






# Theoretical Description for Perillartine Electrochemical Determination, Assisted by Poly(Hydroquinones)/RuO<sub>4</sub> Composite

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**Abstract:** In this work, we analyze the system with the perillartine electrochemical determination, along with its ether derivative, assisted by poly(naphthoquinone) composite with ruthenium (VIII) oxide. As a specific oxidant used to yield oxyranes, it will specifically oxidize perillartine. A mathematical model has been described for the electroanalytical process. It has been shown that the RuO<sub>4</sub> composite with the copolymer of squaraine dye with the naphthoquinones may be an efficient electrode modifier for perillaldehydealdoxime electrochemical determination on a modified anode. The electroanalytical process will be mostly kinetically-controlled with the possibility of the transfer to diffusion-controlled mode. On the other hand, both oscillatory and monotonic instabilities may be realized in the electroanalytical process. Their probability will depend on the direction of the electroanalytical scenario in the concrete conditions due to the possibility of the formation of ionic compounds in the pre-surface layer.

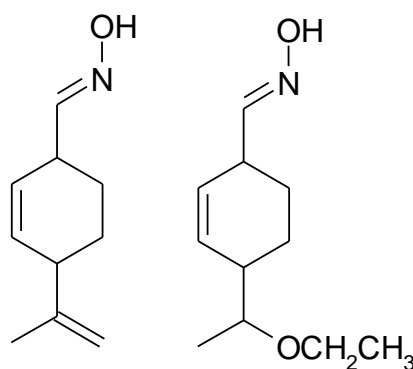
**Keywords:** perillartine; electrochemical sensors; conducting polymers; ruthenium (VIII) oxide; stable steady-state.

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## 1. Introduction

Perillartine (Fig. 1) (perillaldehyde anti-aldoxime) is a natural sweetener from Japanese perilla (*shiso*) leaves [1]. It is considered twice as sweet as sucralose, four times as sweet as saccharin, and 2000 times as sweet as sucrose (common sugar).

The proper perillartine and its ether derivative are used as sweeteners, although the ether is much less sweet (being compared in this relation to aspartame).



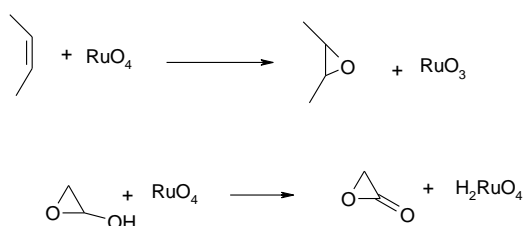
**Figure 1.** Perillartine and its ether derivative.

Contrarily to synthetic sweeteners like aspartame, saccharin, and sucralose, perillartine is biodegradable and bioaccessible. It is not considered toxic or dangerous for the environment.

Nevertheless, it may be allergic to people who are allergic to shiso herb [2]. Also, some toxic nitrogen derivatives like hydroxylamine may form during its metabolism in some people. It is important to mention that perillaldehydealoxime and its derivatives are rarely used as sweeteners outside Japan, so this statement may be used to investigate falsification of allegedly Japanese products claimed to contain the perillartine. Thus, developing an efficient, exact, and rapid method for perillartine determination is an actual task, and the electroanalytical methods would give it a good service.

As for now, no electrochemical methods for perillartine determination have been developed. Nevertheless, the aldoxime may be electrochemically active, being capable either of reducing or oxidizing. In both cases, the chemically modified electrodes are preferred to use, as they diminish the overvoltage and augment the electrode sensitivity and efficiency due to the modifier affinity to analyte [3-8].

One of the interesting modifying materials is ruthenium (VIII) oxide. It is a specific oxidant in organic chemistry used to yield oxyrans from alkenes (Fig. 2). Also, the oxidation of oxyran-2-ol by RuO<sub>4</sub> yields the lactone of 3-hydroxypropionic acid:



**Figure 2.** RuO<sub>4</sub>-assisted oxyran formation and oxidation.

Considering that both perillartine and its ether adduct contain double bonds, ruthenium tetroxide will epoxidize them, converting them to oxyran derivatives. Nevertheless, to enhance the electrochemical stability of the metal oxide nanoparticles, they are inserted in an organic conducting polymeric [9-12] or oligomeric (including squaraine dye [13-18]) matrix, which works as a mediator for electron transfer.

Nevertheless, the organic electrooxidation and, rarely, electro-reduction processes (including the electropolymerization) are capable of being accompanied by electrochemical periodic and chaotic instabilities, like those observed in Briggs-Rauscher and Belousov-Zhabotinski reaction. These instabilities include the oscillatory changes in electrochemical potential and monotonic instabilities [19-22] and influence the electroanalytical efficiency of the system.

Thus, to investigate the parameter values, correspondent to the most efficient monomer and polymer formation, like verifying the possibility and probability of the electrochemical instabilities in this system, an a priori theoretical observation of the electrochemical system is necessary.

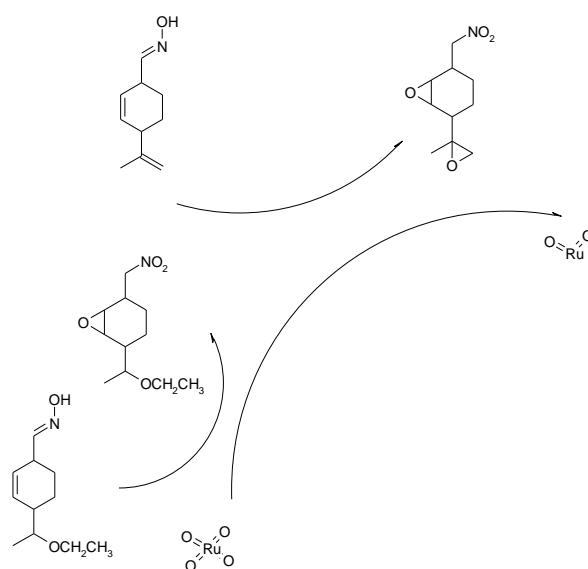
So, this work's goal is to theoretically analyze the electrochemical determination of perillartine and its ether derivative by RuO<sub>4</sub> – poly(naphthoquinone) composite. This analysis will include the mechanism suggestion, model development, stability analysis, and the comparison of the system's behavior with similar systems [23,24].

## 2. Materials and Methods

### 2.1. System and its modeling.

As mentioned above, ruthenium (VIII) oxide easily epoxidizes C=C double bonds, yielding oxyrans. The C = N bond in oxime is oxidized, yielding the pseudo acid, which is isomerized into a nitro compound in neutral media.

Thus, the electroanalytical process will be realized as in Fig. 3:



**Figure 3.** The scheme of the RuO<sub>4</sub>-assisted perillartine electrochemical determination.

The polymeric phase, as mentioned above, stabilizes the ruthenium tetroxide and dioxide by stabilizing the coordination bonds. Those bonds also facilitate the electron transfer mediation between the electroanalytical system and the transducer. In this case, naphthoquinones with amine or phenolic moiety in the neighbor ring (like 5-amino-1,4-naphthoquinone) are recommended as monomers.

Therefore, to describe the system with the electrochemical determination of perillartine, assisted by RuO<sub>4</sub> – Poly(naphthoquinone) composite, we introduce three variables:

- p – perillartine concentration in the pre-surface layer;
- p\* - perillartine ether adduct concentration in the pre-surface layer;
- u- ruthenium dioxide surface coverage degree.

To simplify the modeling, we assume that:

- the background electrolyte is taken in excess so that we can neglect the migration flow and the oxidizing dopant oxidation change;
- the reactor is intensively stirred so that we may neglect the convection flow;

- the pre-surface layer concentration profile is linear, and its thickness is constant, equal to  $\delta$ .

It is possible to prove that the differential equations' set describing the system may be described as:

$$\begin{cases} \frac{dp}{dt} = \frac{2}{\delta} \left( \frac{P}{\delta} (p_0 - p) - r_{11} \right) \\ \frac{dp^*}{dt} = \frac{2}{\delta} \left( \frac{P^*}{\delta} (p^*_0 - p^*) - r_{12} \right) \\ \frac{du}{dt} = \frac{1}{U} (r_{11} + r_{12} - r_2) \end{cases} \quad (1)$$

Herein, P and P\* are diffusion coefficients of perillartine, and its ether adduct,  $p_0$ , and  $p^*_0$  are the bulk concentrations of the sweeteners, U is RuO<sub>2</sub> maximal concentration in the polymer matrix, and the parameters r correspond to the reaction rates. Considering that in neutral media, the pseudo acid ions aren't yielded, the chemical stages won't influence the ionic force of the double electric layer (DEL). Thus, the correspondent reaction rates will be calculated as:

$$r_{11} = k_{11}p(1 - u)^3 \quad (2)$$

$$r_{12} = k_{12}p^* (1 - u)^2 \quad (3)$$

$$r_2 = k_2u \exp\left(\frac{4F\phi_0}{RT}\right) \quad (4)$$

Where the parameters k are correspondent reaction rate constants, F is the Faraday number,  $\phi_0$  is the potential slope, related to the zero-charge potential, R is the universal gas constant, and T is the absolute temperature of the solution.

In basic media, when nitro compound forms the ion of pseudo acid, the behavior would be more dynamic. But in neutral and acidic media, the nitro compound is yielded. Therefore, only the electrochemical stage will influence the DEL. As in [23,24], it will provide a more stable sensor response, as shown below.

### 3. Results and Discussion

We investigate the electroanalytical behavior of the perillartine and its ether adduct electrochemical determination by RuO<sub>4</sub>/Poly(naphthoquinone)-modified electrode; we analyze the equation-set (1) utilizing the linear stability theory. The steady-state Jacobian matrix members will be exposed as:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \quad (5)$$

Where:

$$a_{11} = \frac{2}{\delta} \left( -\frac{P}{\delta} - k_{11}(1 - u)^3 \right) \quad (6)$$

$$a_{12} = 0 \quad (7)$$

$$a_{13} = \frac{2}{\delta} (3k_{11}(1 - u)^2) \quad (8)$$

$$a_{21} = 0 \quad (9)$$

$$a_{22} = \frac{2}{\delta} \left( -\frac{P^*}{\delta} - k_{12}(1 - u)^2 \right) \quad (10)$$

$$a_{23} = \frac{2}{\delta} (2k_{12}(1 - u)) \quad (11)$$

$$a_{31} = \frac{1}{U} (k_{11}(1 - u)^3) \quad (12)$$

$$a_{32} = \frac{1}{U} (k_{12}(1 - u)^2) \quad (13)$$

$$a_{33} = \frac{1}{U} \left( -3k_{11}(1 - u)^2 - 2k_{12}(1 - u) - k_2 \exp\left(\frac{4F\phi_0}{RT}\right) + jk_2u \exp\left(\frac{4F\phi_0}{RT}\right) \right) \quad (14)$$

As in similar systems [23,24], oscillatory behavior is possible in this system. Nevertheless, as on the chemical stages, no ionic compounds formation, destruction, and transformation occur (in neutral media); the unique factor responsible for the oscillatory behavior, as mentioned above and in [23,24], is the influence of the electrochemical stage on double electric layer capacitance and conductivity. It is described by the positivity of the element  $jk_2u \exp\left(\frac{AF\phi_0}{RT}\right) > 0$  if  $j > 0$ . The oscillations are expected to be frequent and of small amplitude.

To investigate the steady-state stability in this system, we apply to the equation-set (1) the Routh-Hurwitz stability criterion. Avoiding the cumbersome expressions and, therefore, simplifying the determinant analysis, we introduce new variables, rewriting the determinant as:

$$\frac{4}{\delta^2 U} \begin{vmatrix} -\kappa_1 - \varepsilon & 0 & \Sigma \\ 0 & -\kappa_2 - \Lambda & \theta \\ \varepsilon & \Lambda & -\Sigma - \theta - \Omega \end{vmatrix} \quad (15)$$

Opening the brackets and applying the  $\text{Det } J < 0$  requirements, derived from the criterion, we obtain the stability requisite, exposed as (16):

$$-\kappa_1(\kappa_2\Sigma + \Lambda\Sigma + \kappa_2\theta + \Lambda\theta + \kappa_2\Omega) - \varepsilon(\kappa_2\theta + \Lambda\theta + \kappa_2\Omega) < 0 \quad (16)$$

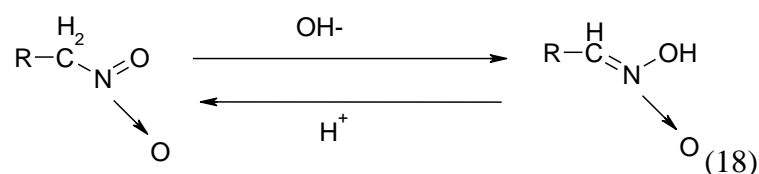
As the second expression in most parameter values has more negative values than the first, the left part of the inequation (16) will easily shift to more negative values. Thus, this inequation describes an electroanalytical efficient diffusion-controlled electroanalytical system.

As in this case, there are no reactions capable of compromising the analyte and modifier stability; the steady-state stability is correspondent to the linear dependence between the sweeteners' concentration and the current (in this system, we describe the amperometric sensor), which is therefore observed in vast measure of the concentrations.

The detection limit is relatively low, corresponding to the margin between stable steady-states and unstable states. This margin is defined by the monotonic instability, described by the condition of  $\text{Det } J = 0$ , or:

$$-\kappa_1(\kappa_2\Sigma + \Lambda\Sigma + \kappa_2\theta + \Lambda\theta + \kappa_2\Omega) - \varepsilon(\kappa_2\theta + \Lambda\theta + \kappa_2\Omega) = 0 \quad (17)$$

As it is known, in basic media, the nitro compounds undergo a tautomeric transformation:



Yielding, therefore, the salt of the pseudo acid, augmenting the DEL ionic force, conductivity, and impedance. This will contribute strongly to the system's behavior, one of the causes of oscillatory instability. This case will be described in one of our next articles.

#### 4. Conclusions

The analysis of the system with the perillartine sugar substituent and its ether adduct, also a sweetener electrochemical determination on RuO<sub>4</sub>/Poly(Naphthoquinone)composite, let us conclude that we deal with an electroanalytical efficient diffusion-controlled system. The steady-state stability, corresponding to the linear dependence between the current and the concentration of both sweeteners, is observed in the vast parameter value. The oscillatory behavior is observed in the cases of strong DEL influences in neutral and acidic media. The

salt-formation is added as an additional factor for the oscillatory behavior in basic media. Either way, those factors are realized far beyond the detection limit without influencing the electroanalytical system strongly.

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## Conflicts of Interest

The authors declare no conflict of interest.

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