

Theoretical Description for the Electrochemical Determination of Two Aryloxyphenoxypropionate Herbicides in Soy Products

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Abstract: In this work, the possibility of the electrochemical determination of two aryloxyphenoxypropionate pesticides in soy products, assisted by copper sulfide nanoparticles, paired with *in situ* trivalent copper sulfohydroxide. Oxidation scenarios, including N-oxidation, intramolecular heterocyclization, and electropolymerization, are included in the model. The model is analyzed using linear stability theory and bifurcation analysis. It confirms that the steady-state stability is easily obtained and maintained so that the electrochemical process may be efficient for either pesticide quantification or removal by their immobilization in the polymer phase, despite the enhanced probability of electrochemical oscillations.

Keywords: soybean; ACCase inhibitors; aryloxyphenoxypropionate herbicides; electrochemical sensors; stable steady-state.

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1. Introduction

Soybean products are among the most planted in the Cerrado biome in the Center-West administrative region of Brazil [1-4]. Soybean plantation and soybean production are among the most important areas of the Brazilian agricultural sector. Soybean crops are very important for the Brazilian federal government and the governments of Brazilian states, including the areas of Cerrado (Goiás, Mato Grosso, Mato Grosso do Sul, Federal District, and parts of the states of Bahia, Tocantins, Maranhão, Piauí, Minas Gerais, São Paulo, and Paraná). A minimal part of Cerrado lies within the borders of Paraguay, which corresponds to the zone of Pedro Juan Caballero, Capitán Bado, and Cerro Corá, in the Paraguayan departments of Amambay, Concepción, and Canindeyú.

In order to enhance the fertility of soy crops by protecting them from grime weeds, concurring with soy for growth resources, the herbicide preparations, including the cyclohexanediones and aryloxyphenoxypropionates, like fluazifop-*p*-butyl and quizalofop-*p*-ethyl (Figure 1) [5-10], are authorized by the Brazilian regulator ANVISA. Their mechanism is based on acetyl-CoA carboxylase (ACCase) inhibition, leading to failure in cell membrane construction, which becomes lethal for the plant. Another popular herbicide group that is applied to soy crop protection in Brazil is the cyclohexanedione family.

Although they are effective for soybean weed control, they may be toxic if they enter soybean products. For this and other reasons, developing a rapid, efficient method for their quantification is necessary, and electroanalytical methods (cathodic or anodic) may be an excellent solution [11-14].

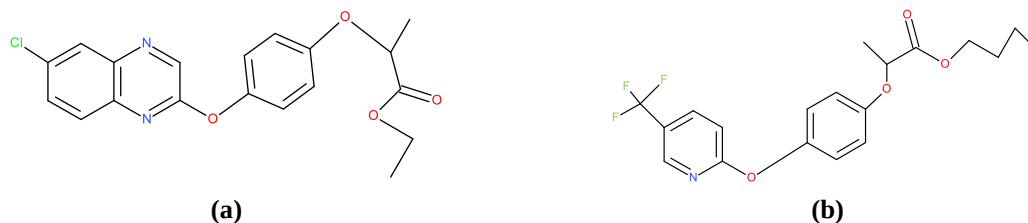
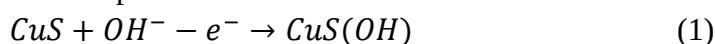


Figure 1. (a) Quizalofop-*p*-ethyl; (b) fluazifop-*p*-butyl.

To date, no theoretical or experimental reports describe electrochemical methods for quantifying either of the mentioned herbicides. Nevertheless, their chemical composition indicates that these compounds contain both donating and accepting groups [15-22], which leads to the conclusion that both cathodic and anodic processes are applicable to them. Moreover, although the cathodic electrochemical determination is preferable, the anodic determination is possible if strong oxidants are used as electrode modifiers. One of these oxidants may be produced *in situ* by the electrochemical oxidation of copper sulfide nanoparticles in a neutral or slightly alkaline medium by (1) would be an interesting option. Such hybrid materials have already been used in electroanalytics [15-22] in either cathodic or anodic processes. Nevertheless, electrochemical instabilities typical of similar electroanalytical and electrosynthetic processes [23-26] may impede clear interpretation of the analytical signal or even cause the electrochemical equipment to break down. On the other hand, the electrochemical instabilities may reveal the presence of a substance or a specific reaction involving the electroactive compound.



The analysis of the theoretical and experimental data shows that the electrochemical instabilities in non-autocatalytic electrochemical systems are caused by the influences of

chemical and electrochemical processes on the double electric layer (DEL) ionic force, capacity, and conductivity, such as the electrode surface material impedance.

Therefore, the theoretical *a priori* investigation of the system's behavior, capable of detecting the conditions of the most effective sensing interpretation, as well as the conditions of the electrochemical instabilities, is an important stage for the development of new electrochemical sensors, especially for new compounds and involving new electrode modifiers. This investigation, which involves developing and analyzing a mathematical model, also allows comparison of similar electroanalytical systems. Therefore, the aim of this work is to investigate, from the mechanistic theoretical point of view, the possibility of electrochemical determination of two aryloxyphenoxypropionate ACCase-inhibiting herbicides on a nano-CuS/conducting polymer composite. It involves proposing a mechanism and analyzing and interpreting the mathematical model, including comparing the behavior of this system with similar systems [27,28].

2. Materials and Methods

Copper (III) sulfohydroxide, a product of copper (II) sulfide *in situ* electrooxidation by reaction (1), is an aggressive oxidant, oxidizing both analytes by three parallel scenarios: - yielding an N-oxide; - realizing the intramolecular heterocyclization, yielding a furan ring; - by electro(co)polymerization.

The last scenario is particularly interesting for pesticide removal from soy products, melioration waters, and natural waters. Considering the above-cited statements, such as the low ionization degree in a neutral medium, we describe the electroanalytical process as shown in Figure 2.

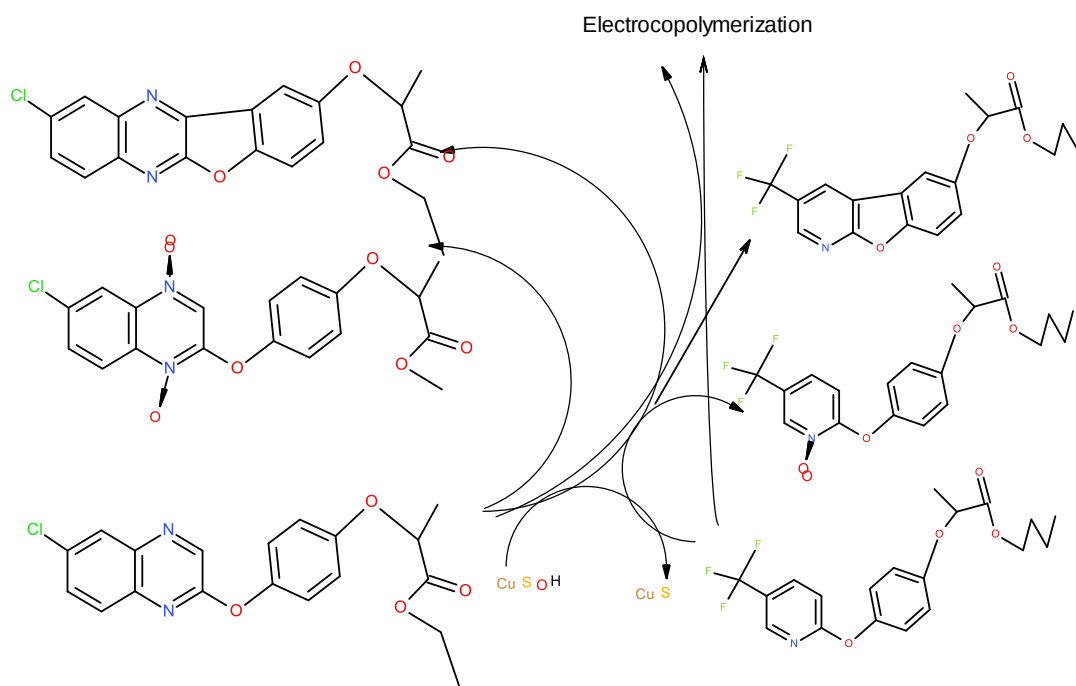


Figure 2. Quinalofop-*p*-ethyl and fluazifop-*p*-butyl.

Taking this into account and making some assumptions [27,28], we describe the behavior of this system by a trivariate balance differential equation set (2):

$$\begin{cases} \frac{dq}{dt} = \frac{2}{\delta} \left(\frac{\Delta}{\delta} (q_0 - q) - r_1 - r_{cq} - r_p \right) \\ \frac{df}{dt} = \frac{2}{\delta} \left(\frac{\Phi}{\delta} (f_0 - f) - r_2 - r_{cf} - r_p \right) \\ \frac{dc}{dt} = \frac{1}{C} (r_1 + r_{cq} + r_p + r_2 + r_{cf} - r_c) \end{cases} \quad (2)$$

Herein, q and f are quizalofop-*p*-ethyl and fluziafop-*p*-butyl electrochemical determinations in the pre-surface layer, Δ and Φ are the corresponding diffusion coefficients, q_0 and f_0 are their corresponding bulk concentrations, c is the copper sulfide nanoparticles matrix coverage degree, C is its maximal matrix concentration, and the parameters r stand for the corresponding reaction rates, calculated as (3 – 8):

$$r_1 = k_1 q (1 - c)^2 \quad (3)$$

$$r_{cq} = k_{cq} q (1 - c)^2 \quad (4)$$

$$r_2 = k_2 f (1 - c) \quad (5)$$

$$r_{cf} = k_{cf} f (1 - c)^2 \quad (6)$$

$$r_p = k_p q^x f^y (1 - c)^z \exp(-\alpha q f) \quad (7)$$

$$r_c = k_c c \exp\left(\frac{F\varphi_0}{RT}\right) \quad (8)$$

Herein, the parameters k correspond to the reaction rate constants, α is the parameter describing the influence of ionic form transformations during electropolymerization, led by the classic Díaz mechanism, on DEL electrophysical properties, x , y , and z are the corresponding polymerization reaction orders, $F = N_A e$ is the Faraday constant, φ_0 stands for the zero-charge-related potential slope in DEL, R is the universal gas constant, and T is the absolute temperature.

Considering that in the neutral medium, the pyridinic nitrogen atoms and esoteric groups have difficulty ionizing and hydrolyzing correspondingly, the transformation of the ionic form affecting DEL only occurs during the assisted electropolymerization (as neither of the two monomers interacts directly with the electrode electrochemically initiating the chain). Therefore, the oscillatory instability will be less probable than in similar systems. For this and other reasons, copper sulfide nanoparticles in the neutral medium are efficient for both quizalofop-*p*-ethyl and fluazifop-*p*-butyl electrochemical determination and removal, as shown below.

3. Results and Discussion

We investigate the electrochemical behavior of the electroanalytical system with the CuS-assisted quizalofop-*p*-ethyl and fluziafop-*p*-butyl electrochemical determination by applying the linear stability theory and bifurcation analysis to the equation set (2). The steady-state Jacobian matrix will be expressed as (9):

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \quad (9)$$

In which:

$$a_{11} = \frac{2}{\delta} \left(-\frac{\Delta}{\delta} - k_1 (1 - c)^2 - k_{cq} (1 - c)^2 - x k_p q^{x-1} f^y (1 - c)^z \exp(-\alpha q f) + \alpha k_p q^x f^y (1 - c)^z \exp(-\alpha q f) \right) \quad (10)$$

$$a_{12} = \frac{2}{\delta} \left(-y k_p q^x f^{y-1} (1 - c)^z \exp(-\alpha q f) + \alpha k_p q^x f^y (1 - c)^z \exp(-\alpha q f) \right) \quad (11)$$

$$a_{13} = \frac{2}{\delta} \left(2k_1 q (1 - c) + 2k_{cq} q (1 - c) + z k_p q^x f^y (1 - c)^z \exp(-\alpha q f) \right) \quad (12)$$

$$a_{21} = \frac{2}{\delta} (-xk_p q^{x-1} f^y (1-c)^z \exp(-\alpha q f) + \alpha k_p q^x f^y (1-c)^z \exp(-\alpha q f)) \quad (13)$$

$$a_{22} = \frac{2}{\delta} \left(-\frac{\Phi}{\delta} - k_2 (1-c) - k_{cf} (1-c)^2 - yk_p q^x f^{y-1} (1-c)^z \exp(-\alpha q f) + \alpha k_p q^x f^y (1-c)^z \exp(-\alpha q f) \right) \quad (14)$$

$$a_{23} = \frac{2}{\delta} (k_2 f + 2k_{cf} (1-c) + zk_p q^x f^y (1-c)^z \exp(-\alpha q f)) \quad (15)$$

$$a_{31} = \frac{1}{c} (k_1 (1-c)^2 + k_{cq} (1-c)^2 + xk_p q^{x-1} f^y (1-c)^z \exp(-\alpha q f) - \alpha k_p q^x f^y (1-c)^z \exp(-\alpha q f)) \quad (16)$$

$$a_{32} = \frac{1}{c} (k_2 (1-c) + k_{cf} (1-c)^2 + yk_p q^x f^{y-1} (1-c)^z \exp(-\alpha q f) - \alpha k_p q^x f^y (1-c)^z \exp(-\alpha q f)) \quad (17)$$

$$a_{33} = \frac{1}{c} \left(-2k_1 q (1-c) - 2k_{cq} q (1-c) - zk_p q^x f^y (1-c)^z \exp(-\alpha q f) - k_2 f - 2k_{cf} (1-c) - zk_p q^x f^y (1-c)^z \exp(-\alpha q f) - k_c \exp\left(\frac{F\phi_0}{RT}\right) + jk_c c \exp\left(\frac{F\phi_0}{RT}\right) \right) \quad (18)$$

Avoiding the cumbersome expressions during the determinant analysis, we rewrite the Jacobian determinant as (19):

$$\frac{4}{\delta^2 G} \begin{vmatrix} -\kappa - \Lambda - \Sigma & -T & H \\ -\Sigma & -\xi - P - T & \Gamma \\ \Lambda + \Sigma & P + T & -H - \Gamma - \Omega \end{vmatrix} \quad (19)$$

Which may be simplified to (20):

$$\frac{4}{\delta^2 G} \begin{vmatrix} -\kappa - \Lambda - \Sigma & -T & H \\ -\Sigma & -\xi - P - T & \Gamma \\ \Lambda & -\xi & -H - \Omega \end{vmatrix} \quad (20)$$

Opening the straight brackets, applying both the Routh-Hurwitz stability criterion and the monotonic instability condition, and changing the signs to the opposite, we obtain the requirement set, expressed as (21):

$$\begin{cases} H(\kappa\xi + \kappa P + \kappa T + \Sigma P) + \Gamma(\Lambda T + \kappa\xi + \Lambda\xi + \Sigma\xi) + \Omega(\kappa\xi + \kappa P + \kappa T + \Lambda\xi + \Lambda P + \Lambda T + \Sigma\xi + \Sigma P) > 0, \text{ steady-state stability} \\ = 0, \text{ monotonic instability} \end{cases} \quad (21)$$

If $-\text{Det } J > 0$, the Routh-Hurwitz stability criterion is valid, and the steady-state is thereby stable, providing an efficient steady-state pesticide determination. Moreover, the wide stability region allows us to use this system in pharmaceutical formulations, biological liquids, and the environment. The polymerization scenario also provides efficient pesticide removal and immobilization in the polymer phase.

This criterion is readily satisfied if the kinetic parameters Σ , T , and Ω are positive. In most cases, they are all positive; since the other variables in the determinant are also positive, this indicates a large steady-state stability region. The electroanalytical process is mostly kinetically controlled.

In the absence of side reactions or other factors capable of compromising the analyte and/or modifier stability, excluding the reactions foreseen by the mechanism, the linearity between the electrochemical parameter and concentration is observed, providing an efficient analytical signal interpretation, which is really important for drug concentration monitoring.

The condition $\text{Det } J = 0$ corresponds to the detection limit, manifested by the *monotonic instability*. This can be seen as an N-shaped part of the steady-state voltammogram, which depicts the margin between stable steady states and unstable states and corresponds to steady-state multiplicity. In other words, multiple steady states, each one unstable, coexist at this point.

As for oscillatory behavior, it is realized beyond the detection limit in the Hopf bifurcation case. Its realization requires positive callback-related addenda in the main diagonal elements.

Observing the main diagonal elements (10), (14), and (18), we may observe that the oscillatory behavior becomes possible if the kinetic parameters a and j are positive, which corresponds to the DEL influences of two electrochemical stages, one of them indirect (electropolymerization) and the other direct (trivalent copper *in situ* regeneration). This factor is typical for similar systems [27,28] and may be described by the positivity of the elements $\alpha k_p q^x f^y (1 - c)^z \exp(-\alpha q f)$ and $\alpha k_p q^x f^y (1 - c)^z \exp(-\alpha q f)$, if $a > 0$, describing ionic forms cyclic transformations during chain initiation and gradual propagation, and $j k_c c \exp\left(\frac{F\varphi_0}{RT}\right) > 0$, if $j > 0$. These elements describe the positive callback, and this callback will depend on the system's characteristics. For example, the oscillation frequency and amplitude will depend on the background electrolyte composition, which has been proven experimentally and theoretically [27,28].

In the case of the lower applied potential, the polymerization scenario becomes excluded or is limited to dimerization, which will make the system even more stable, as shown in our previous works [27,28]. As for the polymerization scenario, it becomes highly important for circular economy purposes, as the resulting polymer has wide possibilities of use, beginning with corrosion protection and ending with energy conversion and sensing.

4. Conclusions

From the theoretical description of the electrochemical anodic determination of two aryloxyphenoxypropionate ACCase-inhibiting herbicides by a CuS/Conducting Polymer-modified anode, it has been possible to conclude that it may be an excellent modifier for the quantification of both pesticides in a neutral medium. The electroanalytical process is mostly kinetically controlled. The oscillatory behavior in this system may be caused by DEL influence through direct and indirect electrochemical stages: electropolymerization and trivalent copper regeneration. The system may be used as an electroanalytical method, providing efficient analytical signal interpretation. In the polymerization scenario, it enables pesticide removal and immobilization in the polymer phase, which is important for the circular economy.

Author Contributions

Conceptualization, T.V.M.; V.V.T.; L.V.R.; O.V.H.; L.N.N.; P.I.Y.; Y.G. I. and G.M.P.; methodology, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; I.M.K.; L.O.K.; validation, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; I.M.K. and L.O.K.; formal analysis, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; I.M.K.; L.O.K. and T.V.M.; investigation, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; I.M.K.; L.O.K. and T.V.M.; resources, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; I.M.K.; L.O.K. and T.V.M.; data curation, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; M.V.K.; I.M.K.; L.O.K. and T.V.M.; writing—original draft preparation, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; M.V.K.; I.M.K.; L.O.K. and

T.V.M.; writing—review and editing, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; M.V.K.; I.M.K.; L.O.K. and T.V.M.; visualization, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; M.V.K.; I.M.K.; L.O.K. and T.V.M.; supervision, V.V.T.; M.J.M.; A.O.S. V.M.O.; S.C.O.; O.O.V.; M.P.K.; B.S.S.; D.M.M.; J.R.G.; J.I.F.P.M.; Z.O.K.; A.V.G.; I.F.B.; M.V.K.; I.M.K.; L.O.K. and T.V.M.; project administration, V.V.T.; M.J.M. J.I.F.P.M.. All authors have read and agreed to the published version of the manuscript.

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Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Barroso, A.L.L.; Dan, H.A.; Procópio, S.O.; Toledo, R.E.B.; Sandaniel, C.R.; Braz, G.B.P.; Cruvinel, K.L. Eficácia de herbicidas inibidores da ACCase no controle de gramíneas em lavouras de soja. [Efficacy of ACCase-inhibiting herbicides in controlling grass weeds in soybean crops]. *Planta Daninha* **2010**, *28*, 149–157, <https://doi.org/10.1590/S0100-83582010000100018>.
2. Rosa, L.E.; Soares Cherem, L.F.; Siame, L. Perda de solos no bioma Cerrado: estudo comparativo entre áreas protegidas e não protegidas por Unidades de Conservação. *Bol. Goia. Geogr.* **2023**, *43*, 70626, <https://doi.org/10.5216/bgg.v43i01.70626>.
3. Castagna, D.; Souza, A.P.d.; Vendrusculo, L.G.; Zolin, C.A.; Santos, C.R. Risco de desmatamento em áreas de Cerrado brasileiro. *Rev. Bras. Geogr. Fis.* **2024**, *17*, 199–212, <https://doi.org/10.26848/rbgf.v17.1.p199-212>.
4. González, O.A.F.; de Molas, L.F.P.; Rodas, R.D.; Vuletich, J.D.E.; Paredes, C.M.M.; Villafañe, D.B. *Handroanthus abayoy* (Bignoniaceae), nuevo registro para la flora del Paraguay. *Candollea* **2023**, *78*, 161–165, <https://doi.org/10.15553/c2023v782a7>.

5. Li, P.; Zhao, A.; Li, R.; Han, S.; Li, N.; Ji, L.; Lei, K. Identifying a Detoxifying Uridine Diphosphate Glucosyltransferase (UGT), MdUGT83K2, Which Can Glycosylate the Aryloxyphenoxypropionate Herbicide. *Agronomy* **2023**, *13*, 306, <https://doi.org/10.3390/agronomy13020306>.
6. Rajak, B.K.; Rani, P.; Mandal, P.; Chhokar, R.S.; Singh, N.; Singh, D.V. Emerging possibilities in the advancement of herbicides to combat acetyl-CoA carboxylase inhibitor resistance. *Front. Agron.* **2023**, *5*, 1218824, <https://doi.org/10.3389/fagro.2023.1218824>.
7. Schelter, M.L.; Souza, M.P.d.; Freitas, L.F.d.; Guerra, N.; Oliveira, A.M.d. Resistance of barnyardgrass biotypes (*Echinochloa crus-galli*) to ACCase-inhibiting herbicides in the main rice-growing regions of the state of Santa Catarina, Brazil. [Resistência de biótipos de capim-arroz (*Echinochloa crus-galli*) aos herbicidas inibidores da ACCase nas principais regiões orizícolas do Estado de Santa Catarina]. *Ciê. Rural.* **2024**, *54*, e20220384, <https://doi.org/10.1590/0103-8478cr20220384>.
8. Liu, Y.; Guo, J.; Liu, W.; Yang, F.; Deng, Y.; Meng, Y.; Cheng, B.; Fu, J.; Zhang, J.; Liao, X.; Wei, L.; Lu, H. Effects of haloxyfop-*p*-methyl on the developmental toxicity, neurotoxicity, and immunotoxicity in zebrafish. *Fish Shellfish Immunol.* **2023**, *132*, 108466, <https://doi.org/10.1016/j.fsi.2022.108466>.
9. Zhao, Y.; Ye, F.; Fu, Y. Research Progress on the Action Mechanism of Herbicide Safeners: A Review. *J. Agric. Food Chem.* **2023**, *71*, 3639-3650, <https://doi.org/10.1021/acs.jafc.2c08815>.
10. Sohrabi, H.; Salahshour Sani, P.; Orooji, Y.; Majidi, M.R.; Yoon, Y.; Khataee, A. MOF-based sensor platforms for rapid detection of pesticides to maintain food quality and safety. *Food Chem. Toxicol.* **2022**, *165*, 113176, <https://doi.org/10.1016/j.fct.2022.113176>.
11. Rezaeivala, M.; Bozorg, M.; Rafiee, N.; Sayin, K.; Tuzun, B. Corrosion inhibition of Carbon Steel using a new morpholine-based ligand during acid pickling: Experimental and theoretical studies. *Inorg. Chem. Commun.* **2023**, *148*, 110323, <https://doi.org/10.1016/j.inoche.2022.110323>.
12. Zhu, S.; Sun, B.; Chen, Y.; Li, T.; Zhou, G.; Zhao, H.; Mao, W.; Zhao, Y. An excellent pH-controlled resistive switching memory device based on self-colored (C₇H₇O₄N)_n extracted from a lichen plant. *J. Mater. Chem. C* **2019**, *7*, 7593-7600, <https://doi.org/10.1039/c8tc06207B>.
13. Almasi, H.; Forghani, S.; Moradi, M. Recent advances on intelligent food freshness indicators; an update on natural colorants and methods of preparation. *Food Packag. Shelf Life* **2022**, *32*, 100839, <https://doi.org/10.1016/j.fpsl.2022.100839>.
14. Yin, J.; Li, J.; Reddy, V.S.; Ji, D.; Ramakrishna, S.; Xu, L. Flexible Textile-Based Sweat Sensors for Wearable Applications. *Biosensors* **2023**, *13*, 127, <https://doi.org/10.3390/bios13010127>.
15. Bordbar, M.M.; Sheini, A.; Hashemi, P.; Hajian, A.; Bagheri, H. Disposable Paper-Based Biosensors for the Point-of-Care Detection of Hazardous Contaminations—A Review. *Biosensors* **2021**, *11*, 316, <https://doi.org/10.3390/bios11090316>.
16. Bilgen, E.; Suvacı, Z.; Persil Çetinkol, Ö.; Forough, M. 26 - Disposable paper-based sensors. In *Fundamentals of Sensor Technology*, Barhoum, A., Altintas, Z., Eds.; Woodhead Publishing: **2023**; pp. 803-860, <https://doi.org/10.1016/B978-0-323-88431-0.00028-4>.
17. Tkach, V.V.; de Paiva Martins, J.I.F.; Ivanushko, Y.G.; Yagodynets, P.I. Dye Electropolymerization for Electrochemical Analysis. A Brief Review. *Biointerface Res. Appl. Chem* **2022**, *12*, 4028-4047, <https://doi.org/10.33263/BRIAC123.40284047>.
18. Liv, L. A facile poly(allura red) film for signal-amplified electrochemical sensing of dopamine and uric acid in human plasma and urine. *Microchem. J.* **2023**, *195*, 109425, <https://doi.org/10.1016/j.microc.2023.109425>.
19. Porfireva, A.; Plastinina, K.; Evtugyn, V.; Kuzin, Y.; Evtugyn, G. Electrochemical DNA Sensor Based on Poly(Azure A) Obtained from the Buffer Saturated with Chloroform. *Sensors* **2021**, *21*, 2949, <https://doi.org/10.3390/s21092949>.
20. Sugiyama, K.; Watanabe, K.; Komatsu, S.; Yoshida, K.; Ono, T.; Fujimura, T.; Kashiwagi, Y.; Sato, K. Electropolymerization of Azure A and pH Sensing Using Poly(azure A)-modified Electrodes. *Anal. Sci.* **2021**, *37*, 893-896, <https://doi.org/10.2116/analsci.20P341>.
21. Karataş, Y.; Çetin, T.; Akinay, Y.; Gülcan, M. Synthesis and characterization of Pd doped MXene for hydrogen production from the hydrolysis of methylamine borane: Effect of cryogenic treatment. *J. Energy Inst.* **2023**, *109*, 101310, <https://doi.org/10.1016/j.joei.2023.101310>.
22. Habibi, M.; Habibi-Yangjeh, A.; Akinay, Y.; Khataee, A. Oxygen vacancy-rich CeO₂ decorated with Cu₃BiS₃ nanoparticles: Outstanding visible-light photocatalytic performance towards tetracycline degradation. *Chemosphere* **2023**, *340*, 139828, <https://doi.org/10.1016/j.chemosphere.2023.139828>.

23. Yigit, A.; Pinar, P.T.; Akinay, Y.; Alma, M.H.; Menges, N. Nanotube-Boramic Acid Derivative for Dopamine Sensing. *ChemistrySelect* **2021**, *6*, 6302-6313, <https://doi.org/10.1002/slct.202101316>.
24. Debbarma, J.; Debnath, R.; Saha, M. Graphene from Sugarcane Bagasse for Nonenzymatic Electrochemical Determination of Glucose. *Lett. Appl. NanoBioSci.* **2023**, *12*, 115, <https://doi.org/10.33263/LIANBS124.115>.
25. Das, I.; Goel, N.; Gupta, S.K.; Agrawal, N.R. Electropolymerization of pyrrole: Dendrimers, nano-sized patterns and oscillations in potential in presence of aromatic and aliphatic surfactants. *J. Electroanal. Chem.* **2012**, *670*, 1-10, <https://doi.org/10.1016/j.jelechem.2012.01.023>.
26. Aoki, K.; Mukoyama, I.; Chen, J. Competition between Polymerization and Dissolution of Poly(3-methylthiophene) Films. *Russ. J. Electrochem.* **2004**, *40*, 280-285, <https://doi.org/10.1023/B:RUEL.0000019665.59805.4c>.
27. Tkach, V.; Morozova, T.; Khrutba, V.; Hlukhonets, A.; Kushnir, M.; Ivanushko, Y.; Kryvetskyi, V.; Kryvetska, I.; Kryvetskyi, I.; Yagodynets, P. The Theoretical Description for Cenobamate CuS-Assisted Electrochemical Determination in Pharmaceutical Formulations and Wastewater. *Orbital: Electron. J. Chem.* **2023**, *15*, 198- 201, <https://doi.org/10.17807/orbital.v15i4.19558>.
28. Tkach, V.V.; Kushnir, M.V.; Storoshchuk, N.M.; Cherevatov, V.F.; de Oliveira, S.C.; Luganska, O.V.; Koptiika, V.V.; Domnich, V.I.; Lukanova, S.M.; Ivanushko, Y.G. Modelagem matemática da detecção eletroanalítica da nereistoxina, assistida pelo compósito de oxihidróxido de cobalto com polímeros condutores. *Rev. Colomb. Cienc. Quím. Farm.* **2023**, *52*, 608-619.

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