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Technical and Economic Comparison of Conventional, Modify Conventional and Electrochemical Coagulation Processes

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ABSTRACT: Electrochemical coagulation and modify conventional processes are alternative to the conventional coagulation method of water and wastewaters treatment. Although, there have been many reports on the technical suitability of electrochemical coagulation and conventional, no study has made a direct comparison of the economics of these processes and modify conventional process. This article demonstrated comparison of the economics of electrochemical coagulation; modify conventional and conventional processes of raw water treatment. Raw water samples were collected from selected villages in Katsina state, Nigeria. The samples were subjected to these treatment techniques. Efficacies of these processes were determined individually and in combination. Operational and capital costs of these techniques were determined and compared for economics selection reasons. The study revealed that concerning the technical feasibility, no significant differences were found in the results achieved by the three technologies in the treatment of raw surface water, when the same values of pH, chlorine and aluminum concentrations were adopted in the reaction systems. Regarding the economic comparison, the electrochemical coagulation and modify conventional processes present lower operating costs for low and intermediate aluminum and chlorine doses. The highest operational costs were obtained with conventional coagulation with aluminum sulphate (alum, conventional water treatment process). It was concluded that conventional coagulation; modify conventional treatment and electrochemical coagulation techniques gave very similar efficiencies in the removal of different types of pollutants; therefore an economic comparison is of major importance in order to recommend the use of one of these technologies.

Keywords: Electrochemical coagulation, modify conventional, conventional processes, raw water treatment

Geleneksel, Düzenlenmiş Geleneksel ve Elektrokimyasal Koagülasyon Yöntemlerinin Ekonomik ve Teknik Açıdan Karşılaştırılması

ÖZET: Elektrokimyasal koagülasyon ve düzenlenmiş geleneksel yöntemler su ve atık su işlemlerinin geleneksel koagülasyon yöntemlerine bir alternatiftir. Geleneksel ve elektrokimyasal koagülasyonun teknik uygunluğu üzerinde çok fazla çalışmalar olmasına rağmen, bu yöntemlerin ve düzenlenmiş geleneksel yöntemlerin direk ekonomik karşılaştırılması yapılmamıştır. Bu makalede işlem görmemiş su işlemlerinin geleneksel, düzenlenmiş geleneksel ve elektrokimyasal koagülasyon işlemlerinin ekonomik karşılaştırılması verilmiştir. İşlenmemiş su örnekleri Nijeryadaki Katsina eyaletindeki seçilen köylerden toplanmıştır. Numuneler üzerinde bu işlem teknikleri denenmiştir. Bu işlemlerin etkinlikleri ayrı ayrı ve bir arada belirlenmiştir. Bu tekniklerin işletimsel ve kapital maliyetleri ekonomik seçim sebepleri için karşılaştırılmış ve belirlenmiştir. Çalışma önemli farklılıklar olmadan bulunan sonuçlarda teknik uygunluk içerisinde işlenmemiş yüzey sularının işlenmesinde üç farklı teknoloji sayesinde aynı pH değerlerine sahip olan klor ve alüminyum yoğunluklarının reaksiyon sisteminde başarıldığını ortaya çıkarmıştır. Ekonomik karşılaştırmada elektrokimyasal koagülasyon ve düzenlenmiş geleneksel işlemler düşük ve orta miktarda alüminyum ve klor dozları için daha düşük işlem maliyeti sunar. En yüksek işlemsel maliyet alüminyum sülfatlı geleneksel koagülasyonda elde edilmiştir. Sonuç olarak geleneksel koagülasyon, düzenlenmiş geleneksel işlem ve elektrokimyasal koagülasyon yöntemleri farklı çeşit kirletici maddelerin arıtılmasında neredeyse aynı etkiye sahiptir. Fakat ekonomik karşılaştırma, bu teknolojilerden birini kullanma tavsiyesinde büyük öneme sahiptir.

Anahtar kelimeler: Elektrokimyasal koagülasyon, düzenlenmiş geleneksel, geleneksel yöntemler, işlenmemiş su işlemleri

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INTRODUCTION

Water quality is a term used to express the suitability of water to sustain various uses or processes. The quality of water may be described in terms of the concentration and state the organic and inorganic material present in the water, together with certain physical characteristics of the water. The composition of surface waters is dependent on natural factors in the drainage basin and varies with seasonal differences in runoff volumes, weather conditions and water levels. Human intervention also has significant effects on water quality. Some of these effects are the polluting activities, such as the discharge of domestic, industrial, urban and other wastewaters into the watercourse. The principal reason for monitoring water quality has been the need to verify whether the observed water quality is suitable for intended uses and treatment processes required to reach an acceptable level (Alaa et al., 2010). Water treatment processes can be in the form of conventional or non-conventional processes. Selection of required water treatment processes depends on pollutants present and required quality. In recent years, studies on electrochemical treatment of surface water have been conducted. It was found that the technique is promising as compared to conventional water treatment processes.

Electrochemically assisted coagulation consists of the in situ generation of coagulants by the electrodissolution of a sacrificial anode, usually of iron or aluminum.

The reactions involved in the electrochemical cell are summarized in Equations (1) to (3), with the oxidation of the metallic anode (M = Fe or Al), and the reduction of water being the main electrochemical reactions. The oxidation of water at the anode is a secondary reaction that competes with the oxidation of aluminium (Umran et al., 2009; Oladepo et al., 2011).

$$\text{At Anode: } M \xrightarrow{oxidationreaction} M^{3+} + 3\bar{e} \quad (1)$$

$$\text{Cathode: } 2H_2O \longrightarrow O_2 + 4H^+ + 4\bar{e} \quad (2)$$

$$2H_2O + 2\bar{e} \xrightarrow{reduction} H_2 + OH^- \quad (3)$$

The advantages of the electrocoagulation process over the conventional dosing of coagulants have been widely reported. The simple equipment required and the easy automation of the process stand out among the main advantages described. The process requires no addition of chemicals, and the amount of coagulant dosed can easily be controlled by varying the electrical current applied. In this context, the low current requirement allows electrocoagulation to be powered by green energy processes such as solar panels, windmills and fuel cells.

The autonomy of some of these green energy processes provides the possibility of using the electrocoagulation technique in rural (or isolated) areas, where other conventional technologies could be carried out only with difficulty.

Regarding energy supply by fuel cells, it must be pointed out that the electrochemical dosing of metal (iron or aluminum) generates important amounts of hydrogen (as sub-product, Equation (3)) that could be used in a fuel cell to produce energy. Other advantages of the electrochemical technology related to the generation of gas bubbles (O_2 and overall H_2) are the production of a soft turbulence that promotes the flocculation process (electroflocculation) and separation of the particulate pollutants, which are carried to the top of the solution where they can easily be collected and removed (electroflotation process).

Thus, with proper design of the electrocoagulation cell (to promote electroflocculation and electroflotation processes) one can achieve destabilization of pollutants and their aggregation and separation in a single-compartment reactor.

In contrast, in the conventional coagulation process three consecutive stages are necessary: the first stage requires vigorous turbulence to achieve mixing of the coagulant added to the wastewater; in the second stage a soft mix is used to favour flocculation of the destabilized pollutants; and finally, separation of the particulate pollutants (by settling or dissolved air flotation) is required. In addition to the supposed technical superiority, some studies report lower operational costs for the electrochemical process compared with those of the conventional process.

Economic comparisons of conventional and electrochemical coagulation of textile wastewaters have recently been reported. They found higher total costs for the conventional coagulation process than for the electrochemical process. Nevertheless, despite the promising results reported in the literature, there are no corresponding practical applications in the treatment of typical rural water sources. This fact can be explained taking into account that electrochemical technology is related to higher costs than conventional coagulation in rural areas (because of similarity of conventional technique to other electrochemical technologies Chen, 2004; Oke, 2007; Pablo et al., 2008).

Literature on technical and economics comparison of these three techniques (electrochemical, modified conventional and conventional water treatment processes) are lacking. This shows that there is a need to provide technical and economics comparison of these techniques on typical rural water sources, which is the main objective of this study.

MATERIALS AND METHOD

Raw water samples were collected from selected villages (four villages) in Katsina, Nigeria (Figure 1). Katsina was selected based on WHO ranking (as among the state in Nigeria with lowest access to potable water, Oke, 2011). Initial water quality parameters were determined to ascertain treatment processes required.

These water samples were subjected electrochemical treatment (Figure 2a, b and c), conventional and modified conventional water treatment techniques in a laboratory scales. Quantity analysis and qualities (initial and final concentrations) of the water samples were determined using standard methods as stated in APHA (1998). Operational and initial costs of these techniques were estimated scaled up using physical model (Dake, 1983). Efficiencies of these techniques were based on ability to remove selected parameters (turbidity, solids, microorganisms etc) were determined. Efficiencies were computed individually and in combination (geometric mean) as follows:

Individual: $$E_1(\%) = 100\left(\frac{C_o - C_1}{C_o}\right) \qquad (4)$$

Combination: $$E_c(\%) = 100\left(E_0 * E_1 * E_2 - - - - - - - E_n\right)^{\frac{1}{np}} \qquad (5)$$

Electrochemical treatment consist of electrochemical treatment of the wastewater samples for 60 minutes with a fixed voltage (20V), fixed separation distance between the electrodes, constant current and using aluminium electrodes (for both anode and cathode) after which chlorination followed. Conventional treatment involves the use of alum (aluminium sulphate) for coagulation /flocculation (Jar tests were conducted to determine optimum alum dose as well as optimum pH) with lime for pH adjustment to be followed by chlorination. In modified conventional treatment mixtures of alum, calcium hypochlorite and lime at an optimized ratio (1.38: 1.02: 1.00 that is 196, 146 and 142 mg/l for alum, lime and hypochlorite respectively using factorial experiment; Oke, (2011) were used for the treatment.

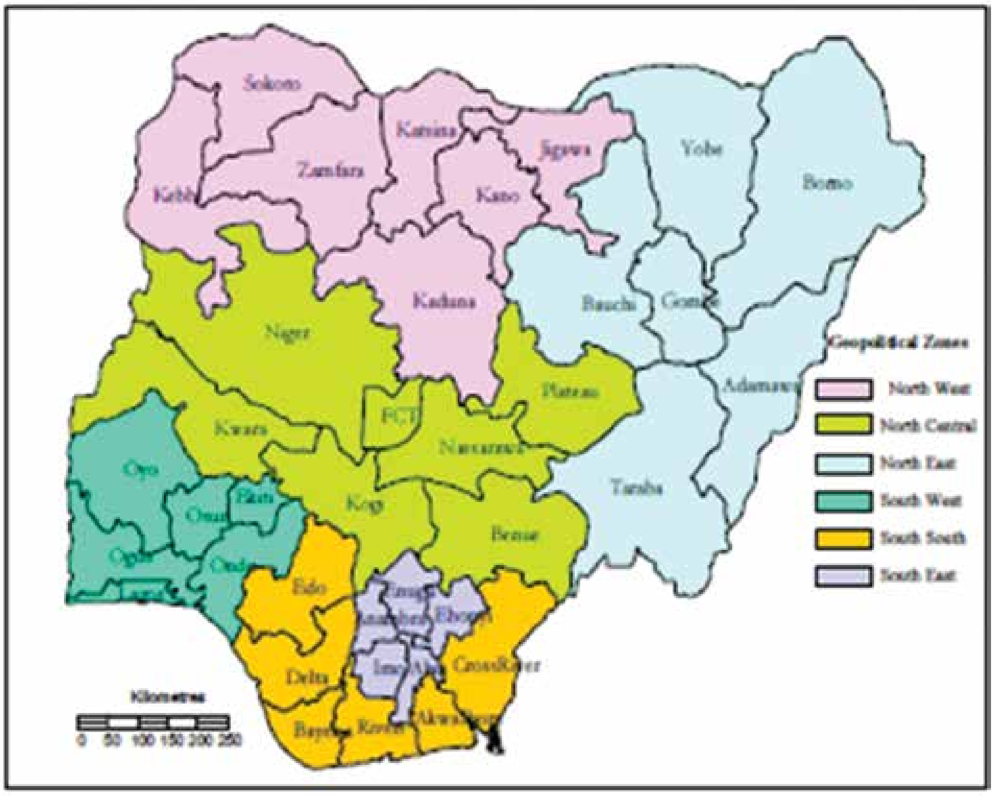

Figure 1. Map of Nigeria showing the states and Federal capital territory

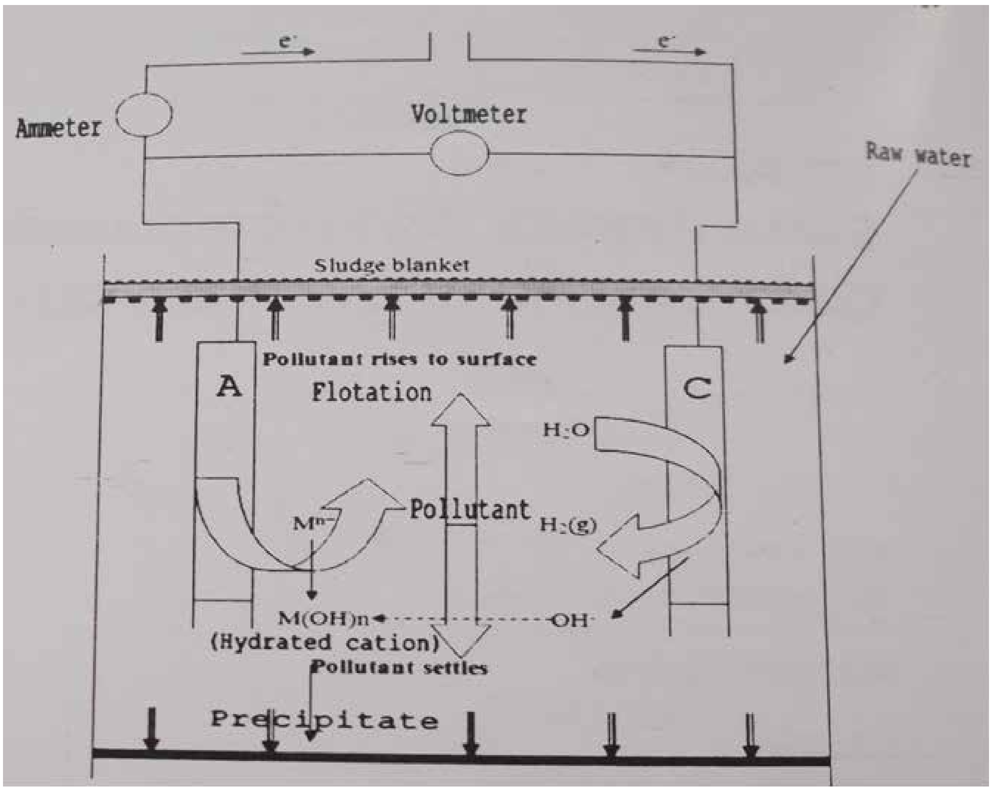

Figure 2a. Picture of a two electrode electrochemical treatment process (A = anode and C = Cathode)

Figure 2b. Laboratory setup of a two electrode electrochemical treatment process

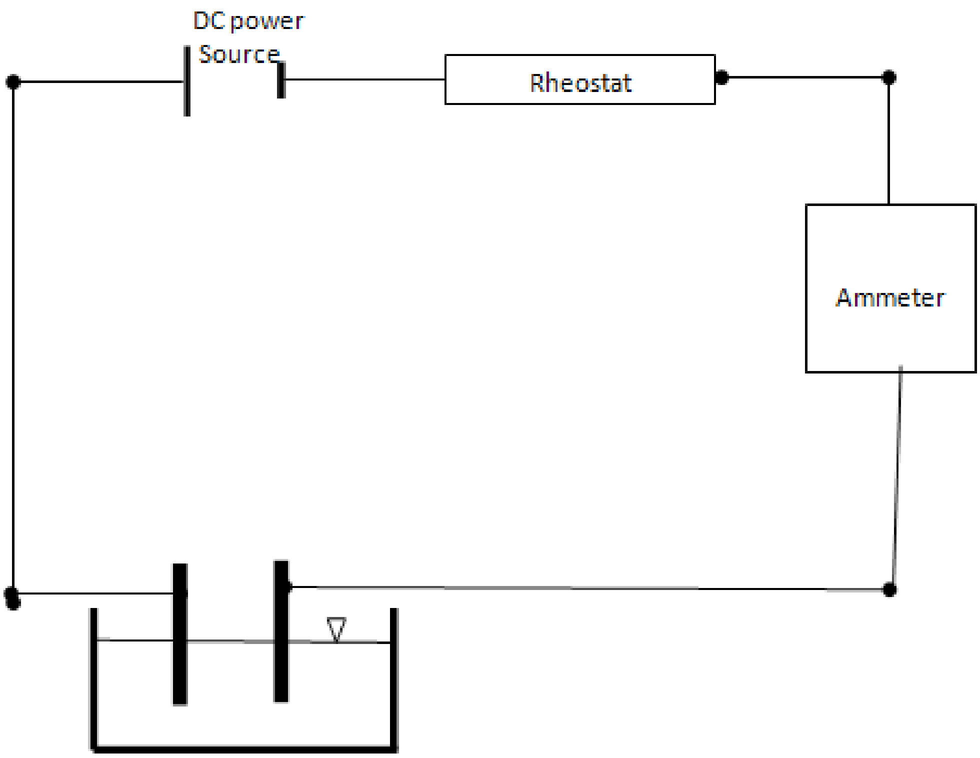

Figure 2c. Schematic diagram of laboratory setup of a two electrode electrochemical treatment process

RESULTS and DISCUSSION

Results of the study have been discussed as follows: quality of the raw water samples; efficacy of the treatment techniques and estimated costs (electrochemical, conventional and modified conventional treatment techniques).

Quality of the raw water samples: Table 1 presents statistical values of the water quality of the water samples. From the table the results reveal that these sources of water can be used as abstractions of drinking water but must be treated (Ellis, 1988). There are three options (A_1; A_2 and A_3) but option A_3 is the best for these types of sources (due to high turbidity and coli form counts).

Cost analyses: Comparison of the performance and efficiency of the three technologies studied can be summarized as follows: under similar conditions of aluminium concentration and pH the three technologies attain similar results (overall efficacies are 93.6; 89.8 and 98.8 % for the processes). For this reason, comparison of the operating costs of the three processes is a critical issue in recommending the use of one of the technologies. In this context, it is important to note that the aim of this study has been to compare the operating costs of the three dosing technologies, and to estimate the total costs of each one. Thus, a preliminary economical evaluation has been carried out, in which the items that can be considered to be the same in both processes, such as labour cost and management of the sludge have not been included in the calculations. In this context, the following assumptions have been made for the economical estimation (Pablo et al., 2008):

- The labour costs required in the three processes should be similar, despite the management of reagents involved in the conventional dosing of reagents, because the three processes can easily be automated. Also, the amount of sludge produced in the three processes must be similar, and therefore, the costs related to management of the sludge can be considered to be the same. The technique of cost estimate in literature such as Steel and McGhee (1979); Oladepo et al (2011) was adopted for capital and operational costs.

- The electrocoagulation cell is properly designed, that is, the turbulence generated by the gas bubbles emerging from the electrode surfaces is conveniently used to promote mixing of the electrodissolved coagulants, and the electroflocculation process. In principle, this fact should not increase the cost of the cell, as a simple layout of the electrodes in a parallel and slightly slanting position allows promotion of both effects. As a consequence, additional mechanical mixing is not required to promote either coagulation or flocculation processes. In addition, in the electrochemical process it is not necessary to consider the energy consumption derived from the dissolution of solid coagulants (salts) to prepare the liquid reagent to dose the coagulation process.

- To estimate the power necessary for mixing in conventional coagulation and modified conventional coagulation processes, the velocity gradient G (s^{-1}) has been used. This parameter is a function of the mixing velocity, the type of impeller, and the ratio between the tank and the impeller sizes as follows:

$$G = \sqrt{\frac{P}{mV}} \tag{6}$$

Typical values of parameter G are reported in the literature for the coagulation stage: 900 s^{-1} for 30 s, and for the flocculation stage: 25 s^{-1} for 30 minutes To calculate the mixing power necessary to prepare the coagulant solution, the author used a medium value for G of 700 s^{-1} for 10 minutes (Steel and McGhee, 1979; Viessman and Hammer, 1993;Tebbutt, 1991; Pablo et al., 2008).

- The operating costs of the conventional and modified convention coagulation process involve the costs related to the price of the coagulant reagents, and the energy consumption required for mixing in coagulation and flocculation processes. In addition, solid coagulants are used, it is necessary to consider the mixing required to prepare the coagulant solution. The energy consumption related to the pumping of the coagulant solutions was not considered to be negligible. To estimate the energy costs, one must take into account that the prices of electricity are highly dependent on the particular country. The present unitary electricity cost for industrial use in Nigeria is around 0.33$kWh^{-1}.

Table 1. Quantitative and quality analysis of the water samples (influent and effluent qualities)

Parameters	Influent	Electrochemical Treatment		Conventional water Treatment technique		Modified Conventional water Treatment technique		WHO limits
		Effluent	Efficiencies (%)	Effluent	Efficiencies (%)	Effluent	Efficiencies (%)	
pH	6.5 ±0.4	6.8 ±0.3		6.8 ±0.5		6.8 ±0.4		6.8-7.2
Turbidity (NTU)	740 ± 70	20 ± 5	97.3	36 ± 5	95.1	28 ± 6	96.2	< 5
Dissolve Oxygen (DO) (mg/L)	3.3 ±0.8	4.8 ±0.4		3.5 ±0.2		3.6 ± 0.3		
Suspended Solid (mg/L)	53 .9±12.2	5.1 ± 0.3	94.0	9.1 ± 0.2	89.2	8.7 ±0.4	89.6	
Dissolved Solid (mg/L)	128.6 ± 37.5	325.6±0.4		354.6 ±0.5		351.5 ±0.7		500
Coliform count (MPN)	3500 ±100	Nil	100	Nil	100	Nil	100	0
Sulphate (mg/L)	4.2 ±1.5	4.3 ± 0.6		80.7 ± 0.6		78.9 ± 0.8		250
Chloride (mg/L)	15.7 ± 8.6	15.7 ± 8.6	0	15.7 ± 8.6	0	15.7 ± 8.6	0	250
Nitrate (mg/L)	14.5 ± 3.6	14.5 ± 3.6	0	14.5 ± 3.6	0	14.5 ± 3.6	0	10 mg/l
Lead (mg/L)	0.05 ±0.01	0.0	100	0.0	100	0.0	100	0
Cadmium (mg/L)	0.03 ±0.01	0.0	100	0.0	100	0.0	100	0
Chemical Oxygen Demand (COD) mg/l	61.5± 18.7	16.3 ±0.1	73.5	23.5 ±0.6	61.8	24.2 ±0.4	60.7	120
Overall efficacies			93.6		89.8		89.8	

- The operating costs of the electrocoagulation process involve the price of the aluminium rod (used as electrodes) and the energy costs for their electrodissolution. The results obtained in the study of electrodissolution of aluminium have been borne in mind in estimating the energy consumption for the electrodissolution of aluminium. Previous study has shown that the concentrations of aluminium electro-dissolved are more than those values predicted by Faraday's Law, due to chemical corrosion of the electrodes.

Thus, the aluminium concentrations have been related to the Faraday's Law by an empirical equation as follows (Pablo et al., 2008):

$$C_{Al} = 100\left(\frac{I.W_{Al}}{F.n.q}X\right) \quad (7)$$

In electrochemical process the power consumption P (W) is given as follows:

$$C_E = \left(\frac{I.E_v}{C_{Al}.q}\right) = 100\left(\frac{F.n.E_v}{W_{Al}.X}\right) \quad (8)$$

The voltage (E_v) in the electrodissolution of aluminium has been set for this estimation according to the experimental results obtained in previous work, although this parameter is strongly dependent on the conductivity of the raw water treated.

- Regarding the separation of solids (pollutants with reduced solubility), in the case of conventional coagulation, the most favourable conditions have been assumed: the solids can settle rapidly, and therefore, it is not necessary to use the dissolved air flotation processes that would increase the cost of the treatment. In this context, in the electrochemical process the gas bubbles produced on the surface of the electrodes promote the separation of solids to the top of the cell (electroflotation process). Taking all of this into account, the separation of solids has not been considered to increase the cost of either of the coagulation processes.

- Concerning the operational comparison of the three processes, it was found that the changes in pH are different in the three dosing technologies. For this reason, it was necessary to adjust the final pH of the raw water to obtain recommended pH value.

The operational costs depend on the characteristics of the raw water, and especially, on the concentration of coagulant necessary to treat it. Figure 3(a and b) shows graphically a comparison of the total and operational costs obtained for the three doses of aluminium studied. It can be observed that the operational costs of the three alternatives studied are of the same order of magnitude, and that they are strongly dependent on the aluminium dose: higher aluminium doses lead to increasing operating costs. In all cases, conventional coagulation with the addition of aluminium sulphate presents the highest operational costs. This fact can be explained taking into consideration that this coagulant (aluminium sulphate) is the most expensive (imported into the country), and in addition, it requires dissolution, giving an important energy consumption and this coagulant is supplied as solid. On the other hand, it can be observed that the electrocoagulation process presents the lowest operating costs for low and intermediate aluminium doses (volume of raw water). In this context, the difference between the operating costs of the three processes is most for the lowest dose of aluminium. This fact can be explained bearing in mind that the conventional process involves fixed costs related to the requirement for mixing, whereas in the electrochemical process mixing is accomplished by the turbulence produced by the formation of gas bubbles of oxygen and hydrogen (and there are no additional costs). Finally, it can be observed that increasing the aluminium dose led to higher operational costs for the electrochemical process. This behaviour can be explained taking into account the economic estimation carried out, as increasing amounts of aluminium electrodissolved lead to decreases in the process yield. This can be attributed to many factors such as high values of electrical charge, higher yields of electrodissolution (X), high electrical charges mean high values of current intensity (I), increasing the cell voltage (E_v) more separation distance between the electrodes, more required treatment time, lower radius of the aluminium rods and less conductivity (higher resistance). However, the increase in cell voltage is strongly related to the characteristics of the raw water, so that the electrocoagulation process has low operating costs when treating raw waters with high conductivity. In addition, it is necessary to consider that operational costs of other factors such as cost of oxygen and hydrogen produced, properties of the sludge and alternative power sources such as fuel, solar panel etc. This would lead to lowering of the operating costs for the global process (electrocoagulation–electroflocculation–electroflotation).

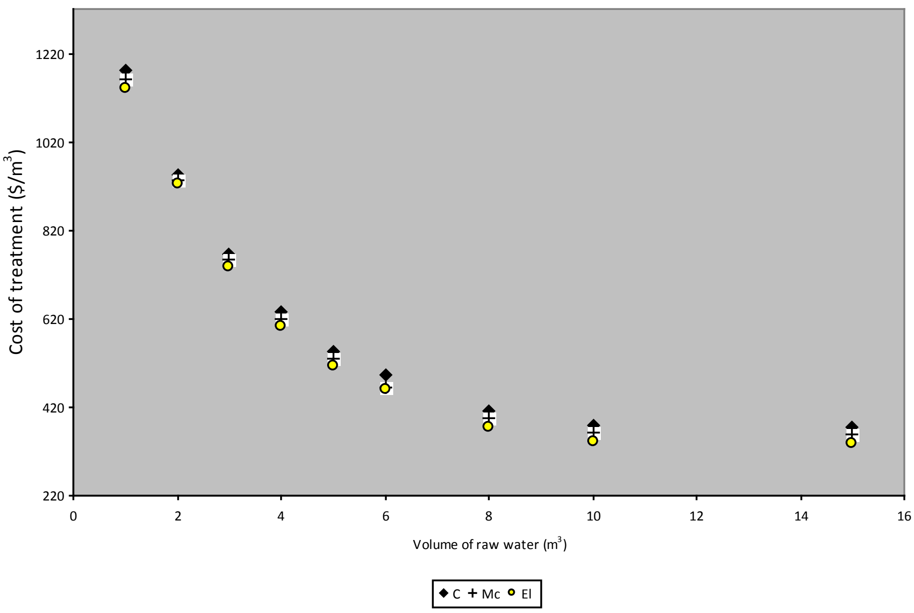

Figure 3a. Estimated total cost of the treatment techniques

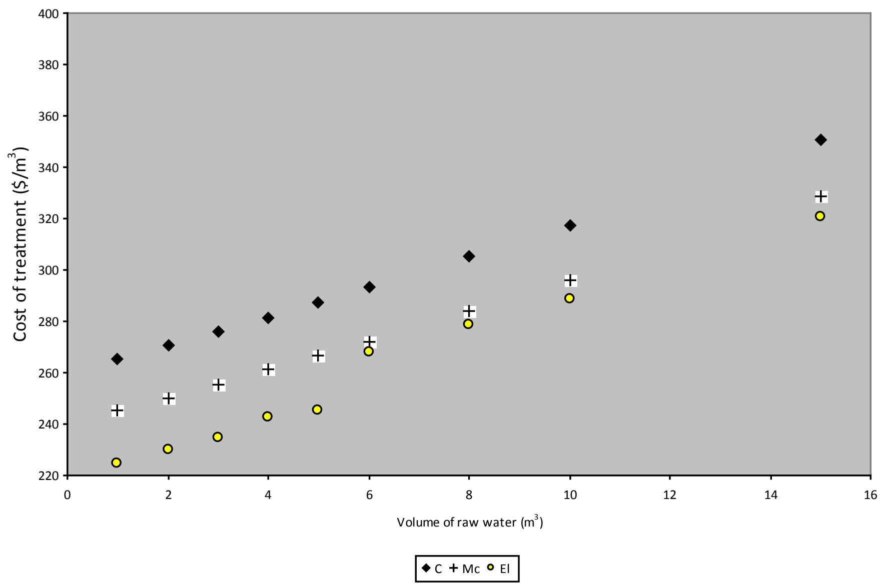

Figure 3b. Estimated operational cost of the treatment techniques

CONCLUSIONS

This study compared efficacies of three water treatment techniques toward production and delivery of safe water to the consumers. Raw water samples were collected and subjected to conventional, modify conventional and electrochemical treatment techniques. Performances of these techniques were monitored. Based on performance of these treatment techniques it was concluded that:

- Electrochemical is a promising technique for treating raw water technically and economically;
- There is a need to conduct a full environmental economy analysis of these water treatment techniques

SYMBOLS

A_1	low turbidity and low pollution
A_2	medium turbidity and low pollution
A_3	high turbidity and high pollution
C_1	final concentration
C_{Al} (g dm^{-3})	aluminium concentration,
CE	consumption of energy (W s g^{-1} Al)
C_o	initial concentration
COD	Chemical oxygen demand
DO	dissolved oxygen (mg/l)
E_0-------E_n	individual efficiency (%)
E_c	Combination efficiencies (%)
E_v	the voltage (V),
F	Faraday's constant,
G	velocity gradient
I	current intensity (A)
mg/l	milligram per litre
MPN	most probable number
n	corresponds to the number of electrons involved,
np	number of parameters
NTU	Nephelometric Turbidity Unit
P	the mixing power (W),
q	volumetric flow rate of the electrolyte (dm^3 s^{-1}).
V	volume of the tank..
W_{Al}	atomic weight of aluminium,
WHO	World Health Organization
X	electrodissolution yield (%)
μ	the viscosity of the liquid,

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