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Tolerance of *Myriophyllum aquaticum* to exposure of industrial wastewater pretreatment with electrocoagulation and their efficiency in the removal of pollutants

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Abstract

The wastewater used in this study was obtained from a treatment plant where it mixed with wastewater of 142 industries and was treated using electrocoagulation with iron electrode and phytoremediation with *Myriophyllum aquaticum*, likewise certain biomarkers of oxidative stress of the plant were evaluated to find out its resistance to contaminant exposure. Electrocoagulation was performed under optimum operating conditions at pH 8 and with a current density of 45.45 A m^{-2} to reduce the COD by 42%, color 89% and turbidity 95%; the electrochemical method produces partial elimination of contaminants, though this was improved using phytoremediation. Thus the coupled treatment reduced the COD by 94%, color 97% and turbidity 98%. The exposure of *M. aquaticum* to electrocoagulated wastewater did not have an effect on the ratio of chlorophyll a/b (2.84 + 0.24); on the activity of SOD, CAT and lipoperoxidation. The results show the potential of *M. aquaticum* to remove contaminants from pretreated wastewater since the enzymatic system of the plants was not significantly affected.

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Introduction

Water is essential for all socio-economic activities. As the population increases and develops there is an increase in the use of groundwater and surface water to service the domestic, agriculture and industrial sectors. Wastewater is produced in large volumes daily, therefore its reuse has become a priority. Water treatment processes have to be affordable, simple and also have to be specific because the contaminants in water and discharge limits vary from site to site (Helmer and Hespanhol, 2004). For this reason innovative, economic accessible, easy to accomplish and effective methods of purifying and cleaning wastewater before discharging into any other water systems are necessary (Roa-Morales *et al*., 2007).

Electrocoagulation (EC) is an electrochemical process in which electric current passes through an electrolytic cell. This technology is environmentally oriented since the “electron” is used as a clean reagent. Due to inherent cost and electric efficiency advantages, it is becoming a popular process to be used for the elimination of pollutants in wastewater (Vlaicu and Ciorba, 2004; Faiqun Ni'am *et al*., 2007).

Electrocoagulation is a complex process, with diverse mechanisms operating synergistically to remove pollutants from water, overall it amounts to an effective process that destabilizes finely scattered particles in wastewater, usually employing iron or aluminum electrodes during the course of a basic electrochemical process that when an electrical current is applied, the anodes release either Fe^{2+} or Al^{3+} ions, which in turn are good coagulants. When iron electrodes are used, the simplified mechanisms of oxidation at the anode and reduction at the cathode are represented by reaction 1-3 (Martine-Huitle and Brillas, 2009):

$$\text{Anode}: Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-} \qquad (1)$$

$$Fe^{2+}_{(aq)} + 2\,OH^{-}_{(aq)} \rightarrow Fe(OH)_{2(s)} \qquad (2)$$

$$\text{Cathode}: 2\,H_2O_{(l)} + 2e^{-} \rightarrow H_{2(g)} + 2\,OH^{-}_{(aq)} \qquad (3)$$

$$\text{Overall}: Fe_{(s)} + 2\,H_2O_{(l)} \rightarrow Fe(OH)_{2(s)} + H_{2(g)} \qquad (4)$$

The electrocoagulation treatment has been tested successfully for the separation of pollutants from wastewater (Holt and Mitchell, 2005) treatment of industrial wastewater (Linares-Hernandez *et al*., 2007) degradation and decoloration of dye solutions (Daneshvar *et al*., 2004; Sanjay *et al*., 2005; Keskin *et al*., 2011), removal of arsenic (Imran *et al*., 2011), removal of total suspended solids, turbidity, nitrates, sulfides, sulfates (Murugananthan *et al*. 2004; Alaadin, 2008; Malakootian *et al*., 2010). A literarure survey indicates that it is an efficient treatment process for different wastewaters.

Some innovative techniques use coupled processes or so called hybrid, where wastewater with high pollutant load is processed in two stages. Often, there is an initial decomposition of high molecular weight compounds using physicochemical methods during the first stage, then the less polluted water resulting from the first stage is treated using a biological method to achieve higher quality, compared to that obtained if the processes had been used isolated. (Hai *et al*., 2007).

In particular phytoremediation, as other biological techniques, is useful to remove pollutants from soil and water, which due to its elegance and extent of contaminated areas, has already granted it significant scientific and commercial attention (Núñez-López *et al*., 2008; Dar *et al*., 2011). In this way, phytoremediation arises as an alternative and complement to already existing techniques (Barceló and Poschenrieder, 2003; Peuke and Rennenberg, 2005).

In the last decades phytoremediation has been used, as an ecological alternative technique akin to efficient cleanup for a variety of organic and inorganic pollutants; it helps to mitigate the problem of contamination with the minimum use of energy and reduction of costs (Susarla *et al*., 2002; Núñez-López *et al.*, 2008). It basically use plants to eliminate or to diminish pollutants of soils and wastewaters, since it has been observed that they have a great capacity to resist relatively high concentrations of organic and inorganic materials with toxics effects that can be assimilated and turned into less toxic metabolites (Susarla *et al*., 2002; Peuke and Rennenberg, 2005; Baldwin and Butcher, 2007).

The plants during metabolic processes producing reactive oxygen species (ROS) such as superoxide anion radicals ($O_2^{\bullet -}$), hydrogen peroxide (H_2O_2) and hydroxyl radicals ($OH^{\bullet}$) are products that arise when subjected to adverse environmental conditions, like ozone exposure, salt stress, drought, heat, heavy metals, toxins and organic pollutants (Foyer and Noctor, 2000; Nimptsch and Pflugmacher, 2007; Ramírez-Serrano *et al*., 2008). High concentrations of ROS can be phytotoxic, while low levels can be used for acclimation signaling. So the controlled modulation of ROS levels in plants is extremely important for growth, homeostasis and stress defense (Nimptsch and Pflugmacher, 2007).

In order to control the ROS's level and to protect cells under conditions of oxidative stress, plants make use of several mechanism of enzymatic and non-enzymatic defense against the ROS, such as the superoxide dismutase (SOD), catalase (CAT), peroxidases (POD), soluble antioxidant (α-tocopherol y β-carotene) and water-soluble antioxidants (ascorbic acid and glutathione). When the levels of ROS exceed the ability of the antioxidant system to cope with them, damage of cellular components, including destruction of membranes with formation of lipid peroxides and oxidized proteins, may occur. These plants mechanisms are usually sufficient to protect them against oxidative damage during the growth period and under conditions of moderate stress (Ferrat *et al*., 2003; Ramírez-Serrano *et al*., 2008; Beladi *et al*. 2011; Dordio *et al.*, 2011).

Myriophyllum aquaticum Vell. (Verdc) is an aquatic plant that has great potential to remove contaminants such as 2, 4, 6-trinitrotoluene, dichloro-diethyl-trichloroethane, perchlorate pesticides and antibiotics in water solutions and contaminants in industrial wastewater (Bhadra *et al*., 1999; Susarla *et al.,* 1999; Gao *et al*. 2000 a, b; Turgut and Fomin, 2002; Ninad *et al*., 2005; Turgut, 2005; Turgut, 2006; Turgut, 2007; Cano-Rodríguez *et al*., 2010; Knezevic *et al*., 2011).

The purpose of this work was to determine the efficiency of combined techniques of electrocoagulation with iron electrodes and phytoremediation using *Myriophyllum aquaticum* Vell. (Verdc) for reducing COD, color and turbidity of industrial wastewater; and also to evaluate plants' tolerance to exposure to contaminants in the wastewater through the analysis of oxidative stress by determining the activity of SOD, CAT and lipid peroxidation.

Materials and Methods

Plant selection, collection and acclimatization : The plants of *M. aquaticum* were collected from Cerrillo Piedras Blancas, State of Mexico (at 2 624 msnm elevation, 19°24'23.5”N and 99°

41'28.8” W). The plants were taken to the laboratory and acclimatized in plastic containers containing tap water and Hoagland nutrient solution which was added weekly (Wilson *et al*., 2000). The culture was maintained at room temperature (20 ± 5 °C), pH of 6.5 to 7.5 and exposed to natural periods of light and dark.

Myriophyllum aquaticum Vell. Verdc is a relatively fast growing cosmopolitan macrophyte that can be easily propagated. Peculiarly, this plant can be submersed bearing also emergent leaves, has few roots, and does not need to be rooted on a substrate. The species parrot feather was chosen because of its phytoremediation capabilities. It is a native species of South America, with lakes, ponds, streams and canals as common habitats. (Susarla *et al*., 1999; Wersal, 2011).

Wastewater sampling : The industrial wastewater samples were collected from the effluent of a primary sedimentation tank of a treatment plant receiving wastewater from 142 companies, located on the margin of the Lerma River, Estado de México. Plastic containers were used for wastewater transport and storage at 4°C, and kept under refrigeration until analysis followed by electrochemical and phytoremediation treatments.

Electrochemical reactor and electrocoagulation process : A batch electrochemical reactor was constructed for the electrocoagulation step; the reactor consisted of series of iron electrodes. Five plates were connected as cathodes and five as anodes (Fig. 1). All the electrodes were flat with a smooth surface having overall electrodes' surfaces of 0.05 m^2. The wastewater was placed in the reactor for the electrocoagulation process, then previous to the electrochemical process the pH was adjusted to 8, where it was maintained by adding of H_2SO_4 [1 M] or NaOH [1 M] solutions. A DC power source supplied the system with 4 A, that corresponded to $80 Am^{-2}$ current density. The volume of liquid treated each time was 0.004 m^3, therefore the area/volume relationship was $12.5 m^2 m^{-3}$, just as reported by Holt (2002). In order to promote turbulence and enhance mass transfer, an aeration system was used; the aeration system consisted of one air diffuser placed at the bottom part of the rectangular vessel (Linares-Hernandez *et al*., 2007). The experiments were performed in triplicate.

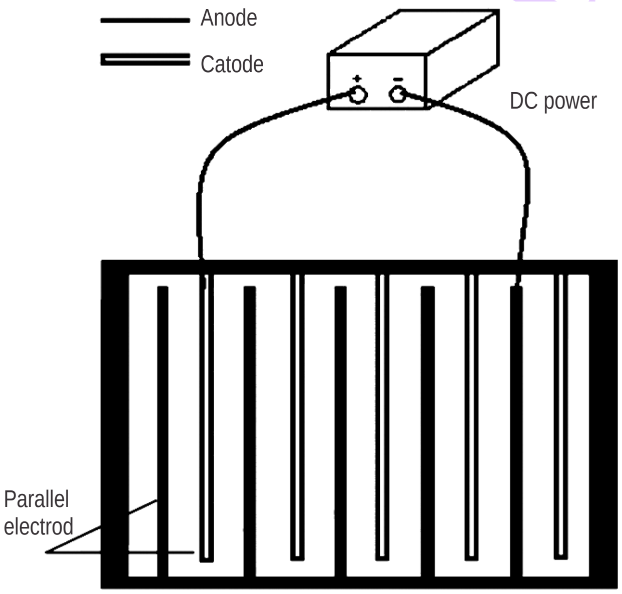

Fig. 1 : A schematic diagram of electrochemical reactor

Phytoremediation systems : The phytoremediation treatment was performed in 12 l glass containers (S). 4 l of wastewater pretreated by electrocoagulation at different concentrations and plants from 36 ± 1 g average weight were placed in each container. The control system, S1 (plant control) contained drinking water; while the other five systems, contained electrochemically treated wastewater of the following concentrations: S2 13%, S3 16%, S4 19%, S5 22% and S6 25%. The experiment was performed in triplicate.

Production of biomass and chlorophyll : Before and after the phytoremediation treatment, each plant used was measured and weighed. Relative growth rates (RGR) were calculated according to the equation

$$RGR = (\ln W_1 - \ln W_0) / (t_1 - t_0) \qquad (5)$$

where W_1 and W_0 are the initial and final weights and length of plants and $(t_1 - t_0)$ is the duration of the experiment (Hunt, 1982).

`The chlorophyll content of *a* and *b*, total chlorophyll and chlorophyll a/b ratio was determined in order to assess their photosynthetic potential and health status (EPA, 1994).

Determination of antioxidative enzymes and proteins : 500 mg of plant tissue were weighed and homogenized with 5 ml of 0.1M potassium phosphate buffer (pH 7.0), c 0.1 mM EDTA and 5% polyvinylpyrrolidone (PVP) in a cold glass mortar. The homogenate was centrifuged at 10,000g for 30 minutes at 4 °C and the resulting supernatants were used for the determinations of enzymes activities.

The catalase (CAT: EC 1.11.1.6) was calculated according to Aebi (1984) method. The activity was determined through the absorbance decrease due to the H_2O_2 reduction at 240 nm for 2 min. The activity of superoxide dismutase (SOD: EC 1.15.1.1) was determined using the Misra and Fridovich (1972) method with modifications, and was measured as the range of oxidation of adrenaline by superoxide radical observed at 480 nm. The lipid peroxidation levels were estimated as the formation of malondialdehyde (MDA) a by-product of lipid peroxidation that reacts with thiobarbituric acid according to the Buege and Aust (1978) method. The concentration of MDA was calculated using an extinction coefficient of 156 $mM^{-1} cm^{-1}$. The protein determination was quantified by method of Bradford (1976), using bovine serum albumin (BSA) as standard.

Analytical methods : The effect of the electrocoagulation - phytoremediation treatment was determined by the analysis of the chemical oxygen demand (COD), color (Pt/CO scale), turbidity (FAU scale) and pH, as indicated in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

Iron determination in the phytoremediation systems : The iron determination was carried out through standard o-phenanthroline spectrophotometric procedure as indicated in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

UV–Vis spectrophotometry : UV–Vis spectra were obtained from samples of raw and treated wastewater using a double beam Perkin-Elmer 25 spectrophotometer. The scan rate was 960 nm s^{-1} within a 200 to 900 nm wavelength range.

Cyclic voltammetry measurements : Cyclic voltammetry of raw and treated wastewater was performed using a standard three-electrode cell. The waveforms were generated using a BAS-100W potentiostat / galvanostat, which was controlled by BAS software. The working carbon paste electrode (CPE) was circular with an approximate 3.5 mm^2 nominal surface area. The CPE was prepared from a 1:1 (w/w) ratio mixture of 99.99% graphite single crystal (Alfa AESAR) and nujol oil (Fluka). This mixture was inserted into a PVC tube and compacted to eliminate trapped air, and then a copper conductor was inserted before the paste set. The surface of the electrode was renovated after each potential scan. The scan rate was 100 mVs^{-1}. The reference electrode was Ag/AgCl saturated with KCl and the counter electrode was a platinum wire.

Statistical analysis : Experimental data was processed using the Sigma Stat 3.5 software; using a variance analysis (ANOVA) considering a Kruskall-Wallis test with a significance level of P ±0.05 to compare the effect of water electrocoagulated exposure on RGR, chlorophyll and enzymatic activities in relation to a control.

Results and Discussion

The value of COD, color, turbidity, pH and conductivity of the wastewater is given in Table 1. The wastewater samples had pH 7.6 ± 0.2, but for the electrocoagulation treatment it was adjusted to 8 with 1 M NaOH. In previous studies carried out on industrial wastewater, Roa *et al*. (2007), found that the pollutant removal was achieved within the pH range of 3-8, while Linares-Hernández *et al.* (2008) found that the best removal of pollutants was carried out at pH 8: therefore, this pH was selected in this study. However, at the end of the electrocoagulation treatment it slightly increased to 8.9 ± 3, which can be explained due to the formation of iron hydroxide as a final product during the electrochemical process (Cañizares, 2005).

Table 1 : Percentage reduction of parameters in raw wastewater and wastewater treated with electrocoagulation using iron electrodes

Parameter	Raw waste water	Electroco-agulation	Reduction %
COD (mg l^{-1})	1462 ± 200	840 ± 30	42
Color (Pt-Co)	2480 ± 300	274 ± 40	89
Turbidity (NTU)	168 ± 30	7 ± 3	95

The color values in the wastewater were 2480 ± 300 Pt-Co. Previous reports have found that dissolved organic matter from the chemical and food industries are responsible for the wastewater color (Barrera-Díaz *et al*., 2006). After applying the electrocoagulation treatment 89% removal of colour was observed (Fig. 2). The result of this study is in confirmation with the earlier reports of Kashefialasl *et al*. (2006). Linares-Hernández *et al.* (2007) and Roa-Morales *et al*. (2007), where 83%, 81% and 57% of color removal from wastewater was achieved using aluminum electrodes. It is considered that the amount of hydroxide produced at the conditions given is sufficient to absorb the molecules that produce color in the solution (Daneshvar *et al*., 2004). Kashefialasl *et al*. (2006) treated a dying solution containing colored index acid yellow 36 using iron electrodes. Their results showed that when the initial dye concentration was 50 mg l^{-1}, it was effectively removed (83%) at pH between 7 and 9.

The turbidity in the wastewater samples was 168 FAU. The turbidity of industrial effluents depends on the type of discharge and sometimes on the sugar used in the food manufacturing process (Barrera-Díaz *et al*., 2006; Roa-Morales *et al*., 2007; Linares-Hernández *et al*., 2008). The wastewater percentage removal in the present study was 95%. Morante (2002) removed 10% of turbidity using iron and aluminum electrodes. Faiqun Ni´am *et al*. (2007) removed 95% turbidity from synthetic wastewater samples made from milk, using iron electrodes and a current density ranging from 3.51 to 5.62 mA, with an operating period between 30 and 50 minutes. Linares-Hernández *et al*. (2008) obtained 99% turbidity removal in industrial wastewater within 7-8 pH range. The results obtained indicated that turbidity decrease was effective.

Electrocoagulation allowed a 42% removal of initial COD when the concentration of wastewater ranged from 1462 to 1680 mg l^{-1} (Fig. 2). Morante (2002) treated industrial wastewater with electrocoagulation using four iron electrodes and four aluminum electrodes and obtained 70% COD removal. Faiqun Ni´am *et al*. (2007), removed 65% COD from solutions prepared using powder milk. Linares-Hernández *et al*. (2008) obtained an 80% COD removal in industrial wastewater. In this work, the electrocoagulation treatment diminished 42% COD, with pH=8 as

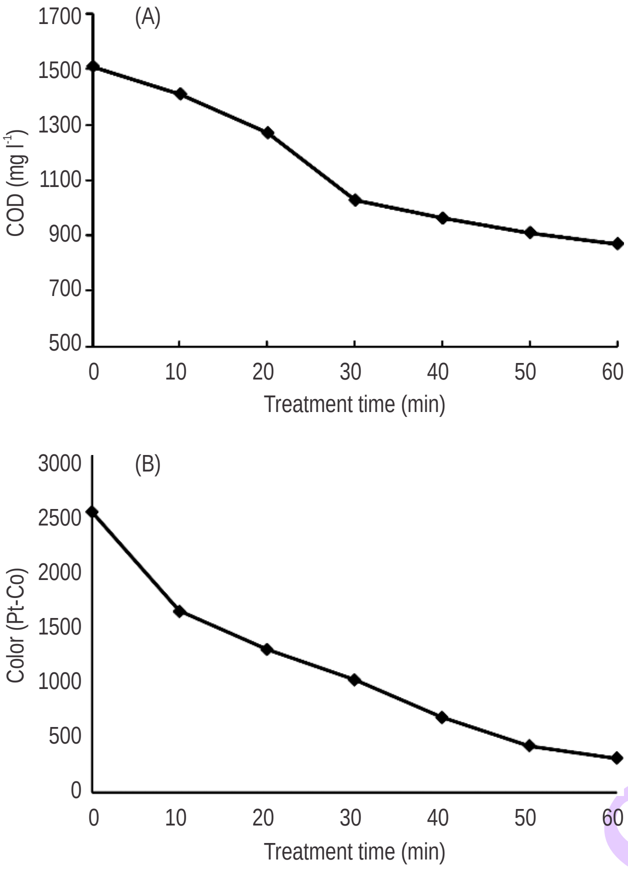

Fig. 2 : Removal of (A) COD and (B) color from raw wastewater as a function of time using electrocoagulation

optimal operation conditions, current intensity 45.45 Am^{-2}, and aeration. Cano-Rodríguez *et al*. (2010) used aluminum electrodes to treat industrial wastewater and obtained a 75% COD removal. However, a further treatment was required, therefore the phytoremediation was applied as polishing treatment. The results of this study demonstrated that *M. aquaticum* had the capacity to reduce 94% COD, 97% color and 98% turbidity, from industrial wastewater pretreated with electrocoagulation (Fig. 3). It is noted that for greater electrocoagulated water concentrations the COD decrease was more efficient, probably because the pollutants are more available than in the less diluted concentrations.

The length of the plants increased mainly at 19, 22 and 25% of electrocoagulated water, showing behavior similar to the control.

The relative growth rate decreased because the plants' roots exposed to different concentrations of electrocoagulated water had a degradation process caused by pollutants present in it. By applying ANOVA to both tests, it appeared that there were no significant difference in biomass production (weight and length) of plants exposed to electrocogulated water with respect to control (Fig. 4).

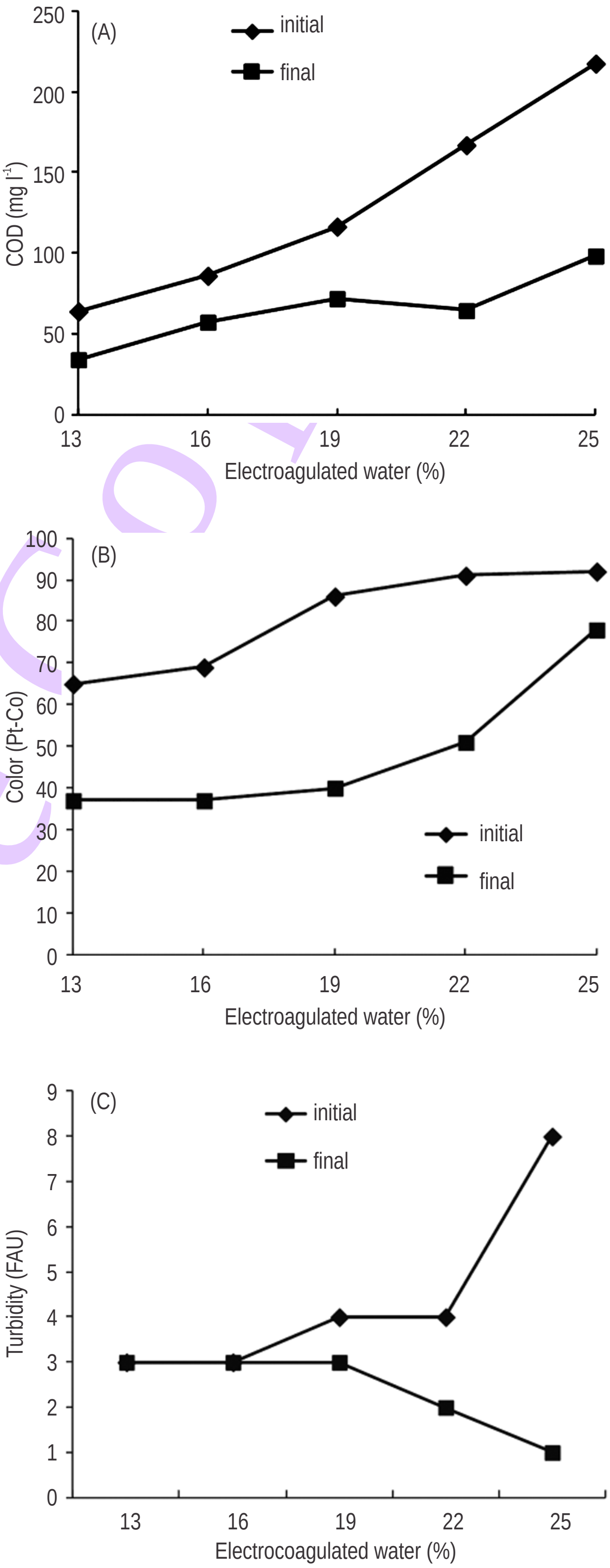

Fig. 3 : Decrease of (A) COD, (B) color and (C) turbidity in the phytoremediation systems after 15 days exposure to electrocoagulated water. ? Initial time (first day), ■inal time (fifteen day)

The results showed that the wastewater toxicity to *M. aquaticum* was low in the systems according to biomarker values. After 15 days of exposure to wastewater, there were no significant difference observed in weight and length. The average total chlorophyll content was 40.4 mg ml^{-1} and chlorophyll a/b ratio was 2.84.

After 15 days of treatment with wastewater, no significant difference was observed in the total chlorophyll content or chlorophyll *a*/*b* ratio between different concentrations. Research indicates that the chlorophyll endpoint, weight and length are an important indicator of health status in plants, the levels observed in this research correspond to a healthy level, change in total chlorophyll or chlorophyll *a*/*b* ratio may directly affect CO_2 uptake during photosynthesis (Delgado, 1993; Pernía, 2008). In this study, the electrocoagulation with iron electrodes did not affect their viability, growth and photosynthetic capacity when used at low concentration. Cano-Rodríguez *et al*. (2010) using electrocoagulated water with aluminum electrodes, at high concentrations (>25%), observed that survival of *M. aquaticum* was not affected and there were no significant difference in the chlorophyll content. However, at concentrations higher than 25% of electrocoagulated water with iron electrodes, caused death of several organisms, we obtained a LC_{50} value of 35% of AEC with a interval confidence at 95 % of 19% to 60%

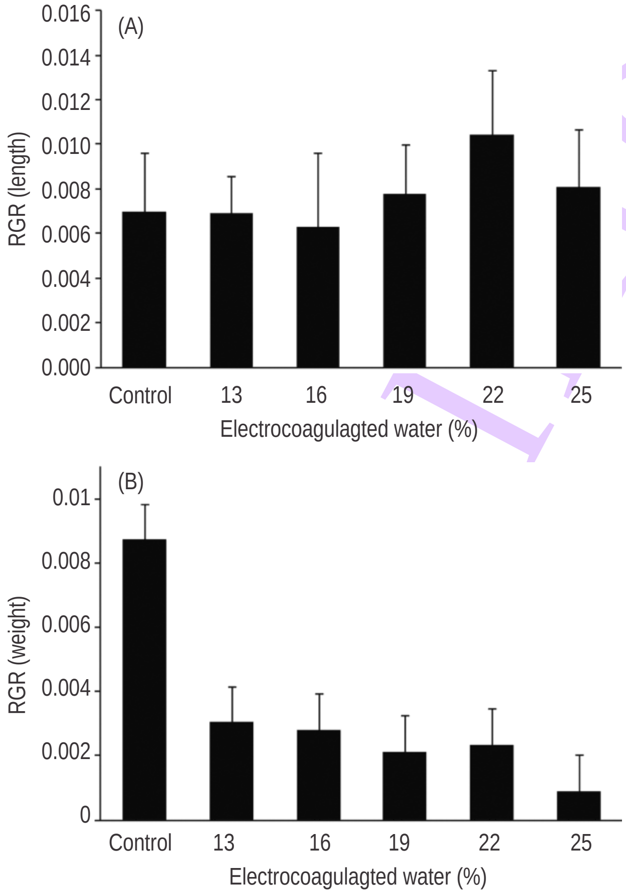

Fig. 4 : Relative growth rate (RGR) of length and weight of *Myriophyllum aquaticum* during phytoremediation process after 15 days of exposure to electrocoagulated water. The lines on the bars indicate the standard error

The plants exposed to 13% and 22% concentrations of electrocoagulated water did not show significant alteration in SOD activity; however 16 and 19% of electrocogulated water caused a significant increase ($p<0.05$); this observation may be due to the novel synthesis of enzymatic proteins by induction that suffers from being in contact with pollutants in the wastewater (Allen *et al*., 1997). The activity reduction appeared higher (25%) that is probably due to increased H_2O_2 levels and ROS causing damage to the enzyme system (Gallego *et al*., 1996) (Fig 5). It is also considered that high concentration or a long-term exposure to any pollutant, may suppress SOD activity (Wang *et al*., 2008); furthermore; SOD efficiency is relatively higher for short stress periods (Sánchez-Rodríguez *et al*., 2004).

The results obtained in this study are similar to those reported by Wang *et al*. (2008), who observed an increase in SOD activity in *Vallisneria natans*, when exposed to 0.4 and 1.2 mM NH_4Cl concentrations, but the activity reduced at higher concentrations (2, 2.8, 2 mM NH_4Cl).

Xu *et al*. (2010) found that SOD activity in *Phragmites australis* increased when exposed to water with 200 mg l^{-1} COD and decreased at 400 and 800 mg l^{-1}. In another study with *Typha angustifolia*, SOD activity increased at COD concentration of 600 mg l^{-1}, but decrease at 800 mg l^{-1} (Xu *et al*., 2011).

CAT is another important antioxidative enzyme, present in the peroxisomes and mitocondria of cells, which degrades H_2O_2 to water and molecular oxygen, that catalyzed reaction by SOD. The CAT activity increase could be explained by plants adaptive mechanism to maintain H_2O_2 at a steady-state level within the cells (Mishra *et al*., 2006; Dordio *et al*., 2009).

In the present study CAT activity increased significantly at 25 % concentration of electrocoagulated water (Fig. 5). This residual concentration of contaminants was sufficient to produce oxidative stress in *M. aquaticum* do, so that with the increase of CAT activity, the plant tried to maintain its homeostasis.

The increased CAT activity has been reported earlier too in several aquatic plants like *Myriophyllum mattogrense* were exposed to 20 to 30 mg l^{-1}concentrat = ion of ammonia. The ammonia triggers the peroxide production and therefore oxidative stress.(Nimptsch and Pflugmacher, 2007). In *Vallisneria natans* CAT activity increased at 1.2, 2 and 2.8 mM NH_4Cl concentrations (Wang *et al.* 2008). In *Typha* spp., CAT activity increased after treatment with 1 and 2 mg l^{-1} clofibric acid (Dordio *et al*. 2009), similarly when exposed to water contaminated with 0.5, 1 and 2 mg l^{-1} ibuprofen (Dordio *et al.,* 2011).

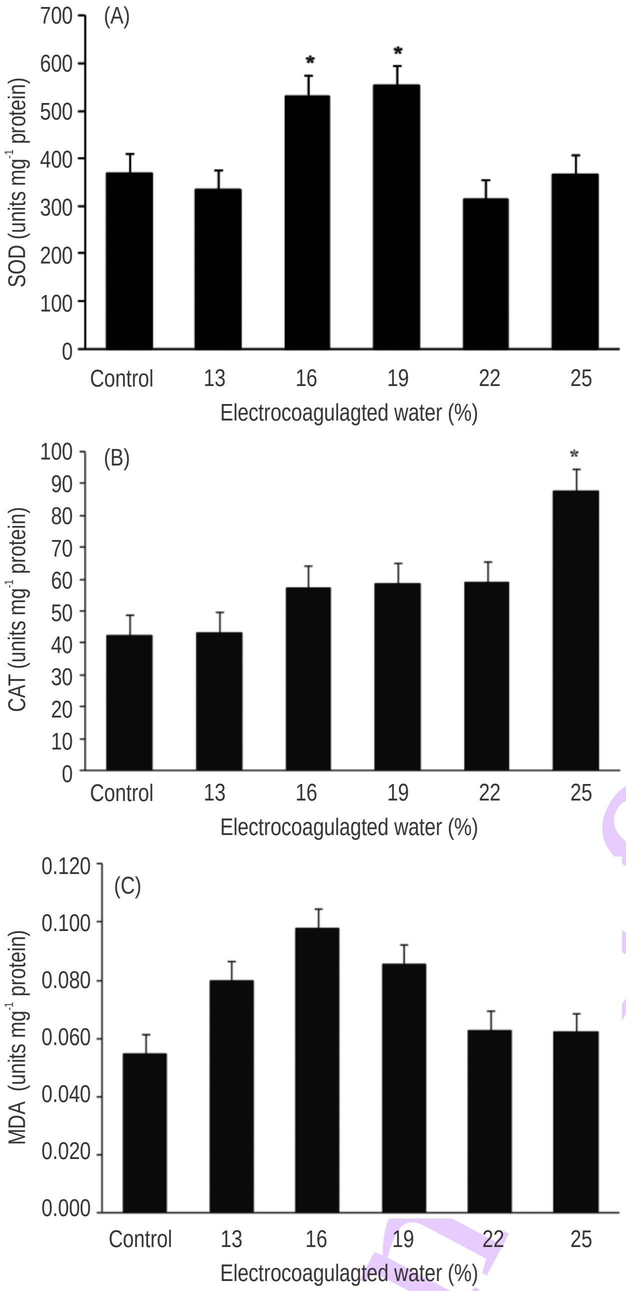

Fig.5 : Activity of the (A) SOD, (B) CAT and (C) lipoperoxidation in *M. aquaticum* exposed to water electrocoagulated for 15 days; Asterisk (*) indicates statistical significance. The lines on the bands indicate the standard error

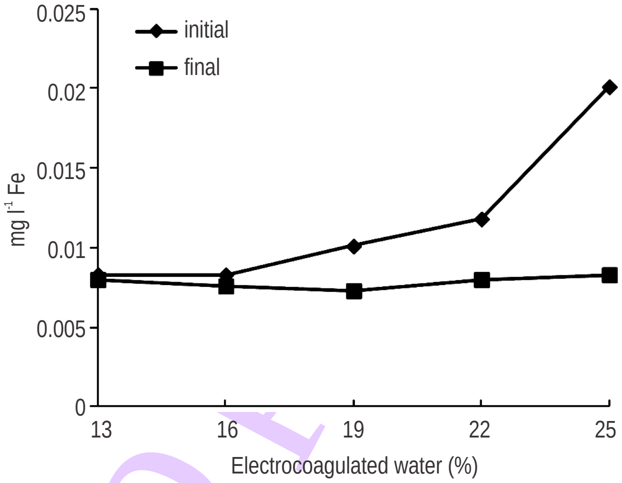

Fig. 6 : Decrease in the concentration of iron in the phytoremediation systems after 15 days exposure to electrocoagulated water

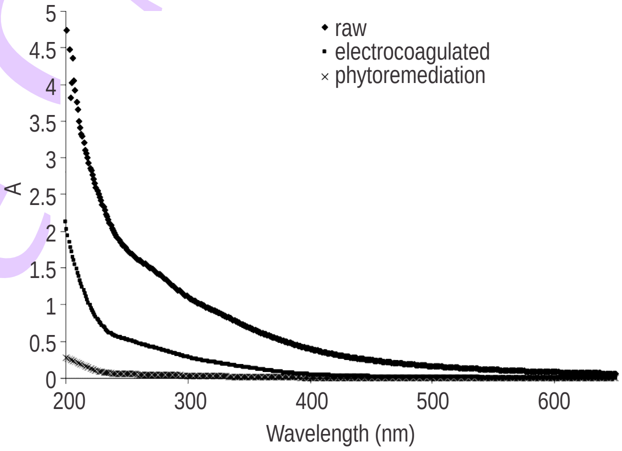

Fig. 7 : UV-Vis spectra of the raw wastewater, electrocoagulation and phytoremediation treated

Active oxygen radicals may induce chain-like peroxidation of unsaturated fatty acids in the membranes leading to formation of lipid peroxidation products like malondialdehyde (MDA). The effect of the water electrocoagulated toxicity on lipid peroxidation of *M. aquaticum* was determined by TBARS (thiobarbituric acid reactive substances). TBARS formation in plants exposed to stress environmental conditions is an indicator of free radical formation in the tissues, and may be used as an index of lipid peroxidation (Singh *et al*., 2006).

The results obtained in this study showed increase in lipid peroxidation level 13, 16 and 19% electrocoagulated water, however there were no significant differences noted when compared with control (Fig. 5), which indicates a possible resistance of *M. aquaticum* to pollutants present in electrocoagulated water.

During electrocoagulation process excess Fe was generated, this phenomenon is known as "superfaradaic efficiency", which can be explained through cathode corrosion in addition to the iron produced during electrocoagulation (Holt, 2002). Excess Fe was reduced by adjusting the pH to 11, to accelerate sedimentation, and then readjusting the pH to 8.5, the value which was obtained after electrocoagulation process.

The amount of iron in electrocoagulated water was 0.050 mg l^{-1}, thereafter determining the amount of initial and final total Fe in each phytoremediation system; it was observed that there was a decrease in all systems, particularly 25% electrocoagulated water with a 58% removal of total Fe (Fig. 6).

Garzón-López (2003) mentioned that the plant resistance to some metals such as aluminum and iron may develop through accumulation of these in the symplasm or exclusion from the apical root zone and its possible storage in the vacuole or immobilization in the cell wall.

UV-Vis spectra of raw wastewater, treated by electrocoagulation and by phytoremediation are shown in Fig. 7. There was a continuous signal curve in the region around 200-400 in the spectra corresponding to the components of the wastewater. It was interesting to mole that the intensity of curves decreased due to treatment effects. These results indicate that there was a significant color reduction of the raw wastewater when the electrochemical treatment and phytoremediation were applied.

To determine the electrochemical characteristics of raw and treated wastewater, and the processes occurring at electrodes, a series of cyclic voltammetry experiments were performed using a CPE as the working electrode. The results obtained indicate that a chemically irreversible oxidation peak in the wastewater was detectable at potentials lower that those corresponding to oxygen evolution as shown in Fig. 8. This peak corresponds to the direct electrochemical oxidation of pollutants present in wastewater. It is important to note that when cyclic voltammetry was applied after electrochemical treatment of wastewater, the peak did not appear in the voltammogram indicating that pollutants in the solution were oxidized. Thus, these voltammograms clearly indicate that there were processes attributable to direct oxidation of pollutants and these phenomena contributed to the destruction of organic matter present in solution, when electrochemical treatment was applied and no

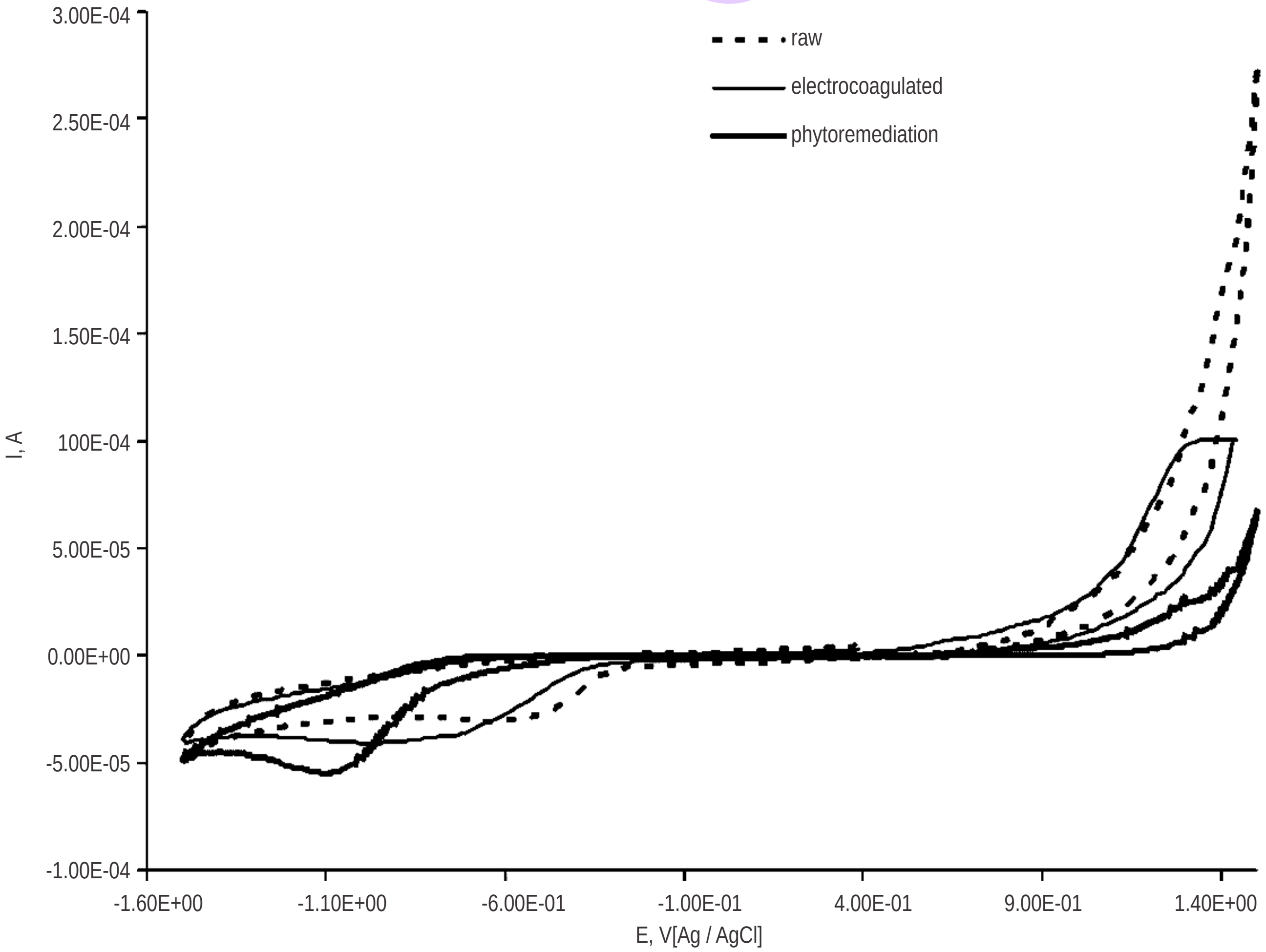

Fig. 8 : Cyclic voltammograms of the raw wastewater, electrocoagulation and phytoremediation treated.

other organic pollutants were introduced into the phytoremediated wastewater. Finally, this study confirmed that quality wastewater was improved using electrochemical-phytoremediation treatment. The electrocoagulation treatment reduced COD by 42% from wastewater. After phytoremediation 94% COD was removed. UV-Vis spectrophotometry and cyclic voltammetry confirmed the improvement of the quality of wastewater.

M. aquaticum was tolerant to contaminants present in the wastewater treated with electrocoagulation with Fe electrodes to minor dilutions than 25%, since at higher concentrations several plants were damaged.

Acknowledgments

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