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# DEVELOPMENT AND MODELING OF ELECTROCHEMICAL BIOSENSORS FOR THE DETECTION OF POLLUTANTS IN AQUEOUS PHASE

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**الملخص**

تتناول هذه الدراسة تطوير مستشعر حيوي كهر وكيميائي موجه للكشف عن البنسلين (Penicillin G) G اعتمادًا على فيلم بوليانيلين/أكسيد الحديد النانوي (PANI/FeNPs) ودراسة سلوكه التحليلي باستخدام تقنيات كهر وكيميائية مختلفة. هدفت هذه العمل إلى تحضير طبقة نشطة على سطح قطب البلاتين وتثبيت إنزيم الميالوبيروكسيداز (MPO)من أجل تحسين الانتقائية والحساسية في الكشف عن المضاد الحيوي. تم تحضير فيلم PANI و PANI/FeNPsباستخدام الطريقتين الكيميائية (البلمرة التأكسدية في وسط حمضي) والكهروكيميائية) الترسيب بالجهد الدوري(CV ، حيث أظهرت النتائج نجاح تكوين طبقة متجانسة ذات خصائص توصيل جيدة. كما أكدت التحاليل الطيفية FTIR) و (UV-Visوجود التآثر بين البوليمر وأكسيد الحديد النانوي وتشكيل البنية الهجينة .أظهرت القياسات الكهروكيميائية CV) و (EISأن تعديل سطح القطب يؤدي إلى تغير واضح في سلوك انتقال الإلكترونات، مع زيادة مقاومة النقل الشحني بعد تثبيت الطبقة الحيوية، مما يؤكد نجاح عملية التعديل والتثبيت. كما بينت النتائج أن المستشعر المطور يمتلك استجابة جيدة تجاه تركيزات مختلفة من البنسلين G في المجال من $10^{-6}$ إلى $10^{-4}$ M، مع علاقة خطية ومعامل ارتباط مرتفع ($R^2 = 0.998$) وحساسية معتبرة.تشير هذه النتائج إلى أن القطب المعدل بـ PANI/FeNPs/SA-MPOيمثل منصة واعدة لتطوير مستشعرات حيوية فعالة للكشف عن المضادات الحيوية، مع أداء تحليلي جيد واستجابة كهروكيميائية مستقرة.

**الكلمات المفتاحية:**

المستشعر الحيوي ، البنسيلينG، بوليانيلين (PANI)، ،الميلوبيروكسيديز، السكسينالديهيد ،FeNPs

، CV، EIS.

## Abstract

This study focuses on the development of an electrochemical biosensor designed for the detection of Penicillin G, based on a polyaniline/iron oxide nanoparticles (PANI/FeNPs) film and investigated using various electrochemical techniques. The work aimed to prepare an active layer on the surface of a platinum electrode and to immobilize the enzyme myeloperoxidase (MPO) in order to improve selectivity and sensitivity toward the antibiotic. PANI and PANI/FeNPs films were prepared using both chemical methods (oxidative polymerization in acidic medium) and electrochemical methods (cyclic voltammetric deposition). The results confirmed the successful formation of a homogeneous layer with good conductive properties. Spectroscopic analyses (FTIR and UV–Vis) also confirmed the interaction between the polymer and iron oxide nanoparticles, leading to the formation of a hybrid structure. Electrochemical measurements (CV and EIS) showed that surface modification of the electrode led to a clear change in electron transfer behavior, with an increase in charge transfer resistance after immobilization of the bioactive layer, confirming the successful modification and enzyme attachment. The results also demonstrated that the developed sensor exhibits a good response toward different concentrations of Penicillin G in the range of $10^{-6}$ to $10^{-4}$ M, with a linear relationship, a high correlation coefficient ($R^2 = 0.998$), and significant sensitivity. These findings indicate that the PANI/FeNPs/SA-MPO modified electrode represents a promising platform for the development of efficient biosensors for antibiotic detection, offering good analytical performance and stable electrochemical response.

**Keywords:**

Biosensor, Penicilline G, Polyaniline (PANI), FeNPs, Myéloperoxydase, Succinaldehyde, CV, EIS.

**Résume**

Cette étude porte sur le développement d'un biocapteur électrochimique destiné à la détection de la pénicilline G, basé sur un film de polyaniline/nanoparticules d'oxyde de fer (PANI/FeNPs) et étudié à l'aide de différentes techniques électrochimiques. Ce travail avait pour objectif de préparer une couche active à la surface d'une électrode de platine et d'immobiliser l'enzyme myéloperoxydase (MPO) afin d'améliorer la sélectivité et la sensibilité vis-à-vis de cet antibiotique. Les films de PANI et de PANI/FeNPs ont été élaborés par des méthodes chimiques (polymérisation oxydative en milieu acide) ainsi que par des méthodes électrochimiques (dépôt par voltampérométrie cyclique). Les résultats ont confirmé la formation réussie d'une couche homogène présentant de bonnes propriétés conductrices. Les analyses spectroscopiques (FTIR et UV-Visible) ont également mis en évidence l'interaction entre le polymère et les nanoparticules d'oxyde de fer, conduisant à la formation d'une structure hybride. Les mesures électrochimiques (voltampérométrie cyclique, CV, et spectroscopie d'impédance électrochimique, EIS) ont montré que la modification de la surface de l'électrode a entraîné une variation significative du comportement du transfert électronique. Une augmentation de la résistance au transfert de charge a notamment été observée après l'immobilisation de la couche bioactive, confirmant ainsi la réussite de la modification de l'électrode et de la fixation de l'enzyme. Les résultats ont également démontré que le capteur développé présente une bonne réponse vis-à-vis de différentes concentrations de pénicilline G comprises entre $10^{-6}$ et $10^{-4}$ M, avec une relation linéaire, un coefficient de corrélation élevé ($R^2 = 0,998$) et une sensibilité remarquable. Ces résultats indiquent que l'électrode modifiée PANI/FeNPs/SA-MPO constitue une plateforme prometteuse pour le développement de biocapteurs performants dédiés à la détection des antibiotiques, offrant de bonnes performances analytiques ainsi qu'une réponse électrochimique stable.

**Mots-clés:**
Biocapteur, Pénicilline G, Polyaniline (PANI), FeNPs, Myéloperoxydase, succinaldehyde, CV, EIS.

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# *General Introduction*

The rapid development of analytical technologies has led to the emergence of highly sensitive and selective detection systems capable of monitoring a wide range of biological and chemical compounds. Among these technologies, biosensors have attracted considerable attention due to their ability to combine biological recognition elements with physicochemical transducers, enabling rapid, reliable, and cost-effective analyses. Their applications extend to numerous fields including medical diagnostics, environmental monitoring, food safety, and pharmaceutical analysis [1-3].

The increasing presence of pharmaceutical residues, particularly antibiotics, in environmental and biological systems has become a major concern. Penicillin G, one of the most widely used β-lactam antibiotics, is frequently detected in environmental matrices and pharmaceutical products. Its excessive use and uncontrolled release contribute to the development of antibiotic-resistant microorganisms, creating significant public health and environmental challenges. Consequently, the development of efficient analytical tools for the rapid detection of penicillin G has become essential [4-6]. Electrochemical biosensors represent an attractive alternative to conventional analytical techniques because of their simplicity, high sensitivity, low cost, and potential for miniaturization. In recent years, conductive polymers and nanostructured materials have been extensively investigated for biosensor fabrication. Among them, polyaniline (PANI) exhibits excellent electrical conductivity, environmental stability, and ease of synthesis, while iron oxide nanoparticles (FeNPs) provide a large active surface area and enhanced electron transfer properties. The combination of these materials leads to hybrid nanocomposites with improved electrochemical performances [7-10].

The present work focuses on the development of an electrochemical biosensor based on a PANI/FeNPs nanocomposite film deposited on a platinum electrode and functionalized with myeloperoxidase (MPO) immobilized through succinaldehyde cross-linking. The objective is to evaluate the potential of this bioactive platform for the detection of Penicillin G and to investigate its electrochemical behavior using cyclic voltammetry and electrochemical impedance spectroscopy. This dissertation is organized into three chapters. The first chapter presents a general overview of sensors, biosensors, enzymatic bioreceptors, and immobilization methods. The second chapter describes the materials, experimental procedures, and electrochemical characterization techniques employed throughout this work. The third chapter is devoted to the elaboration of the PANI/FeNPs nanocomposite, the fabrication of the biosensor, its physicochemical and electrochemical characterization, and its application for the detection of Penicillin G.

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