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Industrial wastewater treatment by electrocoagulation–electrooxidation processes powered by solar cells

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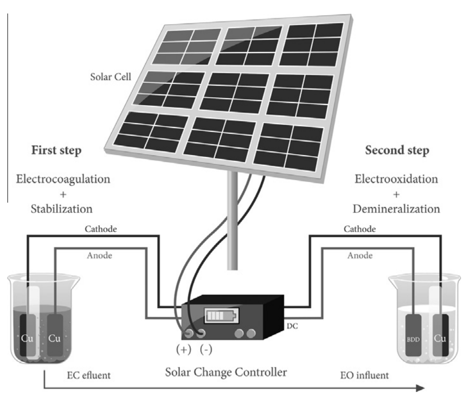
HIGHLIGHTS

- The EC and EO achieved a TOC removal efficiency of 99%.
- The use of copper in EC stabilizes the system.
- The electrooxidation process (BDD/Cu) promotes the demineralization of water.
- The electrooxidation is a clean process that avoids the CO_2 emissions.
- The solar cells supply sustainable energy to the electrochemical processes.

GRAPHICAL ABSTRACT



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ABSTRACT

The goal of this research was the elimination of the chemical oxygen demand (COD), total organic carbon (TOC), color, and turbidity from the industrial wastewater from an industrial park by applying electrocoagulation (EC) and electrooxidation (EO) processes powered by solar cells. The EC process was carried out in a batch monopolar electrochemical cell; copper was used for the anode and cathode electrodes, with an area of 0.00125 m^2, and solar cells supplied the system with 1–3 A of current intensity. The COD reduction was 80% at pH 2 and 89% at pH 4, and a removal efficiency of 97% and 91% of color and turbidity, respectively, were achieved; however, TOC reduction achieved was only 48%. In order to improve the removal of TOC, an EO treatment was applied after the EC process. The EO was carried out in batch cells using a boron-doped diamond (BDD) anode and a copper cathode. The maximum removal efficiency was 70.26% of TOC and 99.7% of COD, with EC + EO processes. Color and turbidity removal were 100% and 95%, respectively. Aside from the strong oxidation capability of the hydroxyl radicals generated, the presence of active chlorine in the solution contributed to COD removal via indirect oxidation.

1. Introduction

Toluca-Lerma is the second most important industrial area of Mexico and has almost 300 companies that provide jobs, economic resources, and a better quality of life. Nevertheless, industrial

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activities use significant quantities of water during their manufacturing cycles and generate significant amounts of wastewater that usually does not meet the environmental regulations for being discharged directly into the receiving water.

The treatment of industrial wastewater is difficult due to the large variations in its volume and composition, high concentrations of organic matter and salts, and the presence of poorly biodegradable organic compounds or substances [1,2]. The biological treatment of wastewater from industrial facilities has reportedly experienced the difficulties of poor biosolid separation, voluminous biological sludge, and low removal efficiencies. The existing wastewater treatment facilities have to improve their operating performance and provide an effluent of higher quality that conforms to more stringent regulations [3].

Nowadays, electrochemical technologies offer the ideal tools for addressing environmental problems. The main reagents used are electrons, which are a clean reagent and eliminate the need for adding an extra reagent. Electrocoagulation (EC) is the process of destabilizing suspended, emulsified, or dissolved contaminants in an aqueous medium by introducing an electric current into that medium. In its simplest form, an electrocoagulation reactor may be made up of an electrolytic cell with one anode and one cathode. The conductive metal plates are commonly known as "sacrificial electrodes" and may be made of the same or different materials (anode and cathode). EC is the electrochemical production of destabilization agents (such as aluminum(III), iron(II) and iron(III)) that bring about the neutralization of the electric charge for removing pollutants. This process is characterized by reduced sludge production, no requirement for chemical use, and ease of operation [4]. EC has been applied successfully to tannery wastewater [5], petroleum refinery wastewater [6], the removal of lignin and phenol from paper mill effluents [7], olive mill wastewater [8], the removal of heavy metals [9], the removal of dairy effluents [10], textile wastewater [11], etc.

In electrooxidation (EO), the pollutants are degraded by either a direct or an indirect oxidation process. In the direct anodic oxidation process, the pollutants are adsorbed on the anode surface and then destroyed by the anodic electron transfer reaction. In the indirect oxidation process, strong oxidants such as hypochlorite/chlorine, ozone, and hydrogen peroxide are electrochemically generated. The pollutants are then destroyed in a bulk solution by the oxidation reaction of the generated oxidant. All the oxidants are generated in situ and utilized immediately [12]. EO has been applied in the purification of the wastewater from a gelatin production plant [13], the oxidation of alcohols in water [14], organic wastewater [15], the distillery industry's wastewater [16], the chemical industry's wastewater [17], ammonia and phosphate wastewater [18], azo dyes [19], olive mills' wastewater [20], etc.

In all cases, the quality of the wastewater treatment depends on the quantity of the ions produced, their current density, the time of operation, and the anode/cathode materials. The current density selection should be made with other operating parameters such as pH, temperature, and flow rate to ensure a high current efficiency.

As mentioned above, the electrical current is extremely important for obtaining the best-quality wastewater for the electrochemical process, and therefore it is of utmost importance to ensure that the current flow is stable and continuous.

The industrial and economic development of many companies is clearly leading to the expansion of electrical power systems. Addressing energy needs in a sustainable manner will greatly contribute to the solutions to 21st century challenges such as climate change, greenhouse gas effects, etc. [21].

At present, direct sunlight is potentially the most powerful renewable energy source. In less than an hour, the Earth receives the same amount of energy from the sun as is used globally by mankind in a year. In contrast to most of the other energy technologies, solar energy is only limited by the cost of conversion and the intermittency in time [22].

The utilization of sunlight can be made with a wide variety of technologies that use the physical principles of energy conversion. These various technologies deliver energy in different forms: electricity, high- or low-quality heat, or synthesized fuels such as hydrogen and hydrocarbons. This means that there are several possibilities as to where and how each conversion option is best applied [22].

The photovoltaic (PV) systems are a renewable and sustainable option for providing electricity [23] due to the universality of solar resources and the systems' easy operation compared with other energy sources. PV systems use the photo-physical properties of materials to create electricity directly from the photons of sunlight. The PV cells, usually quite small, typically generate between 60 and 200 W in full sunlight, depending on the technology and the size [22].

Hence, the purpose of the present study was the treatment of industrial wastewater from an industrial park for the elimination of its COD, TOC, color, and turbidity by applying electrocoagulation and electrooxidation processes powered by solar cells.

2. Materials and methods

2.1. Wastewater samples

Samples of wastewater were collected from an influent of a treatment plant located at the end of an industrial park. This facility receives the industrial discharge from 136 factories. All of these industrial effluents enter into the wastewater treatment plant. The plant has the following treatment operations: shredder, sand separator, oil and grease trap, primary clarifiers, biologically activated sludge reactors, secondary clarifiers, and chlorination chamber. These treatments, however, are not sufficient, as they remove only 50% of the COD. Thus, additional treatment steps are required to improve the wastewater's quality.

After primary treatment, wastewater samples were collected in plastic containers and cooled to 4 °C for analysis and electrochemical treatments.

2.2. Electrocoagulation treatment

A batch monopolar electrochemical cell was used for electrocoagulation (0.125 L), copper was used as the anode and cathode electrodes (Fig. 1), and each electrode was 0.05 m long and 0.025 m wide, which gave an area of 0.00125 m^2 and a total anodic area of $A_a = 0.0031\ m^2$. A solar cell supplied the system with 1–3 A of current intensity (322.5 Am^{-2}, 645.16 Am^{-2}, 967. Am^{-2}, respectively). 5 gL^{-1} of NaCl was added as a supporting electrolyte. Aliquots from EC process were collected at different times for TOC, COD, and color analysis.

Faraday's Law was used to calculate the maximum amount of copper produced in the electrochemical process (Eq. (1)). The amount was calculated considering the experimental conditions of I = 1–3 A of current intensity and t = 50 min (3000 s) of electrolysis, along with the Faraday Constant (F = 96,500 C mol^{-1}) and the charge on the cation (z = 2+).

$$n = It/ZF \tag{1}$$

The copper concentration in the solution was calculated by using Eq. (2),

$$[\mathrm{Cu}] = n/V \tag{2}$$

where n is the amount of copper in moles, and V is the volume of the cell in liters (0.125 L). Additionally, the produced copper