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Electrochemical Impedance Spectroscopy Analysis of Copper Electrodes Coated with Au@$LaFeO_3$ in a Polypyrrole Matrix for Acetaminophen Detection

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Abstract. Environmental contamination by pharmaceuticals is a growing problem that requires innovative solutions for detection. This study aims to develop a nanomaterial-based electrochemical sensor for acetaminophen detection in water bodies. An electrode modified with lanthanum orthoferrite and gold nanoparticles was evaluated as a sensing platform employing electrochemical impedance spectroscopy and cyclic voltammetry techniques. The results showed that the sensor can detect acetaminophen in micromolar concentrations, highlighting the potential of the nanocomposite for biosensor applications.

Keywords. Electrochemical impedance spectroscopy, lanthanum orthoferrite, nanocomposite, polypyrrole, acetaminophen.

1 Introduction

Environmental pollution has gained greater relevance in recent decades, presenting new challenges such as xenobiotics, including pharmaceuticals, which pose a significant ecotoxicological risk when released into water bodies [1] through processes such as human metabolism [2]. Although wastewater treatments exist, the detection and removal of these contaminants are complicated due to their low concentrations (in the range of the µg/l to ng/l) [3].

Among the diversity of drugs currently used for human treatment, the most widely consumed is acetaminophen (paracetamol); this is an important compound that is sold over the counter in tablets and is used to treat pain and fever, and can also be combined with other medications such as non-steroidal anti-inflammatory drugs to enhance the analgesic effect [4]. Due to the above, its consumption is high compared to other medications and even other analgesics; however, the active compound is not completely metabolized by the human body [5] which leads to the excretion of a fraction of the active compound in the sanitary drainage and very possibly in natural bodies of water or in treated water for reuse [6]. The greatest risk of its passive consumption is the inherent toxic effect of acetaminophen for both humans and animals [4].

Although the maximum concentrations found are in micrograms per liter, which is a very low concentration to cause short-term hepatotoxicity,

chronic consumption of contaminated water or food accompanied by direct administration of acetaminophen puts the health of the population at risk, especially of those people with liver disorders; this even without considering the possible risks to wildlife that consume this drug [1].

In recent decades, several methods have been developed to achieve the detection of contaminants in aqueous media, some of them are the following: optical methods, immunoassay tests, techniques based on molecular spectroscopy, fiber optic technology, changes in the intensity of reflected light, fluorescence conjugated with markers and electrochemical methods.

However, with the presence of contaminants such as drugs in wastewater, treatment plants require the use of efficient techniques that allow them to determine them despite being found in low concentrations and thus be able to remove them [7].

Electrochemical techniques emerge as a viable solution for detecting compounds in aqueous media. Additionally, in terms of detection, it is improved when electrochemical techniques are coupled with nanotechnology. opening new possibilities for pharmaceutical detection and treatment [7].

Nanostructured materials incorporated into electrodes present in electrochemical cells involve both nanoparticles and nanocomposites that increase or improve their properties. In the particular case of drug determination in water, the materials used as modifying agents are those based on carbon, noble metals, conductive polymers, metal-carbon composites, and titanium oxide supports, among others [8].

This work discusses the incorporation of nanomaterials in an impedimetric sensor for acetaminophen detection using the technique of electrochemical impedance spectroscopy (EIS). The working electrode was modified with lanthanum orthoferrite and gold nanoparticles. Based on the properties of these materials, the study was focused not only on their performance as a sensor but also on fabrication using the electropolymerization of pyrrole as a conductive polymeric support, without altering the electronic exchange at the sensor's surface.

2 Experimental Section

2.1 Synthesis of Nanoparticles and Nanocomposite

The chemical reagents used for the synthesis of nanoparticles and nanocomposites were iron chloride ($FeCl_3$•$6H_2O$-Sigma Aldrich), lanthanum nitrate hexahydrate ($La(NO_3)_3$•$6H_2O$-Sigma Aldrich), sodium hydroxide (NaOH-Meyer), chloroauric acid ($HAuCl_3$-Sigma Aldrich), ascorbic acid ($C_6H_8O_6$-Sigma Aldrich), cetyltrimethylammonium bromide (CTAB - $C_{19}H_{42}BrN$-J.T. Baker), and dimethyl sulfoxide (DMSO - C_2H_6OS-Sigma Aldrich). In a typical synthesis of lanthanum ferrite ($LaFeO_3$ or LFO), a 1.5 M NaOH solution in 50 ml of degassed water was used as a reducing agent under constant stirring. Then, 0.5 M of $La(NO_3)_3$•$6H_2O$ and $FeCl_3$•$6H_2O$ were added to 50 ml of degassed water. The mixture was added to the NaOH solution dropwise under constant stirring in a nitrogen atmosphere at 70°C for 1.5 hours. The solution was allowed to precipitate, the supernatant was removed by centrifugation, and finally, it was calcined at 800°C for 6 hours.

For the formation of the nanocomposite, 78 mg of lanthanum ferrite, 0.5 ml of 1 M CTAB, and 0.5 ml of 1 M DMSO were used in 1 ml of degassed water under constant stirring for 4 hours. A mixture of 25 µl of 1 M $HAuCl_3$, 0.5 ml of CTAB, and 1 ml of 8 mM $C_6H_8O_6$ was added to the first solution dropwise and under constant stirring for 2 hours.

Nitrogen gas was incorporated into the solution to prevent the hematite formation and to degas the system. The nanocomposite was washed once with deionized water, and the final product remained in an aqueous solution.

2.2 Electrode Modification

The electrochemical cell used as a sensor consists of a three-electrode arrangement, including a silver/silver chloride (Ag/AgCl) wire as the pseudo-reference and a planar copper (Cu) electrode array forming the counter and working electrodes. The working electrode was modified using cyclic voltammetry. First, the Cu surface was passivated to promote polymer deposition. This step was

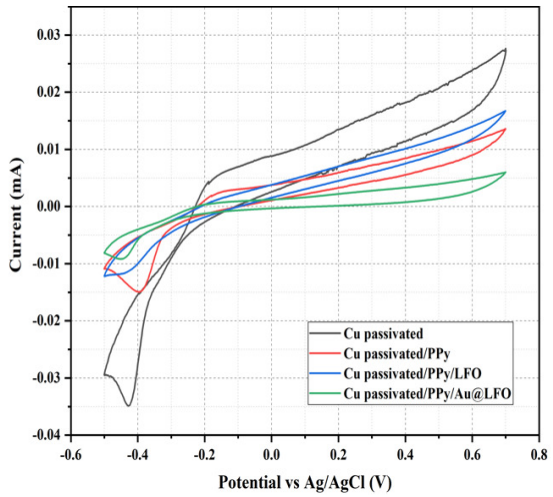

Fig. 1. Cyclic voltamperograms corresponding to passivated copper electrodes measured in the absence of acetaminophen

performed using a 0.1 M sodium hydroxide solution in a window of -1 to 0.3V vs Ag/AgCl at a scan rate of 100 mV/s and 5 cycles. Subsequently, electropolymerization was carried out with a mixture of pyrrole monomer and the Au@$LaFeO_3$ nanocomposite in Britton-Robinson solution in a potential window of -0.5 to 1V vs Ag/AgCl at a scan rate of 100 mV/s and until completing 5 cycles.

2.3 Electrochemical Determination of Acetaminophen

The electrochemical response of the modified Cu electrodes was evaluated in the absence and presence of 1 mM acetaminophen using cyclic voltammetry in a potential range of -0.5 to 0.7 V vs Ag/AgCl at a scan rate of 100 mV/s and during 5 cycles.

These tests were carried out using Cu electrodes, passivated Cu, passivated Cu with electrodeposited polypyrrole and lanthanum ferrite nanoparticles (ppy/$LaFeO_3$), and passivated Cu with electrodeposited polypyrrole and the nanocomposite (ppy/Au@$LaFeO_3$).

The determination of acetaminophen in a range of 1 to 100 mM was carried out using electrochemical impedance spectroscopy in a frequency range of 1 MHz to 1 Hz and with a sinusoidal wave amplitude of 10 mV.

3 Results

3.1 Cyclic Voltammetry

The cyclic voltammograms recorded during the tests in the absence of acetaminophen are illustrated in Figure 1. Peaks with anodic and cathodic currents at -170 and -410 mV, respectively, are observed. The response obtained using the electrode with only passivation stands out, where a typical behavior corresponding to formed oxygen species can be observed.

Figure 2 shows the cyclic voltammograms obtained from experimentation with 1 mM acetaminophen. It can be seen that the electrochemical response is higher in the passivated Cu electrode than in the electrodes with deposits. However, no distinct oxidation and reduction peaks are observed compared to those observed when acetaminophen is absent, so an electrochemical response associated with its presence is ruled out [9]. It is also observed that the response is barely noticeable when lanthanum orthoferrite is incorporated. Furthermore, the electrode that only has polypyrrole and the one that has the nanocomposite of lanthanum orthoferrite and gold present a similar response. This can be interpreted as the possibility that these nanoparticles reduce the reactivity of the electrode, contrary to what could be expected as a co-adjuvant agent. It is also possible that the nanomaterial behaves as a dielectric that interferes even with the electronic conduction of the polypyrrole. That interference for electronic transfer could be compensated by the presence of gold nanoparticles in the nanocomposite and the CTAB around them.

As regards the decrease in current observed in the presence of lanthanum ortho-ferrite deposit, compared with passivation treatment or polypyrrole deposit, it follows that this reduction is the result of a decrease in the electrochemical reactivity or in the efficiency of the electronic transfer between the coating surface and the electrode.

3.2 Electrochemical Impedance Spectroscopy

The results obtained in the impedance tests were plotted in Nyquist diagrams to analyze the charge

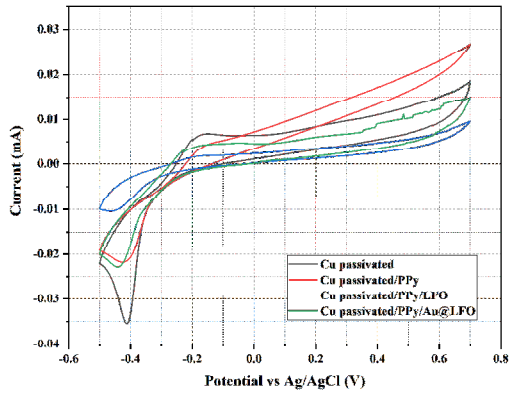

Fig. 2. Cyclic voltamperograms corresponding to passivated and modified copper electrodes measured in the presence of acetaminophen at 1 mM

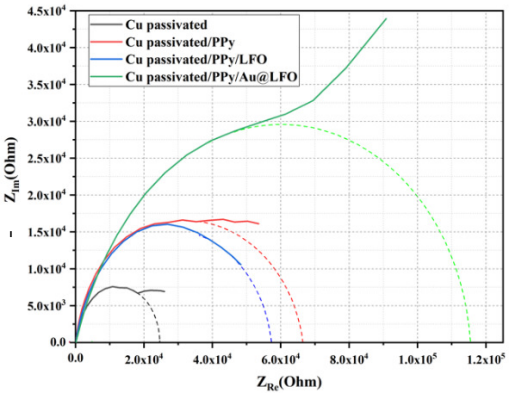

Fig. 3. Nyquist diagrams corresponding to passivated copper electrodes measured in the absence of acetaminophen

Table 1. Resistance to charge transfer in passivated electrodes, with electrodeposits and in the absence of acetaminophen

Treatment	RTC (kΩ)
Cu passivated	24.7
Cu passivated /ppy	66.4
Cu passivated /ppy/ $LaFeO_3$	57.3
Cu passivated /ppy/Au@ $LaFeO_3$	115.2

transfer resistance in the modified electrodes. In Figure 3, a higher charge transfer resistance of 115.2 kΩ (see Table 1) with the ppy/Au@$LaFeO_3$ deposit is mainly observed, corresponding with the result obtained in the cyclic voltammetry test.

On the other hand, Figure 4 shows that in the presence of acetaminophen, the highest charge transfer resistance is presented with the ppy/$LaFeO_3$ deposit with a value of 109 kΩ (see Table 2). For the deposit with ppy/Au@$LaFeO_3$, there was also a decrease from 115.2 kΩ to 51.7 kΩ (see Table 2).

The impedance results obtained in the presence of acetaminophen show that there is a higher charge transfer resistance (CTR) with the ppy/$LaFeO_3$ deposit compared to the response with ppy/Au@$LaFeO_3$; this could be related to the presence of both acetaminophen and the gold nanoparticles, which are contributing to the decrease in charge transfer resistance. However, in the work presented by Padit T. and V. Rana [10], it is detailed that as the concentration of acetaminophen increases, there is a decrease in charge transfer resistance.

This result coincides with the one obtained in this study using acetaminophen concentrations of 1, 10, and 100 mM and electrodes modified with ppy/Au@$LaFeO_3$ (see Figure 5). As a result, a decrease in charge transfer resistance of approximately five times is observed as the acetaminophen concentration increases to 100 mM, compared to the response obtained using only Britton-Robinson solution (see Table 3). Unlike the results reported by Padit T. and V. Rana, there is a consistent trend of decreasing charge transfer resistance with increasing acetaminophen concentration.

Along with the results obtained from cyclic voltammetry and electrochemical impedance, both in the presence and absence of acetaminophen, it was determined that acetaminophen does not exhibit a redox response within the potential window in which the tests were conducted. It was also found that the coatings behave as insulators, which is limited even with the incorporation of gold nanoparticles in the composite film. However, it is noteworthy that the surface of the electrodes coated with ppy/Au@$LaFeO_3$ promotes a decrease in charge transfer resistance in the presence of acetaminophen, as observed in the Nyquist diagrams. Based on this, a resistive sensor would be viable with the nanocomposite as the coating on the working electrode. Although the results obtained at different concentrations of acetaminophen are promising, future work is

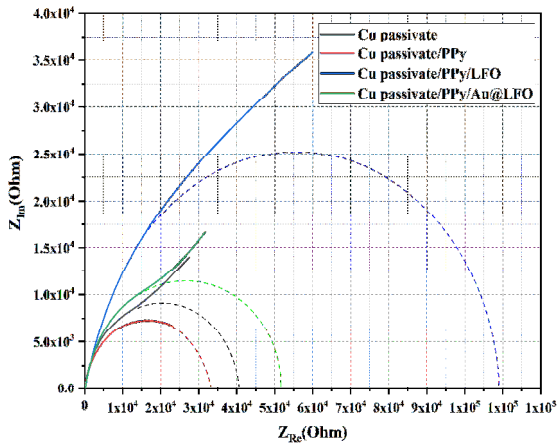

Fig. 4. Nyquist diagrams corresponding to passivated and modified copper electrodes measured in the presence of acetaminophen at 1 mM

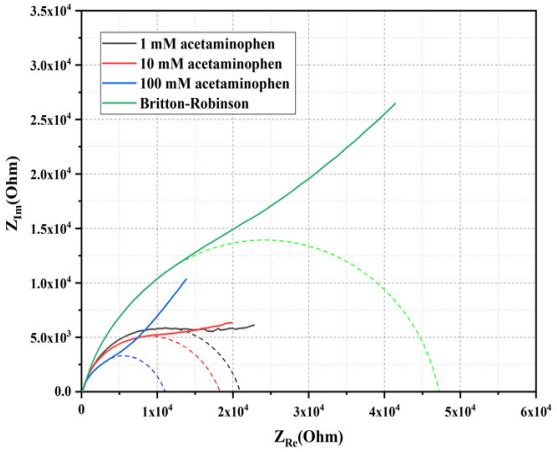

Fig. 5. Nyquist diagrams corresponding to passivated and modified copper electrodes tested with acetaminophen in Britton-Robinson solution at different concentrations

Table 2. Resistance to charge transfer in passivated electrodes, with electrodeposits, and in the presence of acetaminophen

Treatment	RTC (kΩ)
Cu passivated	40.5
Cu passivated /ppy	33.3
Cu passivated /ppy/ $LaFeO_3$	109
Cu passivated /ppy/Au@ $LaFeO_3$	51.7

Table 3. Resistance to charge transfer of the modified electrode with pyrrole/Au@ $LaFeO_3$ and in the presence of acetaminophen at different concentrations in Britton-Robinson solution

Measured solution	RTC (kΩ)
Acetaminophen 100 mM	10.1
Acetaminophen 10 mM	18
Acetaminophen 1 mM	20.8
Britton-Robinson	47.2

expected to involve testing other concentrations of acetaminophen and even in the presence of interferents.

4 Conclusions

Cu electrodes were passivated and modified using a NaOH treatment and pyrrole electropolymerization. Incorporating $LaFeO_3$ nanoparticles and ppy/Au@$LaFeO_3$ nanocomposites into the electropolymerization solution, the passivated Cu electrodes were successfully modified.

According to electrochemical impedance spectra, as the acetaminophen concentration increases, the charge transfer resistance decreases, making it possible to determine acetaminophen in aqueous medium. Although the modifications of the working electrode with polypyrrole and ppy/Au@$LaFeO_3$ nanocomposites should promote electronic transfer and, thus, the oxidation-reduction of acetaminophen, the cyclic voltammetry scans did not present peaks associated with this reaction.

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