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Domestic wastewater treatment by electrocoagulation system using photovoltaic solar energy

Sistema de tratamiento de aguas residuales domésticas por electrocoagulación utilizando energía solar fotovoltaica

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Abstract

This work deals with the design of a domestic wastewater treatment system for the washing machine, which is mainly based on responsibility to the environment in terms of the correct administration and proper management of the most significant asset that man possesses, water. In Mexican homes, one of the main domestic processes is laundry, where a large amount of water is used to clean clothing. Electrocoagulation is a process that can be used in the treatment of different wastewater due to its versatility and environmental compatibility. In the present investigation, the applicability of electrocoagulation for the treatment of domestic wastewater from the washing machine through the use of photovoltaic solar energy was analyzed. The effects of operational parameters such as current density, treatment time on turbidity, pH, and conductivity were studied. The objective of this project is to research alternatives to domestic wastewater treatment systems from the washing machine, through the use of photovoltaic panels taking advantage of and reusing the water from the washing machine after each washing process. Reduce the waste of the resources from homes, can contribute positively to the environment, and demonstrate that electrocoagulation is a viable alternative in the challenge of protection, conservation, and recovery of water resources.

Keywords: wastewater treatment, washing machine, electrocoagulation process, photovoltaic solar energy, photovoltaic panels.

Resumen

El presente trabajo se basa en el diseño de un sistema de tratamiento de aguas residuales domésticas provenientes de la lavadora, que se fundamenta principalmente en una responsabilidad con el medio ambiente en cuanto a la correcta administración y adecuado manejo del activo más significativo que posee el hombre, el agua. En los hogares, mexicanos uno de los principales procesos domésticos es el lavado de ropa, en donde se emplea una gran cantidad de agua en la limpieza de las prendas de vestir. La electrocoagulación es un proceso que puede emplearse en el tratamiento de distintas aguas residuales en virtud de su versatilidad y compatibilidad ambiental. En la presente investigación, se analizó la aplicabilidad de la electrocoagulación para el tratamiento de aguas residuales domésticas provenientes de la lavadora mediante el uso de energía solar fotovoltaica. Se estudiaron los efectos de parámetros operativos como la densidad de corriente, el tiempo de tratamiento sobre la turbiedad, pH y conductividad. La intensión de este proyecto es buscar alternativas para obtener un sistema de tratamiento de aguas residuales domésticas provenientes de la lavadora a través de la utilización de paneles fotovoltaicos centrado en aprovechar y reutilizar el agua de la lavadora después de cada proceso de lavado, para reducir el desperdicio del recurso desde los hogares, contribuyendo de forma positiva con el medio ambiente, demostrando que la electrocoagulación es una alternativa viable en el desafío de la protección, conservación y recuperación del recurso hídrico.

Palabras clave: tratamiento de aguas residuales, lavadora, proceso de electrocoagulación, energía solar fotovoltaica, paneles fotovoltaicos.

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1 Introduction

Water treatment plants (WTP) are typically based on traditional technologies such as biological and physicochemical processes, while new technologies based on electrochemical processes have recently been introduced.

Physicochemical and biological processes can be used for the decomposition of many organic contaminants, but these methods require large amounts of chemical reagents or bacteria that are detrimental to health.

Physicochemical processes use primary coagulants such as aluminum sulfate or iron salts for the coagulation process and synthetic polymers which can become mixed with contaminants during their manufacturing process with monomers or other toxic compounds, among which is acrylamide that can react with other chemicals added to the water during treatment, such as ozone and chlorine, creating substances that are harmful to health (Pérez Carrión, 1980).

Biological processes (activated sludge, natural methods, and adsorption), use bacteria for the water purification process, being an efficient process that, however, has a high cost in its operation and maintenance (since the bacteria depend on certain conditions of pH and organic load). Likewise, activated sludge has a high concentration of total and fecal coliforms, which produce bad odors, as well as the presence of harmful and toxic compounds that, due to their anaerobic nature, pollute the environment and can cause respiratory diseases in those who are close to these compounds (Reyes López, 2016).

Natural purification processes are those in which the main treatment is provided by components of the natural environment (land application treatment methods and aquatic systems). In them, the purifying effect corresponds to the action of vegetation, soil, microorganisms (terrestrial and aquatic), and to a lesser extent to the action of higher animals without the use of artificial agents (Delgadillo *et al*., 2010).

Gaseous chlorine is used as a disinfectant in WWTPs of the physicochemical and biological types (tertiary treatment); however, organochlorine compounds are generated when chlorine reacts with organic matter, the most abundant being trihalomethanes. According to Reyes López (2016), these compounds are harmful to human health. When water contains ammoniacal nitrogen, chloramines are produced, which are compounds derived from ammonium; these compounds can cause respiratory problems and are toxic to aquatic life (Reyes López, 2016).

The use of electrochemical processes for the removal of contaminants are gaining importance for WWT containing organic and inorganic compounds such as phenols (Belaid *et al*., 2013), tannins (Muruganananthan *et al*., 2007), dyes (Muthukumar *et al*., 2007); and hexavalent chromium (Lakshmipathiraj *et al*., 2008).

Electrochemical methods have few negative effects on the environment, as this technique does not involve the use of harmful reagents. Among the different electrochemical methods, the most applied technologies include the oxidation of organic pollutants by cathodic generation of hydrogen peroxide (Linares-Hernández *et al*., 2011); anodic oxidation using different electrodes (Panizza & Cerisola, 2001); the cathodic extraction of metals (Fu & Wang, 2011), the photodegradation of organic, inorganic oxidizable compounds (Ángel-Hernández *et al*., 2021), the advanced oxidation of toxic pollutants and/or difficult to treat by generating hydrogen peroxide known as electro-fenton (Casado J., Fornaguera J., & Galán, M. I. 2006), (San-Pedro *et al*., 2021) and electrocoagulation (Acosta *et al*., 2013).

The OFFICIAL MEXICAN STANDARD NOM-003 is the Mexican legal instrument that establishes the maximum permissible limits of contaminants for treated wastewater that is reused in services to the public. Domestic wastewater is that which comes from the private use of individuals and households, among which there are the so-called greywater (GW) or soapy waters that are generated in daily cleaning activities, which is the term used for waters that come only of toilets, sinks, showers and washing machines (Garduño, Gutiérrez and Bulnes, 2016). For each address, this represents a significant flow of volume per area. The production of graywater could represent up to 75 % of all wastewater produced by households (Leal, *et al*., 2011).

The mixture of which graywater is made up depends on factors such as: the number of people living in the house, types of physical activity, different socioeconomic levels, etc. These types of water contain surfactants, high amounts of soap, and organic matter (Niño & Martínez, 2013).

Table 1. Average mix of graywater (Niño & Martínez, 2013).

Parameter	Unit	Concentration
pH	U	6.3-8.1
Turbidity	NTU,	29-375
Conductivity	mS/cm	82-1845
Total Suspended Solids (TSS)	mg/L	25-183
Biochemical Oxygen Demand (BOD)	mg/L	47-466
Chemical Oxygen Demand (COD)	mg/L	100-700
Methylene blue active substances (MBAS)	mg/L	45-170
Fat, oil and grease (FOG)	mg/L	7-230
Total Coliforms (TC)	CFU/((100 mL))	$56\text{-}8.03\times10^7$
Fecal Coliform Forms (FC)	CFU/((100 mL))	$0.1\text{-}1.5\times10^8$
Escherichia Coli (*E. coli*)	CFU/((100 mL))	$0\text{-}2.51\times10^7$

Currently, EC draws a lot of attention, as it is a simple, efficient and sustainable process. The advantages of the EC process are simple equipment, easy operation, shorter reaction time, no chemical additions, and less sludge, which settles quickly.

The environmental impact induced by the use of photovoltaic solar energy is minimal and this makes the EC process powered by photovoltaic panels environmentally attractive. Photovoltaic panels (PV) are an excellent option for water treatment applications due to their long life, modularity, low maintenance, and low noise level (Fu and Wang, 2011).

The objective of this research focuses on the use of domestic wastewater from washing machines, since laundry is one of the most common domestic activities, resulting in the consumption of a significant amount of drinking water, so building a wastewater treatment system after the laundry cycle, which allows it to be collected and recycled through a process that allows to take advantage of and prolong the useful life of the water, which has a direct effect on the water resource and, as a result, a reduction in the impact of the environment.

According to the OFFICIAL MEXICAN STANDARD NOM-127-SSA1-1994, drinking water is understood as water for human use and consumption that does not contain objectionable contaminants, whether they are chemicals or infectious agents, and that does not cause harmful effects to humans. In Mexico, according to the National Water Commission (CONAGUA), the consumption of drinking water per person in Mexicali, Baja California, Mexico is equivalent to 278 liters per person per day (L/p/d) (Salgado, Güitrón de los Reyes and López, 2018), the supply per person per day in dry or very dry weather should be 190 L/p/d, which is an indicator of the inadequate use of the resource in our region. In this way, according to statistics from the national survey on energy consumption in private homes (ENCEVI, 2018), more than 70 % of the population in Mexico has automatic washing machines and 37 % of the water consumed by each household is due to that use. According to the CONAGUA, the total annual consumption is 93.65 hm^3/year (Salgado, Güitrón de los Reyes and López, 2018), so it is inferred that around 35 hm^3/year are the ones consumed in our city for washing clothes.

Therefore, it can be concluded that washing clothes is the domestic activity that consumes the most drinking water in the home, with an average daily intake of 38.57 (L/p/d), or 27.99 % of the total water consumed per day by a person.

Thus, the implementation of a device that allows the treatment of this wastewater would permit its recovery, conservation, and reuse after washing clothes, and could become a good solution for reducing water consumption and pollution, allowing a more efficient use of water supply in various domestic activities, such as the toilet, the greenhouse, car washing, house cleaning, etc. This is mainly due to the fact that this water has an adequate level of pollution, since it mostly includes contaminants from soap, detergents, bleach, fabric softeners, and fabric particles, which are easy to extract from the water.

The current work presents a prototype that allows the treatment of gray water from a washing machine in quantities that correspond to the actual use of a dwelling home, allowing us to confidently state that the electrocoagulation process can be used to treat the total water generated during the washing process in a household.

The proposed design is environmentally friendly, and aims to use the same amount of water during several wash cycles, thus extending the useful life of the water.

2 Methodology

2.1 *Prototype design*

In this research, a prototype was designed for the treatment of domestic laundry wastewater from the washing machine (DLW), using the EC process (Medrano *et al*., 2018; Medrano *et al*., 2019).

The experiments were carried out using wastewater with soap & paint for clothes which were characterized by measuring pH, electrical conductivity (j), turbidity and color. To execute the investigation, the sieving of the water tests was carried out after the electrocoagulation process, the behavior of different physicochemical variables in the aqueous medium was observed, a priori data were collected that allowed determining the values of electric current, the distance between electrodes, and treatment time, in the aqueous medium, which led to the application of the EC process with pH values of current density (j) with a value of 3.8 A/m^2 and time (t) with monitoring at 0, 15, 30, and 45 min. The pH was allowed to vary freely throughout the performance of each sample. The percentage of turbidity removal was determined by measuring the parameters before and after each treatment through the taking of samples that were sent to a certified laboratory in the locality named "LAB SIN Servicios Profesionales S. A. de C. V. Análisis Químicos, Físicos y Bacteriológicos". Throughout the process, measurements of pH and conductivity of the aqueous medium were made. All analyzes were performed in the laboratory mentioned above. The EC was carried out for each test in an electrolytic cell built in High Density Polyethylene (HDPE) with a capacity of 290 L, provided with four 2024 T351.250 bare plate aluminum electrodes; two used as sacrificial electrodes, with separations of 7 cm in parallel arranged in alternate order, which were connected to a polycrystalline photovoltaic panel of 280 W with voltage at maximum power (Vmp) of 32.27 V with current at maximum power (Imp) 8.69 A. The response variables were the percentage reduction in turbidity, conductivity and color. Figure 1 (a and b) shows the reactor. Table 2 shows the parameters and conditions of the system to be controlled.

3 Results and discussion

The electrocoagulation system with photovoltaic solar energy (ECSPV) can be successfully applied to DLWs, verifying that said process works with the use of PV for large amounts of water (domestic use), moving from the prototype with HDPE 50 L fed through a source from 15 Vdc with capacity up to 10 A

Table 2. Parameters and conditions of the system (own elaboration).

Parameters to be measured:	Parameters to be controlled:	Operating conditions
Total current consumed in the system. Voltage between anode and cathode	Turning the process (ON/OFF) Alternate anode and cathode to reduce plate wear.	Reactor Type: Batch. Sample: Residual water with soap and paint for clothes. Volume: 290 L. Physical dimensions of the electrolytic reactor: vertical water storage tank (VWST) Capacity 290 L/Measure: 1.2×0.6×0.4 m. Number of electrodes: 4. Separation between electrodes: 7 cm. Plate dimensions: 0.50 m×1 m×0.0254 m Surface area of electrodes [2(ab+ac+bc)]: 1.0762 m^2. Cathode: 2 aluminum electrodes 2024 T351.250 bare plate. Anode: 2 aluminum electrodes 2024 T351.250 bare plate. Voltage: 32,27 Vdc Current: 3,8 Adc. EC cycle time: 15, 30 and 45 min.

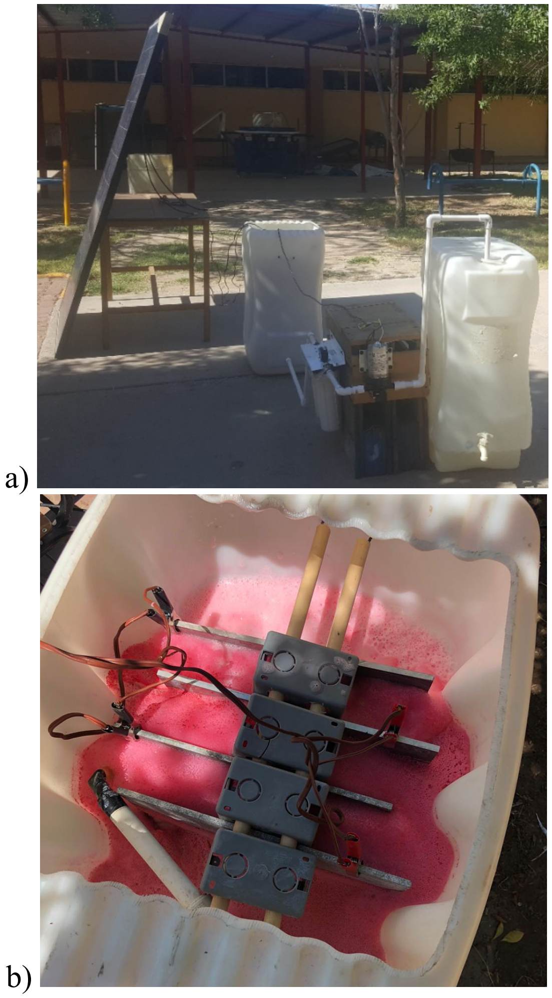

Fig. 1. Electrolytic reactor (prototype): a) side view, b) internal view of the reactor.

(Medrano *et al*., 2019), to one fed through the use of polycrystalline PVs of 280 W, with Vmp 32.27 V, Imp 8.69 A, verifying that the values remain stable, being able to justify that this type of projects are viable, simple, efficient and sustainable.

The characterization of the water sample from the storage container before applying the EC process has initial parameters of: 8.18 U, turbidity 160 U Turbidimetric, and conductivity 1.275 mcmhos/cm.

Figure 2a) presents the results for turbidity decrease and color variation (Figure 2b) at H 8.18, 7.96, 7.88, 7.93 U and a current density of 3.8 A/m^2 for treatment times of 15, 30 and 45 min. This graph shows that the percentage of turbidity decrease increases with the decrease in conductivity as the treatment time progresses, with a presenting a decrease in pH.

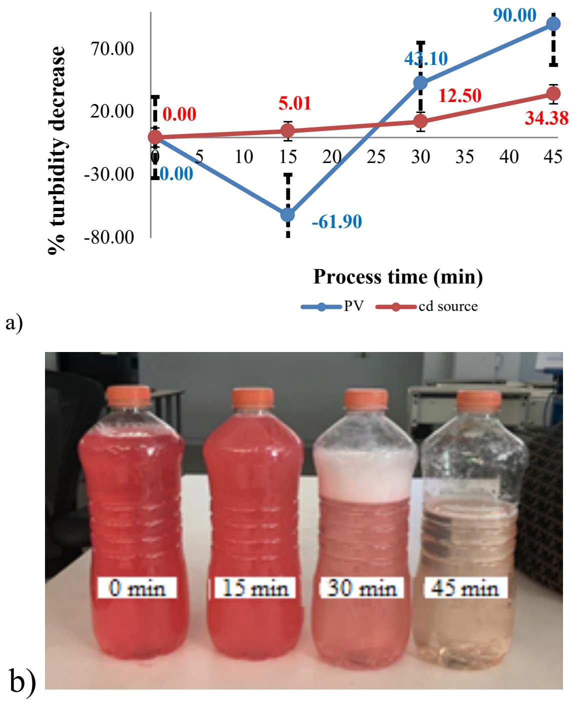

Fig. 2. a) % turbidity decrease, b) color variation.

It is observed that the greatest decrease in turbidity is obtained at 45 min, an intermediate decrease at 30 min and the lowest turbidity is obtained at 15 min because flocculation is being carried out in the effluent, so that the water is more turbid as the soap is removed and agglutinated, which due to its behavior tends to remain suspended in the water, making the development of the process more visible. It is important to indicate that the state of the art indicates that the EC process presents better results for pH values close to 7.

Figure 3a) shows the final pH obtained by applying electrocoagulation. It is observed that the pH during the EC process decreases over time in relation to the initial pH of the wastewater; in approximately 0.25 U, this decrease can be explained by the increase in the current level with respect to those used with the direct current power supply (which was 1.8 A) (Photovoltaic panel data sheet). It is observed that even when the final pH is lower than the initial pH of the tests, it increases with respect to the time of 30 min (7.88 U) up to 7.93 U (at 45 min) due to an increase in water temperature in response to current levels circulating through in the EC's system. Figure 3b) shows the percentages of conductivity variation; it is observed that the conductivity is reduced up to 13.1 % in the 45 min of the process. Increased current levels in the

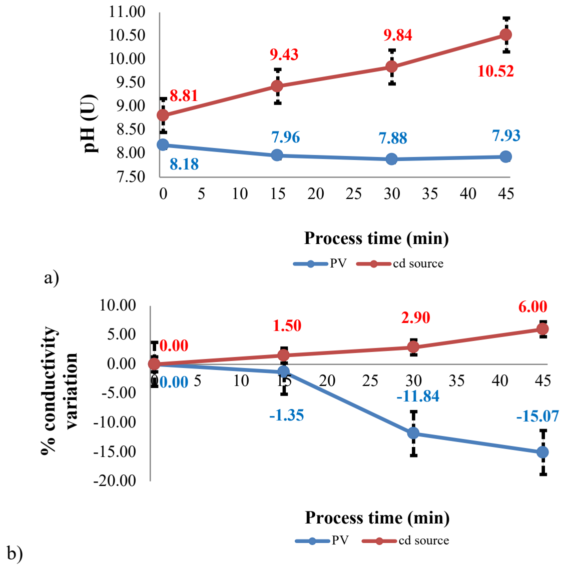

Fig. 3. a) pH (U), b) Conductivity (mcmhos/cm).

EC system can explain this behavior.

The removal efficiency was calculated as:

$$\text{Removal efficiency }(\%) = \frac{(C_o - C)}{C_o} \times 100 \qquad (1)$$

where: C_o = Initial turbidity, C = Final turbidity.

The calculations were carried out with the initial and final turbidity and the conductivity before and after the EC process.

Conclusions

In the present study, it was shown that the continuous process of an EC system with photovoltaic solar energy and aluminum electrodes to treat wastewater with soap and paint for clothes with treatment tanks with a capacity of 290 L is effective.

The optimal condition that allows obtaining the highest percentage of turbidity reduction for water with residues of soap and paint for clothes is with a hydraulic detention time of 45 min; turbidity removal efficiencies for PFV is 90 % and the dc source is 34.38 %; and for the conductivity variation for PFV it is -15.07 % and 6.00 % for the dc source. The pH for the PFV is between 8.18 -7.93 U and for the dc source between 8.81 -10.53 U, so no additional treatment is required to correct the pH. A decrease in the pH of the aqueous solution is observed. The conductivity of the aqueous medium shows a decrease throughout the treatment.

The results of the tests showed that the EC treatment provides a reduction in the concentration of contaminants, evaluated in the experiment through the removal of turbidity, conductivity and color.

EC is an emerging technology that shows itself as an alternative in wastewater treatment, it is very promising in terms of removing a wide range of contaminants found in wastewater from various sources.

Emphasizing the different electrochemical processes applied to TAR and drinking water processing, this demonstrates advantages over chemical processes, including greater efficiency, lower costs and no environmental impact.

The cost related to the energy consumption of electrochemical treatments is determined by the voltage used, the operating time and the current established during the process, therefore, the use of new technologies such as solar through the use of photovoltaic panels to achieve a reduction in the carbon footprint, as well as a reduction in electricity costs, achieving the challenge of preserving, conserving and recovering water resources.

More tests are needed with different types of electrodes in order to find the appropriate ones, carrying out a cost-benefit study, in order to scale up the wastewater treatment through the electrocoagulation process and reach the electro-oxidation (EO) process, and thus be able to correct the main disadvantage of EC that represents the replacement of the sacrificial electrodes.

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