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RESEARCH PAPER

Development of a low-cost electrochemical sensor based on babassu mesocarp (*Orbignya phalerata*) immobilized on a flexible gold electrode for applications in sensors for 5-fluorouracil chemotherapeutics

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Abstract

There are increasing concerns regarding the risks arising from the contamination of manipulators of antineoplastic drugs promoted by occupational exposure or even in the dosage of drugs. The present work proposes the use of an electrochemical sensor based on a biopolymer extracted from the babassu coconut (*Orbignya phalerata*) for the determination of an antineoplastic 5-fluorouracil (5-FU) drug as an alternative for the monitoring of these drugs. In order to reduce the cost of this sensor, a flexible gold electrode (FEAu) is proposed. The surface modification of FEAu was performed with the deposition of a casting film of the biopolymer extracted from the babassu mesocarp (BM) and modified with phthalic anhydride (BMPA). The electrochemical activity of the modified electrode was characterized by cyclic voltammetry (CV), and its morphology was observed by atomic force microscopy (AFM). The FEAu/BMPA showed a high sensitivity (8.8 μA/μmol/L) and low limit of detection (0.34 μmol/L) for the 5-FU drug in an acid medium. Electrochemical sensors developed from the babassu mesocarp may be a viable alternative for the monitoring of the 5-FU antineoplastic in pharmaceutical formulations, because in addition to being sensitive to this drug, they are constructed of a natural polymer, renewable, and abundant in nature.

Keywords Babassu mesocarp · Flexible gold electrode · Sensor · 5-Fluorouracil · Electrochemistry

Introduction

Antineoplastic drugs are chemicals capable of inhibiting the growth and/or vital processes of tumor cells with tolerable toxicity to normal cells [1]. However, potentially undesirable effects have been reported with regard to the health of professionals exposed to these drugs, even over short time intervals [2].

Exposure to antineoplastic drugs can lead to skin rashes, nausea, hair loss, abdominal pain, nasal ulcers, allergic reactions, dizziness [3], or chronic effects related to occupational exposure, which can lead to DNA damage [4], spontaneous abortion [5], increased incidences of congenital anomalies in offspring [4], reproductive damage [6], and increased incidence of cancer [7, 8].

There is no known level of 5-FU exposure that is considered safe and does not show toxic effects, and it is therefore necessary that exposure levels be minimized to the furthest extent possible [9]. Contamination by antineoplastic drugs can occur directly, through the skin, membranes, mucosa, and inhalation, or indirectly, through body fluids and excreta from patients who have received the medication in the preceding 72 h [10].

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Among the antineoplastic agents, 5-FU is one of the most widely consumed drugs worldwide, being an antimetabolite belonging to the class of pyrimidine analogues [11, 12]. It is a broad-spectrum drug used in the treatment of neoplasias, such as glioblastoma and several other cancers, including head and neck, gastrointestinal tract, and breast cancers [13–15]. 5-FU contamination may result in side effects, such as mucositis, leukopenia, nausea, diarrhea, alopecia, neurotoxicity, ocular toxicity, and cardiac toxicity [16–18].

Currently, there are several analytical techniques for the determination of 5-FU, such as Raman spectroscopy [19], capillary electrophoresis [20], high-performance liquid chromatography [21], chromatography [22], and mass spectrometry [23]. However, these methods are usually complex, are associated with time-consuming analyses, and use analytical standard solvents, requiring expensive devices and high maintenance. The use of electrochemical sensors presents an alternative to the methods cited for the determination of 5-FU. It is a promising option because it is a simple, low-cost, precise, sensitive, and selective methodology [24].

The use of metallic electrodes, such as gold electrodes, in electrochemical sensors enables the work to be performed at a wide range of potentials and allows for the modification of their work surface, resulting in the so-called chemically modified electrodes or CMEs [25]. The flexible gold electrode (FEAu) used in this work was fabricated from a sheet of polyester metallized with gold and had a low manufacturing cost (~ USD 0.027).

The electronic transfer rate is promoted by modifying the surface of the working electrode, amplifying the current signals obtained for the system, and/or increasing the sensor selectivity [26, 27]. Polymeric films are among the materials used in the modification of these electrodes, and the present study used a biopolymer from the babassu mesocarp (BM).

The BM is characterized as a non-toxic, renewable material, rich in lignocellulosic materials, with a high potential for industrial applications [28]. This substance is found between the epicarp and endocarp of the babassu coconut (*Orbignya phalerata*) and is chemically composed of compounds rich in glycerol, phosphoric acid, and choline [29]. The high reactivity of the BM is due to the presence of hydroxyl groups available on the surface of the polysaccharides [30].

Given the need for monitoring antineoplastic drugs, the aim of this study was to develop an electrochemical sensor for use in the determination of 5-FU. The sensor consists of a flexible gold electrode (FEAu) with its surface modified by a cast film of BM. The BM was used without modification or modified with phthalic anhydride (BMPA), in order to improve its solubility and electrochemical properties.

Experimental procedure

Materials

The mesocarp of the babassu coconut *in natura* (BM) was acquired at the Department of Agrarian Sciences of the Federal University of Piauí (Brazil), in the form of a powder with a grain size of approximately 0.074 mm. The BM powder was passed through a set of sieves of 50 to 200 meshes for the grain size selection. Dimethyl sulfoxide (DMSO) (Aldrich), sulfuric acid (Aldrich), and isopropyl alcohol (Aldrich) were used in the stock solution used for film deposition, both presenting an analytical standard without requiring prior purification. The whole process of obtaining the BMPA, as well as its characterization (X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA) and DTG, zeta potential analysis, scanning electron microscope (SEM), and cyclic voltammetry (CV)), has been published in another study [31].

The 5-FU antineoplastic (Aldrich) was used as a stock solution at 1×10^{-3} mol/L in H_2SO_4 0.05 mol/L for the detection tests.

Methods

Construction of the FEAu

The procedure of cleaning and deposition of gold on the polyester foil for the FEAu development is described in detail in a previous paper [32]. After the metallization of the polyester foil with a layer of gold ~ 97 nm thick, it was used fabricate flexible electrodes with a geometric area of 0.0314 cm^2 and diameter of ~ 2.0 mm. The electrical contact was guaranteed by a copper wire (0.25 mm). A schematic of this electrode is shown in Fig. 1.

Before the experiments, the FEAu was subjected to an electrochemical cleaning through successive scans in the potential range of 0.3 to 1.5 V vs. SCE and $v = 100$ mV/s using cyclic voltammetry and in a 0.5 mol/L H_2SO_4 medium (supporting electrolyte) until stable redox processes were obtained [33]. The electrode was further washed with ultrapure water (Milli-Q system), dried with a smooth N_2 jet, and immediately modified with a BM or BMPA casting film.

Solutions used in the casting film deposition

The solutions of BM (1.0 mg/mL) or BMPA (1.0 mg/mL) used in the deposition of the films were prepared at the time of their use using DMSO as a solvent followed by the addition of H_2SO_4 (0.05 mol/L) in the ratio 1:6 (*v*/*v*), respectively. The BM or BMPA solutions were brought to the ultrasonic bath at 25 °C for 10 min and then stored at room temperature until the time of their use.

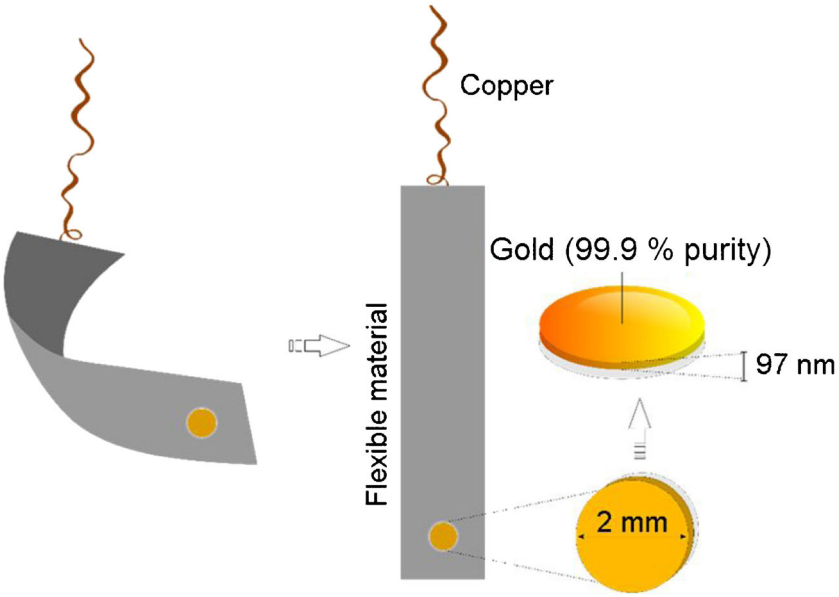

Fig. 1 Schematic of the flexible gold electrode (FEAu) used in this study

Immobilization of BM or BMPA by casting technique

The adsorption procedure of the film consisted of dripping a microdroplet (10 μL) of the solution containing BM or BMPA on the previously cleaned FEAu substrate. Then, the substrate containing the BM or BMPA solution was left on a flat surface at a temperature of 25 °C in an air-conditioned room until it was completely dried, which occurred after approximately 4 h in a closed environment, free of contamination. The chemically modified gold electrode with BM or BMPA casting film was obtained at the end of the drying process.

Characterization of FEAu/BM and FEAu/BMPA by voltammetric techniques

The films deposited on FEAu were electrochemically characterized using the techniques of cyclic voltammetry (CV) and square wave voltammetry (SWV) with the aid of METROHM's Dropsens μStat 400 BiPotentiostat/Galvanostat equipment and an electrochemical cell with three electrodes. The saturated calomel electrode (SCE) was used as a reference electrode, a platinum electrode ($A = 2.0$ cm^2) was used against the electrode, and the FEAu modified with BM or BMPA casting film was used as the working electrode. As a supporting electrolyte, 0.05 mol/L H_2SO_4 was used. The following parameters were adopted for the SWV: 10 s of equilibrium time, 50 mV amplitude, and 20 Hz frequency.

In a later step, the FEAu/BM and FEAu/BMPA were employed in a detection test of 5-FU using a solution of 1×10^{-3} mol/L in 0.05 mol/L H_2SO_4. To calculate the limit of detection (LoD) and limit of quantification (LoQ) of the electrodes, the following equations were used [34]:

$$\mathrm{LoD} = 3 \times \mathrm{Sd}/s \quad (1)$$

$$\mathrm{LoQ} = 10 \times \mathrm{Sd}/s \quad (2)$$

where Sd is the standard deviation and s is the slope of the calibration plot.

Results and discussion

Electrochemical behavior of FEAu, FEAu/BM, and FEAu/BMPA

The cyclic voltammogram obtained from the FEAu (Fig. 2) shows the characteristic electrochemical behavior of gold under the conditions used, presenting an oxidation process in the region of + 1.2 V vs. SCE and a well-defined reduction process in + 0.7 V vs. SCE. These processes were due to the formation of auric oxide (Au_2O_3) during the sweep in the anodic direction. These oxides remain adsorbed on the surface of the electrode and are subsequently reduced during the cathodic sweep. These reactions can be described by the following equations:

(1) $\mathrm{Au} + \mathrm{H_2O} \rightarrow AuOH + \mathrm{H^+} + \mathrm{e^-}$
(2) $AuOH + 2H_2O \rightarrow \mathrm{Au(OH)_3} + 2H^+ + 2e^-$
(3) $\mathrm{Au(OH)_3} + 3e^- + 3H^+ \rightarrow \mathrm{Au} + 3H_2O$

Here, steps 1 and 2 refer to oxidation processes and step 3 refers to the reduction process. The product formed in step 2,

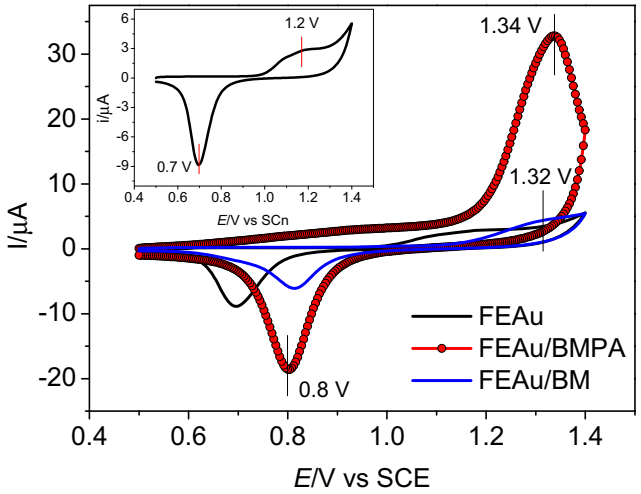

Fig. 2 Cyclic voltammograms obtained for electrodes: FEAu, FEAu/BM, and FEAu/BMPA. The inset shows the details of the FEAu response. The measurements were performed in H_2SO_4 0.05 mol/L, with $v = 50$ mV/s. BM, babassu mesocarp; BMPA, BM chemically modified with phthalic anhydride

$Au(OH)_3$, may also be represented as $Au_2O_3.3H_2O$, corresponding to the hydrated auric oxide [35]. It is important to note that the entire process is restricted to the electrode surface so that the water molecules that participate in the reactions are adsorbed into the metal surface [35, 36].

In Fig. 2, the voltammograms presented different oxidation processes from those observed for the unmodified FEAu; for the FEAu/BM, this process occurred at + 1.32 V vs. SCE and for the FEAu/BMPA at + 1.34 V vs. SCE. The oxidation process of BMPA appears very intense only at the first scan, and then the current level decays, as shown in Fig. 3A.

In the cathodic sweep, a reduction process close to + 0.80 V was observed for both the FEAu/BMPA and FEAu/BM. Therefore, in this case, these systems can be treated as almost reversible systems under the conditions used. In addition, both modified electrodes showed an increase in the current values compared with the unmodified FEAu, thus demonstrating the modification of its surface.

In Fig. 2, the modification performed in the babassu improved the electroactivity of the FEAu/BMPA system compared with that of the FEAu/BM, as also reported in previous studies performed by this group, but with BM and BMPA adsorbed onto tin-doped indium oxide (ITO) electrodes [31].

Study of the electrochemical mechanism of the proposed electrodes

To determine the nature of the electrochemical mechanism involved in the proposed electrodes, a study of variations in the scanning velocity was carried out by means of cyclic voltammetry. The measurements were carried out by varying the velocity in the range 25–250 mV/s, using H_2SO_4 0.05 mol/L

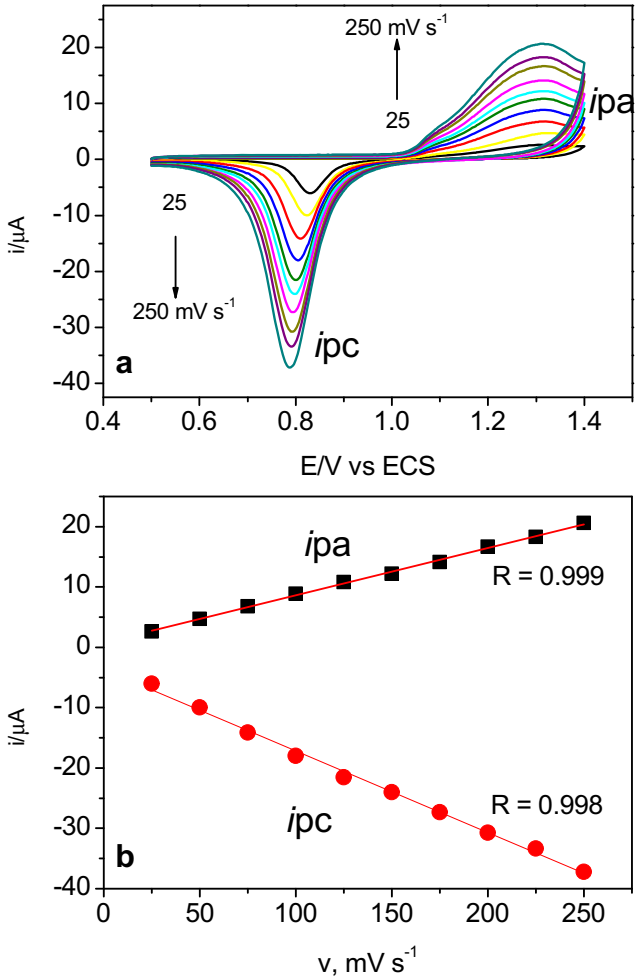

Fig. 3 **A** Variation of the potential scanning rate at 25, 50, 75, 100, 125, 150, 175, 200, 225, and 250 mV/s. **B** Linear relationship between the scan rate and peak current values for the processes (i) anodic (*i*pa) and (ii) cathodic (*i*pc) for the FEAu/BMPA. All measurements were carried out in H_2SO_4 0.05 mol/L

as the support electrolyte. The results obtained for the FEAu/BMPA are shown in Fig. 3A, B.

It can be observed in Fig. 3 that for an increase in the scan speed, there was a linear increase of the anodic and cathodic peak currents for the FEAu/BMPA, with linear correlation indexes, *R*, of 0.999 and 0.998, respectively. The values of *R* confirm that the electrochemical mechanism governing the response of the FEAu/BMPA system is purely adsorptive and further indicate that the BMPA casting film is strongly adhered to the FEAu surface [37]. This same behavior was observed for the FEAu/BM; therefore, it is not necessary to show the details here.

Electrochemical determination of 5-FU

The FEAu/BMPA electrodes developed in this study were used for the detection of 5-FU at the concentration of 100 μmol/L. Initially, the electrochemical response of the 5-

FU on the surface of the electrode of interest was studied using 0.05 mol/L H_2SO_4 as the electrolyte and a scanning rate of v = 50 mV/s (Fig. 4). For comparison, the cyclic voltammogram of 5-FU using an electrode without modification (FEAu) is also shown in Fig. 4.

When the voltammetry of FEAu was performed in the presence of 100 μmol/L of 5-FU, a new and discrete oxidation process was observed in the region of + 1.1 V, which can be directly attributed to the electrochemical oxidation of 5-FU on the surface of this electrode (see Fig. 4). However, for the modified electrode of FEAu/BMPA, the oxidation process of 5-FU appears much more defined with a current intensity ~ 276% higher than that observed for the unmodified electrode.

Moreover, it can be observed in Fig. 4 that after contact with 5-FU, the current of the oxidation process observed for BMPA at + 1.34 V suffered a considerable decrease and the potential of the reduction process, previously observed at + 0.8 V, was displaced to + 0.84 V, with a further decrease in current. A new process of reduction was also observed at + 0.58 V for the FEAu/BMPA system in the presence of 5-FU. All these modifications in FEAu/BMPA response, when in the presence of 5-FU, suggest a strong interaction of this analyte with the active layer of the sensor. Probably, there is a binding between the 5-FU and the BMPA adsorbed on the electrode surface, also involving a coordinated reduction of the antineoplastic in the region of + 0.58 V. This behavior may be advantageous as it improves the selectivity capabilities of the sensor in relation to the proposed analyte. However, our research group is still studying these hypotheses.

The electrooxidation of 5-FU on FEAu/BMPA surface was proposed based on the literature and showed in Fig. 5. Under conditions employed here, 5-FU presented an irreversible oxidation process, which involves the transfer of two electrons. The literature reports that there may be the participation of the

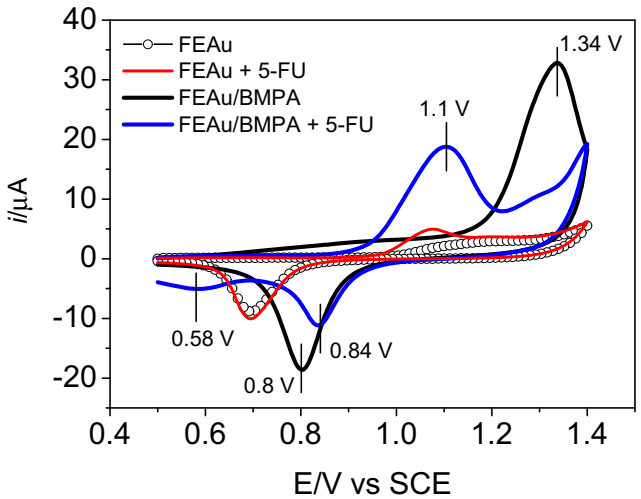

Fig. 4 Cyclic voltammograms obtained for the electrodes of FEAu and FEAu/BMPA in the presence and absence of 100 μmol/L of 5-FU. The measurements were carried out in H_2SO_4 0.05 mol/L with v = 50 mV/s

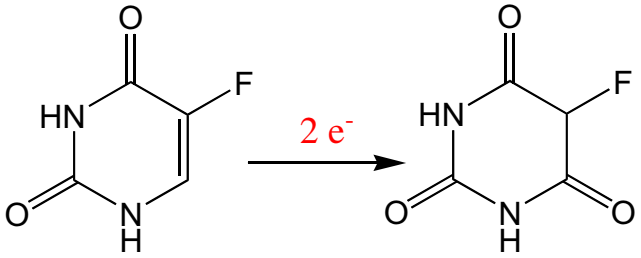

Fig. 5 Redox mechanism of 5-FU, adapted in [38]

same amount of protons and reduction process, depending on the pH and electrolyte used [38–40].

Morphology characterization by atomic force microscopy

Figure 6 shows atomic force micrographs of a clean FEAu (Fig. 6A, C) and representative images for the FEAu/BMPA-modified electrode (Fig. 6B, D). For the clean FEAu, there was a granular morphology with grain size varying between 10 and 50 nm (media of 20 nm) with valleys similar to grooves with an average depth of ≅ 23 nm. The grooves presumably originated from the acetate film used as the substrate due to manufacturing defects, while the globular features presumably originated from the evaporated gold film.

FEAu/BMPA presented a completely different morphology, as well as a granular pattern; these grains appeared with a much larger size, having a mean of ≅ 66 nm, but varying from 25 to 130 nm. These larger grains were attributed to the presence of BMPA on the electrode surface. It was not possible to characterize BM by atomic force microscopy (AFM) because the unmodified polymer had much larger grains when in film form, probably due to its low solubility being above the limit of the technique employed. This behavior has been discussed in another study of the group [31]. The roughness averages for FEAu and FEAu/BMPA were estimated at 2.74 ± 0.21 and 6.38 ± 0.89 nm, respectively.

5-FU electrochemical sensing

Since the SWV technique is more sensitive than CV, it was used in the study of 5-FU detection at concentrations ranging from 2.0 to 20 μmol/L for the electrode of FEAu/BMPA. To investigate the effects in the BM modification, the FEAu/BM was also tested. However, in this case, it was not possible to detect concentrations below 4.0 μmol/L (see Fig. 7).

In Fig. 7A, it is possible to observe the variation of the peak current response of the 5-FU oxidation process at concentrations ranging from 4.0 to 20 μmol/L when the FEAu/BM was used. Figure 7B shows the same behavior for concentrations between 2.0 and 20 μmol/L of 5-FU, using the FEAu/BMPA. In Fig. 7C, the calibration curves (current vs. concentration) for these respective systems are shown.

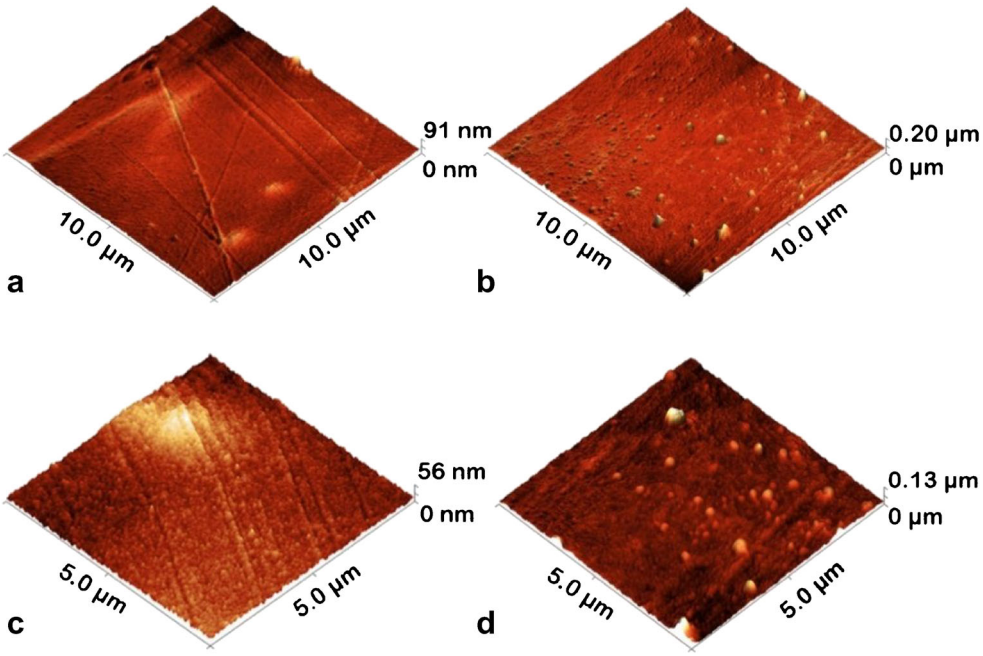

Fig. 6 Representative micrographs obtained by atomic force microscopy (AFM) in the intermittent mode for FEAu (**A**, **C**) and FEAu/BMPA (**B**, **D**). The upper and lower images were scanned in areas of 10.0 × 10.0 μm and 5.0 × 5.0 μm, respectively

From the analysis in Fig. 7C, a more pronounced slope was observed for the detection of 5-FU using the FEAu/BMPA. This was due to a higher analytical sensitivity for 5-FU when the FEAu/BMPA was used, compared with the FEAu/BM. These results confirm that babassu can be used as an active layer in sensors for 5-FU detection, and the modified babassu improves both the babassu solubility and electroanalytical properties of the sensor, such as LoD, LoQ, and analytical sensitivity (given in Table 1).

The linearity observed in Fig. 7C provides the possibility of calculating the LoD and LoQ for each electrode used (see Table 1). The LoD can be defined as the lowest analyte concentration that can be detected, in this case, by the voltammetric method. However, this was not quantified

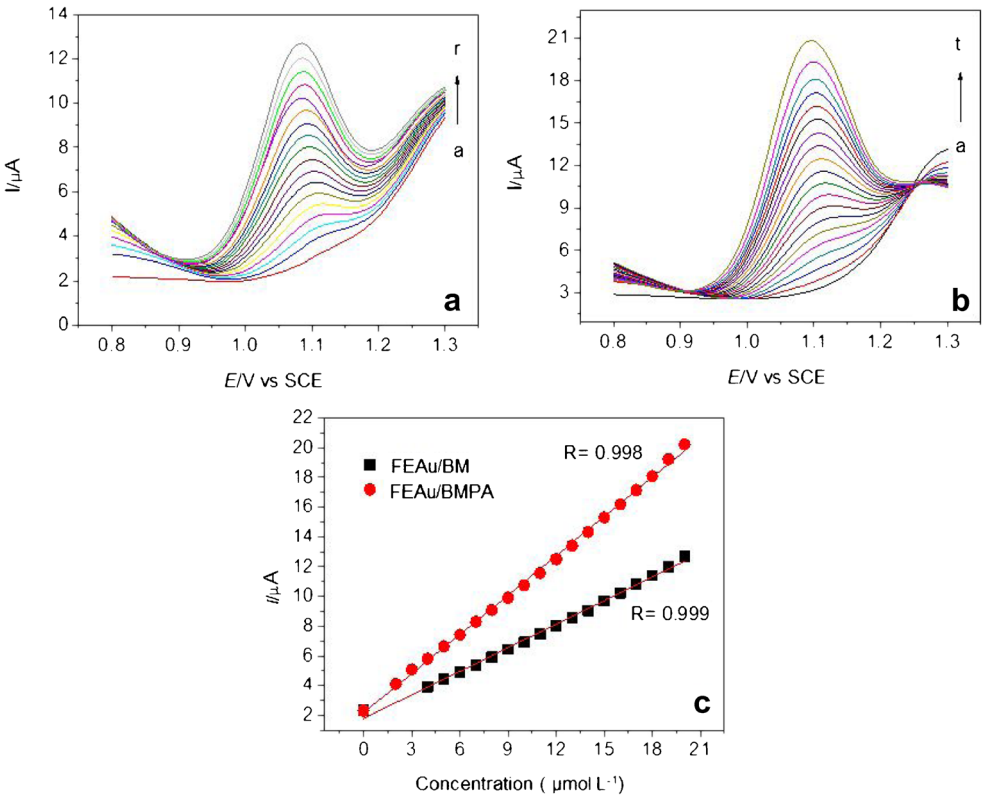

Fig. 7 **A** Square wave voltammograms (SWVs) obtained for FEAu/BM in the presence of 5-FU at concentrations of (a) 0.0, (b) 4.0, (c) 5.0, (d) 6.0, (e) 7.0, (f) 8.0, (g) 9.0, (h) 10.0, (i) 11.0, (j) 12.0, (k) 13.0, (l) 14.0, (m) 15.0, (n) 16.0, (o) 17.0, (p) 18.0, (q) 19.0, and (r) 20.0 μmol/L. **B** SQVs of FEAu/BMPA in the presence of 5-FU FU at concentrations of (a) 0.0, (b) 2.0, (c) 3.0, (d) 4.0, (e) 5.0, (f) 6.0, (g) 7.0, (h) 8.0, (i) 9.0, (j) 10.0, (k) 11.0, (l) 12.0, (m) 13.0, (n) 14.0, (o) 15.0, (p) 16.0, (q) 17.0, (r) 18.0, (s) 19.0, and (t) 20.0 μmol/L. **C** A calibration plot for these respective systems. The measurements were carried out in H_2SO_4 0.05 mol/L.

Table 1 Analytical characteristics of the 5-FU sensors developed in this work

	LoD (μmol/L)	LoQ (μmol/L)	Analytical sensitivity (μA/μmol/L)
FEAu/BM	0.57	1.89	5.29
FEAu/BMPA	0.34	1.10	8.80

within an acceptable certainty level with the produced analytic signal being distinct of equipment noise [41]. The LoQ is defined as the lowest analyte concentration that can be detected and quantified by a method with a high level of certainty [42, 43].

The obtained LoD and LoQ were 0.567 and 1.89 μmol/L for the FEAu/BM and 0.34 and 1.10 μmol/L for the FEAu/BMPA, respectively. The equations of the analytical curves obtained for the FEAu/BM (Eq. 3) and FEAu/BMPA (Eq. 4) electrodes are:

$$\text{Concentration } (\mu\text{mol/L}) = (\text{current in } \mu\text{A} - 1.796)/0.529 \quad (3)$$

$$\text{Concentration } (\mu\text{mol/L}) = (\text{current in } \mu\text{A} - 2.172)/0.880 \quad (4)$$

In order to show the efficiency of the sensor developed for 5-FU detection, Table 2 provides a comparison of the detection limits reported in the literature. The sensor was also tested for its ability to detect 5-FU in pharmaceutical formulations. In this case, only the FEAu/BMPA was used, which provided a better analytical performance (see Table 3).

It can be seen from Table 2 that the FEAu/BM and FEAu/BMPA sensors for 5-FU detection had lower detection limits than those of the AuNP-SPE and P(BCP)/DNA/GCE sensors, but higher than the MWNTs/BTB/GCE, GNP-MWCNT-Chit/GCE, and $ZnFe_2O_4$/MNPs/IL/CPE electrodes. It is noteworthy that the sensors that presented lower detection limits have high-cost metallic structures as elements of the electrode modifications, while FEAu/BM and FEAu/BMPA present low-cost natural biopolymers as a modifying element of the electrode. Additionally, the electrodes proposed here are very easy to assemble, providing an economically viable alternative for the determination of 5-FU.

Table 3 Determination of 5-FU in pharmaceutical formulations containing different concentrations of the drug using the FEAu/BMPA

Pharmaceutical formulation	Concentration on the label (μmol/L)	Obtained concentration (μmol/L)
A	5.0	4.85 ± 0.22
B	10.0	9.92 ± 0.12
C	15.0	15.01 ± 0.13

Selectivity and interference test

In order to evaluate the FEAu/BMPA behavior in the presence of other drugs, a test with this electrode was performed in the presence of 10.0 μmol/L 5-FU + the following drugs: amitriptyline, testosterone, and sodium alendronate, at different concentrations. Testosterone was used as an example of a naturally occurring drug (naturally produced hormone); amitriptyline and sodium alendronate were used as two different classes of synthetic drugs (antidepressant and bisphosphonate, respectively).

The electrode showed response only for amitriptyline, which, like 5-FU, is electroactive on the FEAu/BMPA surface (Fig. 8). However, it should be emphasized that amitriptyline oxidation occurs at ≅ 0.56 V, that is, very distant from 5-FU (at ≅ 1.1 V), which could allow the simultaneous determination of both, if more studies are carried out. Testosterone and

Table 2 Limit of detection (LoD) and limit of quantitation (LoQ) for the FEAu/BM and FEAu/BMPA used as sensors for 5-FU compared to other 5-FU electrochemical sensors found in literature

Technique used *	Work electrode**	LoD (μmol/L)	References
DPV	GNP-MWCNT-Chit/GCE^{I}	0.020	[44]
SWV	AuNP-SPE^{II}	0.769	[45]
DPV	P(BCP)/DNA/GCE^{III}	2.383	[46]
CV	MWNTs/BTB/GCE^{IV}	0.267	[47]
SWV	$ZnFe_2O_4$/MNPs/IL/CPE^{V}	0.07	[48]
SWV	FEAu/BM^{VI}	0.567	This study
	FEAU/BMPA^{VII}	0.340	

*CV, cyclic voltammetry; *SWV*, square wave voltammetry; and *DPV*, differential pulse voltammetry

**I GNP-MWCNT-Chit/GCE, glass carbon electrode–modified gold nanoparticle–decorated multiwall carbon nanotube; II SPE/AuNps, gold nanoparticle–modified screen-printed electrode; III P(BCP)/DNA/GCE, glass carbon electrode modified with poly(bromocresol purple) and DNA; IV MWNTs/BTB/GCE, glassy carbon electrode modified with bromothymol blue and multiwalled carbon nanotubes; V $ZnFe_2O_4$/MNPs/IL/CPE, $ZnFe_2O_4$ magnetic nanoparticle ionic liquid carbon paste electrode; VI FEAu/BM, flexible gold electrode modified with BM; and VII FEAu/BMPA, flexible gold electrode modified with BMPA

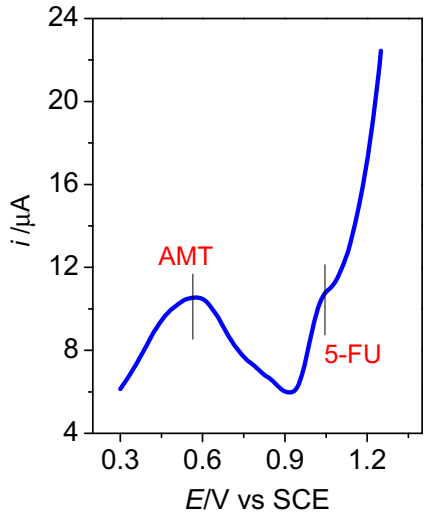

Fig. 8 SWV voltammograms for FEAu/BMPA in the presence of 10.0 μmol/L 5-FU + amitriptyline 20.0 μmol/L. The measurements were carried out in H_2SO_4 0.05 mol/L

sodium alendronate did not show potential interferences, as they did not oxidize on the surface of the electrode under the conditions studied and did not interfere in the peak current of the 5-FU oxidation process. It is important to notice that the pharmaceutical formulations containing 5-FU are usually based only on the drug + HCl in low concentration and this acid does not cause interference in electrode response either. This allowed to evaluate the dosage of different formulations of 5-FU (Table 3) with precision. More specific studies will be necessary to apply this electrode to other analysis matrices.

Conclusions

In this study, FEAus modified with BM and chemically modified with BMPA were developed and used in the detection of 5-FU. Modification of a FEAu with BM or BMPA biopolymers resulted in higher current values for these systems and detection limits of 0.567 and 0.34 μmol/L, respectively. Both the FEAu/BM and FEAu/BMPA exhibited good abilities in detecting 5-FU chemotherapy compared with a FEAu without modification. The developed electrodes are simple, fast, and efficient alternatives for applications in the monitoring of 5-FU, mainly in pharmaceutical formulations based on 5-FU.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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