponding values were 3 and 2.5 log

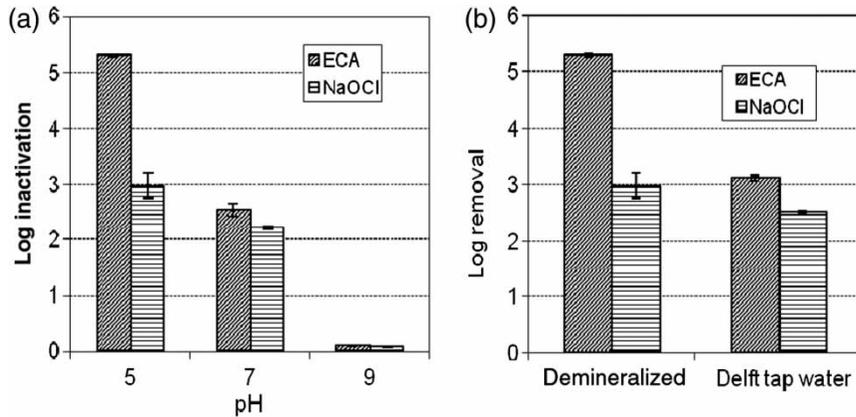


Figure 1 | *E. coli* inactivation with 2.0 mg/L ECA and NaOCl after 3 min contact time at room temperature: (a) at different pH values in demineralized water and (b) at pH 5 in Delft tap water and deionized water. Results are the average of duplicate samples and the error bars are for standard deviation.

units. Lower efficacy in Delft tap water can be explained by the presence of DOC (1.9 mg/L) and other dissolved substances (Twort *et al.* 2000). This result is consistent with the findings of Huang *et al.* (2008) and Park *et al.* (2008), who observed the diminishing effect of DOC on the efficacy of ECA. Presence of some other dissolved substances in the tap water may also possibly contribute to lower disinfection efficacy of both ECA and NaOCl.

The effect of DOC on *E. coli* inactivation is shown in Figure 2. As expected, the results indicate that disinfection efficacy reduced with increase in DOC. In the presence of 2 mg/L DOC, the disinfection efficacy of MIOX[®] reduced from about 5.3 to 3.3 log units and it was further reduced to 2.1 log units in the presence of 4 mg/L DOC. This is attributed to the high chlorine demand of DOC (Hugo & Russell 1999; Binnie *et al.* 2002; Park *et al.* 2008). Figure 2

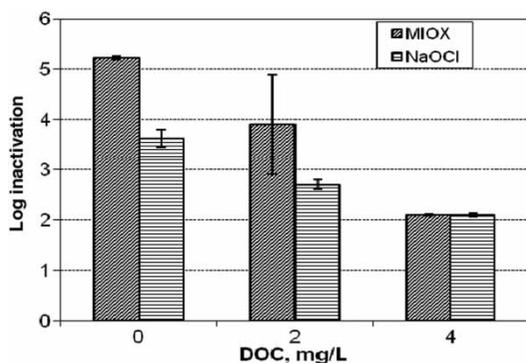


Figure 2 | Effect of DOC on disinfection effectiveness of MIOX[®] and NaOCl in terms of *E. coli* inactivation at pH 5, disinfectant concentration of 2 mg/L and contact time of 3 min. Results are the average of duplicate samples and the error bars are for standard deviation.

also shows that at high DOC value (4 mg/L) the two disinfectants show similar performance. In the presence of 4 mg/L DOC, the residual chlorine of both ECA and NaOCl was about 0.5 mg/L after reaction time of 30 min.

Effect of storage of ECA on disinfection efficacy

Comparison of disinfection effectiveness of ECA solutions stored (in cold room at 4 °C) for one week ('new') and two months ('old') indicated that disinfection efficacy decreased with storage time. At pH 5 and chlorine concentration of 2 mg/L, the disinfection efficacy of 'new' ECA and 'old' ECA were 5 log and 3 log units, respectively. The log inactivation of the 'new' and 'old' ECA at pH 7 were 3.3 and 2.5, respectively. Cui *et al.* (2009) observed that disinfection efficacy of ECA was significantly affected by storage. Higher differences in inactivation of both 'new' and 'old' ECA at pH 5 can be explained by the reduction of HOCl with storage time. Kunigk *et al.* (2008) reported that HOCl, which is the main disinfectant, undergoes self-decomposition over time to OCl⁻ which is a weaker oxidant. At pH 7, however, the percentage of HOCl is low (compared with pH 5) and the effect of storage was not as pronounced as at pH 5.

THM formation

Purge and trap method

THM formation of MIOX[®] after 2 h contact time at pH 5, in buffered solution with 4 mg/L DOC was <2 µg/L (Figure 3).

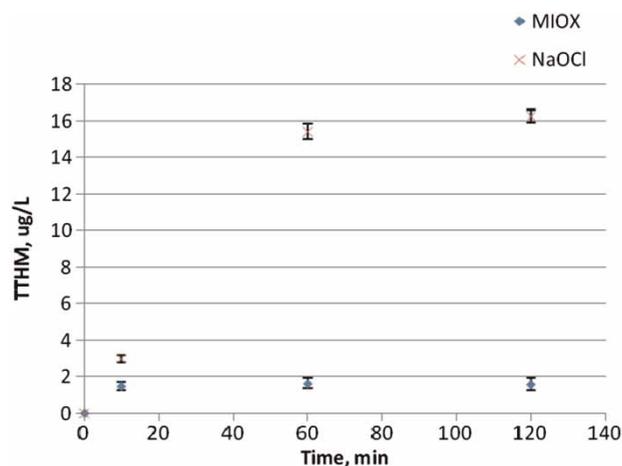


Figure 3 | TTHM formation of NaOCl and MIOX[®] at pH 5 buffered solution and varying reaction times with disinfectant dosage of 2 mg/L and DOC concentration of 4 mg/L.

At pH 7, the THM formation by both disinfectants was about 27.5 µg/L. The observed increase in THM with pH is in agreement with Amy *et al.* (2000) and Xie (2004). Since THM is a hydrolysis end product, its formation is accelerated at higher pH values (Amy *et al.* 2000). Some DBPs, for example trihalopropanone, undergo a hydrolysis reaction to form THMs. Moreover, HOCl favours formation of HAAs while OCl⁻, which is dominant at high pH, favours formation of THMs (Amy *et al.* 2000).

Analysis of the speciation showed that in both disinfectants, chloroform (CHCl₃) was the dominant THM species formed with about 99% of TTHM (Table 1).

Comparison of THM formation by the two disinfectants indicated that at pH 5, NaOCl produced more THM compared with MIOX[®]. At pH 7 THM formation by both NaOCl and MIOX[®] were similar; however, NaOCl produced more THM. This is in agreement with Gonzalez (2002), who reported that formation of THMs was lower with the use of MIOX[®] in comparison with chlorine at pH 7.

Determination of THM formation using mathematical modelling

Mathematical estimation of TTHM was performed using the empirical model for raw water (Equation (1)) developed by Amy *et al.* (1998) based on the following conditions: 10 µg/L Br⁻, 4 mg/L DOC, at 20 °C and varying contact

Table 1 | Species of THMs formed with 2 mg/L NaOCl and MIOX[®] in buffered water with 4 mg/L DOC at pH 5 and pH 7 after a reaction time of 2 h

	pH	5	7
THM species (µg/L)-NaOCl	CHBrCl ₂	<0.5	<0.5
	CHBr ₃	<0.5	<0.5
	CHCl ₃	16.3	31.3
	CHBr ₂ Cl	<0.5	<0.5
	TTHM (Total)	16.5	31.3
THM species (µg/L)-MIOX [®]	CHBrCl ₂	<0.5	0.6
	CHBr ₃	<0.5	<0.5
	CHCl ₃	1.3	26.9
	CHBr ₂ Cl	<0.5	<0.5
	TTHM (Total)	<2	27.6

time, chlorine dose and pH. The chemical DBP models are established based on chlorine disinfection (NaOCl) and it would be important to check if the models also fit THM formation by ECA/MIOX[®]. Tables 2 and 3 show comparison of TTHM values estimated from the model and measured values in experiments conducted in this study.

At pH 7 the predicted and measured TTHM values for both disinfectants were comparable (Table 2). It should be noted that TTHM formation by MIOX[®] at pH 5 was below the detection limit and does not correspond to the model estimate.

Table 3 indicates that at a chlorine dose of 2 mg/L and contact time of 1 h, the predicted and measured TTHM formation by MIOX[®] were similar. For extended reaction times and higher disinfectant dosages, however, the measured and model estimates did not correspond to each other. This may be explained by the fact that the model was developed for low chlorine doses and for raw ground or surface waters (Sohn *et al.* 2004). This could explain the observed disparities at high disinfectant doses of 5 mg/L.

Table 2 | Comparison of the predicted and measured TTHM with 4.0 mg/l DOC and 2 mg/L chlorine dosages at pH 5 and 7 and reaction time of 1 h and 2 h

pH	Time (h)	Predicted TTHM (µg/L)	Measured TTHM (µg/L)	
			NaOCl	MIOX [®]
5	1	20.0	15.3	<2.0
	2	24.0	16.5	<2.0
7	1	34.3	29.7	27.2
	2	41.1	31.3	27.6

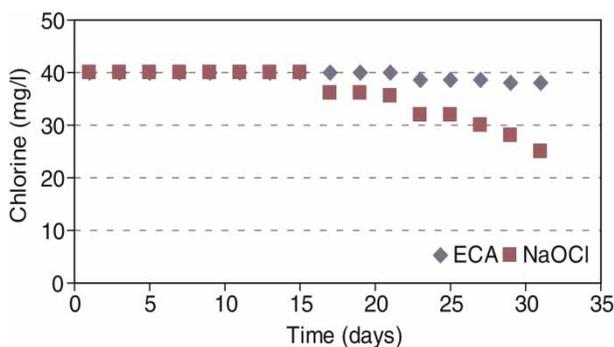
Table 3 | Comparison of the predicted and measured TTHM for extended reaction time and varying MIOX[®] doses with 4.0 mg/L DOC at pH 7

MIOX [®] (mg/L)	Time (h)	Predicted TTHM (µg/L)	Measured TTHM (µg/L)
2	1	34.5	33.5
	24	79.1	31.95
5	1	39.4	117.9
	24	90.9	136.1

The results indicate the limitations of the model to predict the DBP formation of MIOX[®]/ECA, particularly at higher doses and longer contact time. This may require further study but it indicates the need to revisit the models for other chlorine-based disinfectants.

Stability of stock solutions of ECA and NaOCl

Studies of stability of stock solutions of ECA and NaOCl indicated that ECA was more stable in comparison with NaOCl under the same storage conditions (Figure 4). In ECA solution, initial concentration of 40 mg/L was reduced to 38.0 mg/L after 30 days (with a decay rate of 2.8×10^{-3} /h) while in the case of NaOCl, the chlorine concentration reduced to 25.0 mg/L (with a decay rate of 20.8×10^{-3} /h). This finding concurs with the work of Kunigk *et al.* (2008), who observed that decay was faster in NaOCl (5.28×10^{-3} /h) than in ECA (2.45×10^{-3} /h). On the other hand, Cui *et al.* (2009) reported decay in ECA of about 50% for a storage period of 30 days which differs from the observed decay of 5% in this study. This can be explained by the differences in initial chlorine concentrations in the stock

**Figure 4** | Effect of storage time on the stability of ECA and NaOCl in 30 days.

solutions and the temperature used in the two studies. The chlorine concentration in the stock solution of Cui *et al.* (2009) was 24 mg/L and the solution was stored at room temperature, whereas in this study, the solution was stored in a refrigerator below 5 °C. According to CRC (1998) chlorine decay is reduced with increase in stock concentration and with decrease in temperature.

After 30 days of storage time, the rate of chlorine decay in ECA increased. The chlorine concentration reduced from 37.5 mg/L at day 30 to about 30 mg/L at day 60. This is probably due to increased self-decomposition of the chlorine in the ECA solution with increase in time (Cui *et al.* 2009). It is therefore important to produce a high concentration of stock solution and limit storage times in order to avoid significant loss of disinfectant strength.

Analysis of oxidants

In order to assess the possible presence of oxidants other than chlorine, analysis of chlorine dioxide (ClO₂) and ozone (O₃) were made in a freshly generated MIOX[®] solution and ECA solution generated by the commercial unit that was stored for about one week.

Chlorine dioxide and ozone

In a freshly generated MIOX[®] solution with about 200 mg/L chlorine, the concentration of ClO₂ was about 36.9 mg/L. This is in line with the work of Pillai *et al.* (2009) and Bergmann & Koparal (2006), who reported the presence of ClO₂ in ECA water. On the other hand, Gauw *et al.* (1999) reported that ClO₂ was not present in a freshly generated ECA. In ECA of 262 mg/L chlorine content (generated by the commercial unit and stored for one week at 4 °C in a cold room) the ClO₂ concentration was about 35.5 mg/L, but O₃ was not detected in the solution.

This study confirmed that a freshly generated MIOX[®] solution with chlorine content of about 200 mg/L, contained about 5.3 mg/L ozone. The ozone decayed to 0 mg/L within 30 min. This finding disagrees with Emmert (1999) and Gordon *et al.* (1998), who did not detect ozone in ECA, but concurs with the work of Bergmann & Koparal (2006), who confirmed the presence of ozone.

CONCLUSIONS

This study was conducted to assess the performance of sodium hypochlorite (NaOCl) and ECA water in terms of disinfection efficacy, DBP formation and the stability of the disinfectant with respect to storage. Experiments were carried out at pH 5, 7 and 9; DOC concentration of 0, 2 and 4 mg/L; and disinfectant dosage of 2–5 mg/L. Possible presence of oxidants other than chlorine were also checked. Two sets of ECA were used in this study: (i) ECA generated from a hand-held MIOX[®] unit; and (ii) ECA obtained from an industrial production unit and stored for over a week (during transportation).

The main conclusions of this study are:

- In the absence of or at low concentrations of DOC, ECA showed better disinfection efficacy in terms of *E. coli* inactivation compared with NaOCl at both pH 5 and 7. In the presence of DOC both disinfectants showed similar efficacy.
- ECA formed fewer THMs compared with NaOCl. THM formation was observed to be lower at pH 5 compared with pH 7, which is similar to reports in the literature.
- ECA was more stable during storage compared with NaOCl.
- The major component of ECA was chlorine. In a freshly generated MIOX[®] solution, a small amount of ClO₂ and ozone were detected. In stored ECA only ClO₂ was detected.
- In general ECA showed better inactivation of *E. coli* compared with NaOCl, at pH 5 and 7.

This study showed that ECA can be effectively used as an alternative to NaOCl for disinfection in decentralized water treatment.

ACKNOWLEDGEMENT

The authors would like to thank the Coca-Cola Company for supporting the research by financing the MSc study and by providing access to analytical facilities.

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First received 28 June 2010; accepted in revised form 24 January 2011