



Green Nanoparticles for Enhanced Electrochemical Monitoring of Pharmaceutical Contaminants: Comparative Investigation Between Monometallic and Bimetallic Nanoparticles

Soumaya Nasri, Amani Chrouda, Shazalia Mahmoud Ahmed Ali, Bakheit Mustafa, Manahil Babiker Elamin, Laila M Alhaidari, Hamdi Ben Halima, Nicole Jafezic-Renault

► To cite this version:

Soumaya Nasri, Amani Chrouda, Shazalia Mahmoud Ahmed Ali, Bakheit Mustafa, Manahil Babiker Elamin, et al.. Green Nanoparticles for Enhanced Electrochemical Monitoring of Pharmaceutical Contaminants: Comparative Investigation Between Monometallic and Bimetallic Nanoparticles. *Micromachines*, 2025, 17 (1), pp.60. <10.3390/mi17010060>. <hal-05597338>

HAL Id: hal-05597338

<https://hal.science/hal-05597338v1>

Submitted on 20 Apr 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Article

Green Nanoparticles for Enhanced Electrochemical Monitoring of Pharmaceutical Contaminants: Comparative Investigation Between Monometallic and Bimetallic Nanoparticles

Soumaya Nasri ^{1,†}, Amani Chrouda ^{1,*}, Shazalia Mahmoud Ahmed Ali ¹, Bakheit Mustafa ², Manahil Babiker Elamin ¹, Laila M. Alhaidari ¹, Hamdi Ben Halima ³ and Nicole Jafezic-Renault ^{3,*}

¹ Department of Chemistry, Faculty of Science Al-Zulfi, Majmaah University, Majmaah 11952, Saudi Arabia; soumaya.n@mu.edu.sa (S.N.); sm.ahmed@mu.edu.sa (S.M.A.A.); m.elamn@mu.edu.sa (M.B.E.); l.alhaidari@mu.edu.sa (L.M.A.)

² Department of Chemistry, College of Science, Qassim University, Buraidah 51452, Saudi Arabia; b.salih@qu.edu.sa

³ UTINAM Institute, UMR CNRS 6213, University Marie et Louis Pasteur, 16 Gray Road, 25030 Besançon, France; hamdi.ben_halima@univ-fcomte.fr

* Correspondence: amain.c@mu.edu.sa (A.C.); nicole.jafezic-renault@univ-fcomte.fr (N.J.-R.)

† These authors contributed equally to this work.

Abstract

Study presents a comparative analytical investigation into the green synthesis of monometallic and bimetallic nanoparticles using *Punica granatum* (pomegranate) extract, aimed at developing high-performance electrochemical sensors for the detection of ciprofloxacin (CIP) as a representative pharmaceutical pollutant. Three nanoparticle systems were successfully synthesized: monometallic Au@NPs and TiO₂@NPs, as well as the bimetallic AuTiO₂@NPs. Their structural and physicochemical characteristics were comprehensively analyzed using UV–Vis spectroscopy, FTIR, SEM, TEM, and XRD techniques. The obtained nanoparticles exhibited predominantly spherical morphologies with average particle sizes of approximately 40 ± 5 nm for Au@NPs, 50 ± 7 nm for TiO₂@NPs, and 60 ± 6 nm for AuTiO₂@NPs. These nanomaterials were subsequently employed to modify electrode surfaces for electrochemical sensing applications. Their analytical performance was evaluated using cyclic voltammetry (CV) and square-wave voltammetry (SWV). The sensors displayed excellent sensitivity, with limits of detection of 0.8 ppb for TiO₂@NPs, 0.8 ppb for Au@NPs, and 0.2 ppb for the AuTiO₂@NP-based sensor. The bimetallic platform demonstrated superior electrochemical behavior, enhanced signal intensity, and strong selectivity, achieving recovery rates of 98% in tap water and 103% in wastewater. Overall, the results confirm the effectiveness of green-synthesized bimetallic nanoparticles as efficient, low-cost materials for environmental monitoring of emerging pharmaceutical contaminants.

Keywords: monometallic nanoparticles; bimetallic nanoparticles; pharmaceutical pollutants; electrochemical measurements



Academic Editor: Cong Wang

Received: 4 December 2025

Revised: 24 December 2025

Accepted: 28 December 2025

Published: 31 December 2025

Copyright: © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Although water covers approximately 71% of the Earth's surface, only about 2.5% constitutes freshwater resources that are accessible for essential ecological and human needs [1–3]. Among the emerging threats to these limited resources, pharmaceuticals have become a critical global concern, posing then serious risks to both human health and aquatic ecosystems [4]. They enter water bodies through various pathways, including household

wastewater, agricultural runoff, and industrial discharges [4]. Due to their chemical stability and resistance to conventional water treatment methods, pharmaceuticals tend to persist in the environment, further complicating efforts to ensure water safety and long-term water security [5]. More dangerous pharmaceutical products, even at trace concentrations, exhibit toxic effects on aquatic organisms, including fish, algae, and invertebrates [6]. Addressing this environmental concern requires the implementation of stricter regulatory frameworks, the development of advanced analytical wastewater monitoring, proper disposal practices, and the promotion of eco-friendly alternatives in pharmaceuticals and personal care formulations.

Compared to conventional techniques for water monitoring, which are often complex, time-consuming, require extensive sample preparation, and depend on skilled staff, electrochemical sensors offer significant advantages, including rapid response, ease of miniaturization, high selectivity, and specificity [7,8]. In particular, electrochemical sensors functionalized with nanomaterials have shown great potential for the effective detection of various contaminants in polluted water sources [9]. This enhanced performance is largely attributed to the unique properties of nanomaterials, such as their high specific surface area, tunable porosity, and superior adsorption and catalytic capabilities [10–14]. These characteristics not only improve the sensitivity and detection limits of the sensors but also contribute to their overall efficiency and practicality in real-world environmental monitoring applications.

A wide range of physical and chemical techniques has been developed for the synthesis of nanoparticles, including magnetron sputtering [15], metal-vapor synthesis [16], chemical reduction [17,18], sonochemical processes [19], and sol-gel methods [20]. While these approaches offer control over particle size and morphology, they often require prolonged reaction times, elevated temperatures, and the use of hazardous chemical reagents, leading to concerns about environmental impact, energy consumption, and potential toxicity [21]. These limitations have highlighted the urgent need for sustainable, eco-friendly synthesis strategies. Green synthesis has emerged as a promising alternative, leveraging natural reducing and stabilizing agents, such as plant extracts, microorganisms, and biopolymers, to produce green bimetallic nanoparticles under mild conditions with minimal environmental footprint [22,23].

Green synthesis nanoparticles involve the concurrent sorption or reduction of metal ions in the presence of suitable reducing and capping agents. Biogenic materials, including plant extracts, biomolecules, including proteins, carbohydrates, and nucleic acids, are considered ideal green reagents due to their relative safety, low cost, and ease of use [21–24].

While monometallic nanoparticles have demonstrated good performances, combining two different metals could probably offer clear advantages that can significantly boost detection and remediation efficiency [24,25]. These nanomaterials are in fact able to provide: (i) greater stability and resistance to agglomeration and oxidation because the combination of metals stabilizes the nanoparticle structure, preventing surface degradation and extending their useful life [26,27]; (ii) synergistic interaction between the two metals enhances adsorption and catalytic performance, surpassing what monometallic particles can achieve [26,27]; (iii) specific interaction with different surface compositions and electronic properties, enabling selective targeting of pollutants while minimizing interference from other substances [28,29]. Their versatile composition, morphology, and surface chemistry make them highly adaptable for different environmental conditions [30]. Different sensors based on green bimetallic nanoparticles have already explored for several analyte detection. A simple method was developed for the green synthesis of bimetallic silver-palladium nanoparticles (BG-AgPd-NPs) using bael gum (Aegel marmelos). The designed bimetallic

nanoparticles have shown a potential for lead ion detection with a limit of detection (LOD) inferior to 1 μM [31]. Ag-Au bimetallic nanoparticles (Ag-AuNPs) supported on reduced graphene oxide (RGO) with alginate as reductant and stabilizer were also designed. The peroxidase-based sensor demonstrated excellent performance in detecting H_2O_2 , with a linear range of 0.1 to 10 mM, and a low detection limit of 0.57 μM [32]. In other investigations, silver-platinum (Pt-Ag) bimetallic nanoparticles were synthesized by a biogenic reduction method using plant extracts. The sensor limit of detection (LOD) was 0.03 μM , and the limit of quantification (LOQ) was 0.11 μM [33]. One work used green-synthesized silver nanoparticles and carbon black for the electrochemical detection of ciprofloxacin. A detection limit of 0.48 μM [34].

However, to the best of our knowledge, no previous study has compared the performances of monometallic and bimetallic nanoparticles for the detection of pharmaceutical pollutants. For these reasons, the present work reports a comparative investigation of sensors functionalized with green monometallic and bimetallic nanoparticles using *Punica granatum* (pomegranate) extract, for ciprofloxacin (CIP) detection, which is employed here as a model pharmaceutical contaminant. Three types of nanoparticles were then synthesized: Au@NPs, TiO_2 @NPs, and AuTiO_2 @NPs. The successful synthesis and characterization of these nanoparticles were confirmed using various analytical techniques, including UV-Vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), and X-ray diffraction (XRD). Furthermore, the modification and the analytical performances of the electrochemical sensor surface were evaluated using cyclic voltammetry (CV) and square wave voltammetry (SWV).

2. Materials and Methods

2.1. Products

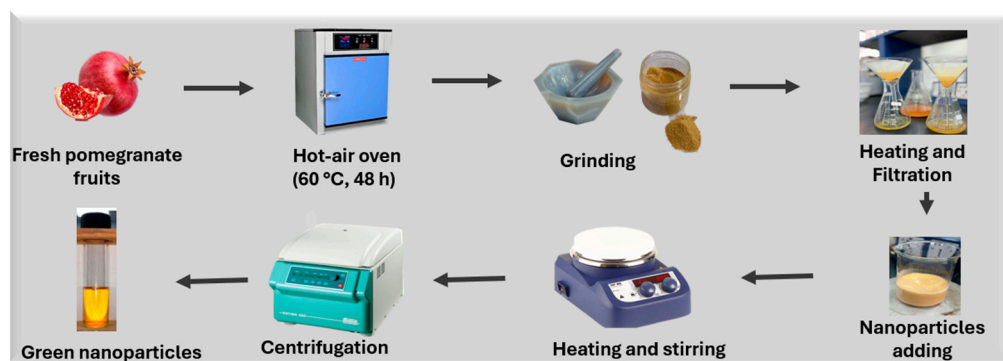
All chemicals and reagents were of analytical grade and used as received without further purification. Titanium dioxide (TiO_2 , $\geq 99\%$), hydrogen tetrachloroaurate (III) (HAuCl_4 , $\geq 99.9\%$), potassium ferricyanide (III) ($\text{K}_3[\text{Fe}(\text{CN})_6]$, $\geq 99\%$), potassium ferrocyanide (II) ($\text{K}_4[\text{Fe}(\text{CN})_6]$, $\geq 99\%$), and buffer components including phosphate-buffered saline (PBS, pH 7.4), acetate buffer, borate buffer, and Tris buffer (tris(hydroxymethyl)aminomethane, $\geq 99\%$) were purchased from Sigma-Aldrich, St. Louis, MO, USA. The antibiotics ciprofloxacin ($\geq 98\%$), norfloxacin ($\geq 98\%$), amoxicillin ($\geq 98\%$), tetracycline ($\geq 98\%$), sulfamethoxazole ($\geq 98\%$), and chloramphenicol ($\geq 98\%$) were also obtained from Sigma-Aldrich.

2.2. Instrumentation

The UV-Visible spectra were recorded with a Perkin Elmer (Springfield, IL, USA) Lambda 950 UV spectrophotometer, scanning wavelengths from 200 to 800 nm with a resolution of 1 nm, with samples in chloroform at room temperature. The Fourier Transform Infrared Spectroscopy (FTIR) spectra of the *Punica granatum* extract (PP), Titanium Nanoparticles TiO_2 @NPs, gold Nanoparticles Au@NPs, and the gold Titanium Nanoparticles AuTiO_2 @NPs were recorded in the $4000\text{--}400\text{ cm}^{-1}$ domain using a Perkin Elmer FT-IR spectrophotometer. Transmission electron microscopy (TEM) was performed using a high-resolution TEM instrument (e.g., JEOL 2100F, (Peabody, MA, USA)), with an acceleration voltage of 200 kV, ensuring detailed imaging at the nanometer scale. To prepare the samples for TEM analysis, a small drop of the nanoparticle dispersion was deposited onto a copper grid coated with a thin carbon film and dried under ambient conditions. X-ray diffraction was carried out using a Bruker (Allentown, PA, USA) D8 Advance polycrystalline powder/X-ray diffractometer (PXRD) equipped with a Cu X-ray source (wavelength = 1.5406 Å) in Bragg–Brentano geometry operating at 40 mA and 40 kV.

2.3. Nanoparticle Synthesis

This study employed a green synthesis approach for the fabrication of metal and metal oxide nanoparticles using *Punica granatum* peel extract as a natural reducing and stabilizing agent. A schematic representation of the overall concept of green nanoparticle synthesis is presented in Scheme 1.



Scheme 1. Green synthesis of nanoparticles using *Punica granatum* green extract.

2.3.1. Preparation of *Punica granatum* Peel Extract

Fresh pomegranate fruits were obtained locally and thoroughly rinsed with distilled water. The peels were manually separated from the fruit pulp and cut into small pieces to facilitate drying. The peel fragments were then dried in a hot-air oven at 60 °C for 48 h to ensure complete dehydration while preserving bioactive compounds. Once dried, the peels were ground into a fine powder using a mechanical grinder and passed through a sieve to achieve a uniform particle size. For extract preparation, 5 g of this powder was mixed with 100 mL of distilled water in a beaker. The mixture was heated at 100 °C for 5 min to extract phytochemicals such as polyphenols, flavonoids, and tannins, which are known to play a role in nanoparticle formation. After heating, the solution was allowed to cool to room temperature and filtered using Whatman No. 1 filter paper. The resulting clear yellow extract was stored at 4 °C and used within 24 h to ensure activity. All extraction processes were carried out under ambient laboratory conditions (~25 °C, 45–55% relative humidity), without any need for an inert atmosphere.

2.3.2. Coating of Titanium Dioxide Nanoparticles (TiO₂@NPs)

Titanium dioxide nanoparticles were coated with the previously prepared *P. granatum* extract. Specifically, 0.04 g of TiO₂ powder was gradually added to 100 mL of the extract under magnetic stirring to ensure uniform dispersion. The reaction mixture was maintained at 80 °C and continuously stirred for 4 h. During this period, a gradual color change in the solution was observed, indicating nanoparticle formation. The phytochemicals in the extract facilitate the reduction and stabilization of TiO₂ nanoparticles by acting as both capping and reducing agents. After the reaction, the mixture was allowed to cool, then centrifuged at 8000 rpm for 10 min to collect the solid nanoparticles. The resulting pellet was washed three times with distilled water to remove unreacted biological residues and dried in an oven at 80 °C until a constant weight was achieved. The final product, referred to as TiO₂@NPs, was stored in airtight containers for further characterization.

2.3.3. Synthesis of Gold Nanoparticles (Au@NPs)

Gold nanoparticles were synthesized in the presence of *Punica granatum* peel extract. A solution of 0.08 g of hydrogen tetrachloroaurate (III) (HAuCl₄) was prepared in 100 mL of the *Punica granatum* peel extract. The mixture was stirred and heated at 80 °C

for approximately 30 min. A color transition from light yellow to deep purple was observed, confirming the formation of gold nanoparticles due to the localized surface plasmon resonance (LSPR) effect. This visual change serves as a preliminary indicator of successful nanoparticle synthesis. After the reaction, the solution was cooled and centrifuged at 9000 rpm for 15 min. The pellet containing Au@NPs was washed repeatedly with deionized water to eliminate excess plant biomolecules and dried in an oven at 80 °C. The obtained nanoparticles were stored in a desiccator until use. All synthesis steps were conducted under ambient pressure and atmospheric conditions without inert gas protection, further confirming the green and accessible nature of the method.

2.3.4. Synthesis of Gold-Supported Titanium Dioxide Nanoparticles (AuTiO₂@NPs)

To prepare bimetallic nanoparticles with enhanced physicochemical properties, gold nanoparticles were supported on titanium dioxide using a hybrid green synthesis protocol. In a 1:1:1 volume ratio, 50 mL of 1.5 mM HAuCl₄ solution, 50 mL of *Punica granatum* peel extract, and 50 mL of distilled water were mixed in a round-bottom flask and stirred at 60 °C for 1 h to initiate the reduction of gold ions. The gradual appearance of a purple hue indicated successful AuNP formation. Subsequently, 500 mg of pre-synthesized TiO₂@NPs were added to the reaction mixture, which was then subjected to continuous stirring at 200 °C for an additional 2 h in a sealed system to promote the loading of gold onto the TiO₂ surface. After completion, the resulting AuTiO₂@NPs were separated by centrifugation at 10,000 rpm, washed multiple times with a 1:1 methanol–distilled water solution to remove unbound species and residual phytochemicals, and air-dried at room temperature under ambient conditions. This method required moderate thermal energy and avoided the use of organic solvents, toxic reducing agents, or complex equipment, making it eco-friendly and scalable.

2.4. Electrochemical Sensor Design

A screen-printed gold electrode (SPGE) purchased from Metrohm Dropsens, Herisau, Switzerland, including a gold working electrode (diameter: 4 mm) integrated with a platinum auxiliary electrode and an Ag/AgCl pseudo-reference electrode, was employed for the sensor fabrication. Before modification, the electrode surface was thoroughly cleaned by sequential rinsing with absolute ethanol and distilled water, followed by drying under ambient conditions. After that, the surface was modified with the different prepared nanoparticles, separately.

Electrochemical characterization and measurements were conducted at room temperature using a potentiostat system (Ivium Technologies, Eindhoven, The Netherlands) housed in the Department of Chemistry, Faculty of Science, Majmaah University. Cyclic voltammetry (CV) was utilized to assess the electrochemical properties of the modified sensing surfaces in the presence of a standard redox couple, 5 mM [Fe(CN)₆]^{3−/4−} prepared in 0.1 M phosphate-buffered saline (PBS, pH 7.4). Following surface characterization, square-wave voltammetry (SWV) was employed for quantitative analysis. SWV parameters were: initial potential: −0.1 V; end potential: +0.5 V; step potential: 0.01 V; modulation amplitude: 0.05 V. The sensor was incubated in varying concentrations of ciprofloxacin, and SWV was subsequently performed to construct the calibration curve, enabling evaluation of the sensor's sensitivity and dynamic detection range.

For the electrochemical measurements, all experiments were repeated three times to ensure the reproducibility of the results.

3. Results and Discussion

3.1. Nanoparticles Synthesis

3.1.1. UV-Spectroscopy

To confirm the successful synthesis of Au@NPs, TiO₂@NPs, and AuTiO₂@NPs, UV-Visible spectroscopy was performed over a wavelength range of 200–800 nm. The UV-Vis absorption spectrum of *Punica granatum* peel extract, shown in Figure 1A, reveals a prominent peak at 280 nm and a secondary peak at 370 nm. These absorption features are attributed to the rich presence of bioactive compounds in the *Punica granatum* peel extract, including flavonoids (such as flavanols and anthocyanins), condensed tannins (e.g., proanthocyanidins), and hydrolysable tannins (e.g., ellagitannins and gallotannins), all of which contribute to strong absorbance in this spectral region. The observed peaks are consistent with those reported in the literature for *Punica granatum* peel extracts, validating the extract's composition [35,36].

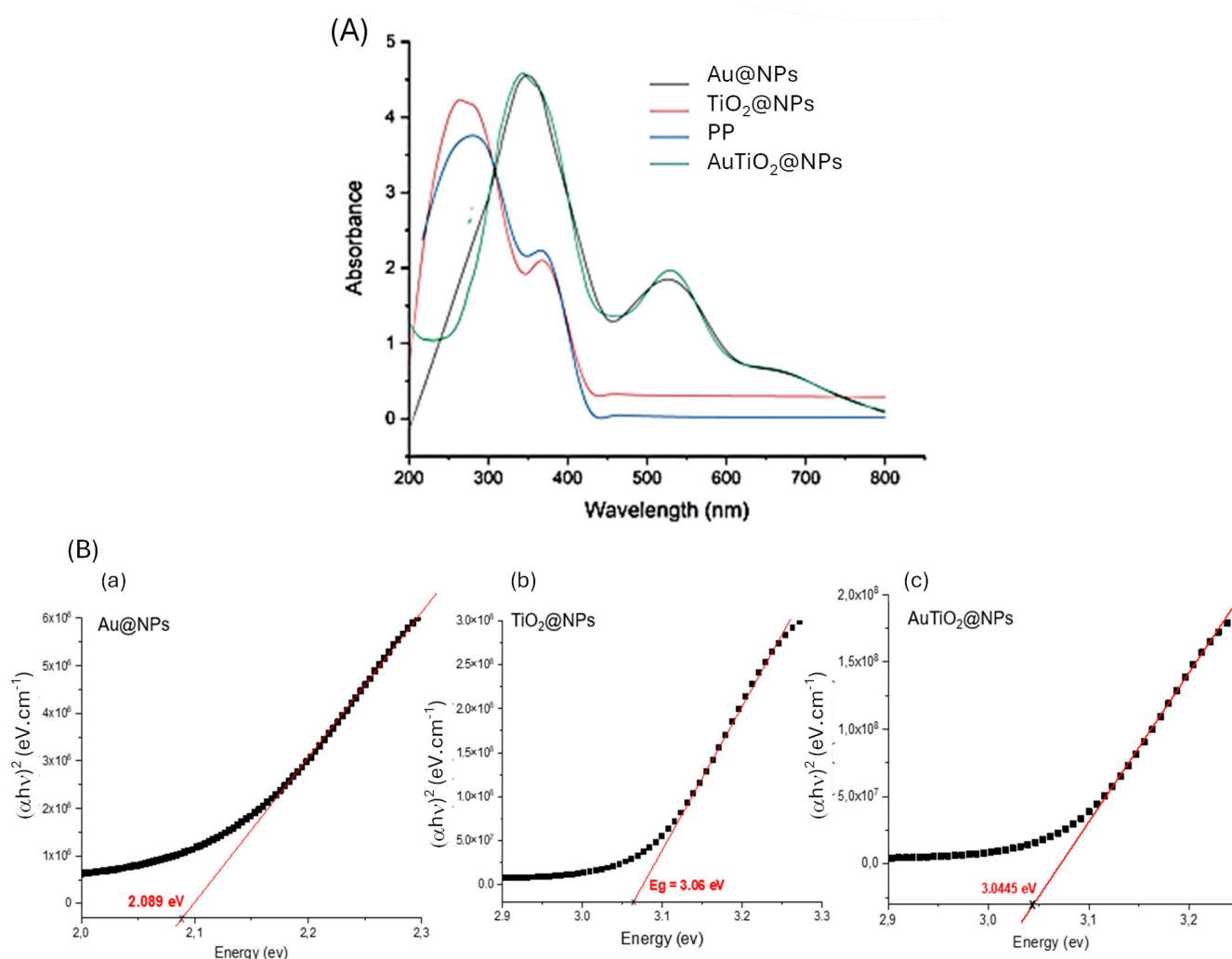


Figure 1. (A) UV Visible spectra of *Punica granatum* (PP), Au@NPs, TiO₂@NPs, and AuTiO₂@NPs in the wavelength range of 200–800 nm; and (B) Tauc plot of the $(\alpha h\nu)^2$ versus $h\nu$ plots: (a) Au@NPs, (b) TiO₂@NPs, and (c) AuTiO₂@NPs.

Following the synthesis of TiO₂@PP nanoparticles, a spectral shift and an increase in absorbance intensity were observed, indicating a successful nanoparticle coating. Polyphenols, flavonoids, and other phytochemicals in the extract act as in fact as coating and stabilizing agents, adsorbing onto the nanoparticle surface through hydrogen bonding or

coordination with surface titanium atoms. These interactions prevent particle agglomeration, enhance colloidal stability, and can slightly alter the electronic environment of TiO₂, leading to the observed spectral shifts. These findings align with those reported by H. M. Abdelmigid et al. [37], suggesting that the extract efficiently facilitates the stabilization of metal oxide. For the Au@NPs, the UV-Vis spectrum exhibited a characteristic band around 370 nm, which may be attributed to phytochemicals from *Punica granatum*, and a distinct band at 530 nm corresponding to the LSPR of gold nanoparticles, thereby confirming their successful formation. The LSPR peak is in agreement with previous studies by S. Bawazeer et al. [38] and S. S. Dash et al. [39]. Notably, the UV-Vis spectrum of the bimetallic AuTiO₂@NPs displayed similar absorption characteristics to that of AuTiO₂, reflecting the combined properties of the gold and titanium oxide components in the nanoparticle structure.

To provide insight into the material's potential functionality and its suitability for targeted electrochemical applications, an accurate determination of the band gap is essential. The optical band gap energy of the synthesized nanoparticles was estimated based on UV-Vis spectroscopy measurements using the Tauc method [40], as described by the following equation:

$$(\alpha h\nu)^n = A(h\nu - E_g) \quad (1)$$

In the given equation, α : absorption coefficient, $h\nu$: photon energy, E_g : band gap energy; n : constant depending on the type of transition (typically 2 for direct allowed, $\frac{1}{2}$ for indirect allowed transitions), and A : a constant.

The band gap was determined by extrapolating the linear region of the Tauc plot of the $(\alpha h\nu)^2$ versus $h\nu$ plots, as illustrated in Figure 1B. The resulting computations revealed that the Au@NPs, TiO₂@NPs, and AuTiO₂@NPs exhibited band gap energies of 2.089 eV, 3.06 eV, and 3.044 eV, respectively. The variation in the band gap energies for different nanoparticles could be attributed to differences in their composition and electronic interactions. The relatively low band gap of Au@NPs is associated with the localized surface plasmon resonance (LSPR) and interband transitions characteristic of metallic gold nanoparticles, which do not possess a conventional semiconductor band gap [41]. In contrast, TiO₂@NPs exhibit a band gap of 3.06 eV, consistent with the anatase phase of TiO₂, a wide bandgap semiconductor known for its strong UV absorption [42].

The slight reduction in the band gap for AuTiO₂@NPs (3.044 eV) compared to pure TiO₂ suggests a synergistic interaction between the gold and TiO₂ components. This interaction results from electronic coupling at the Au and TiO₂ interface, where gold nanoparticles can facilitate electron transfer from the conduction band of TiO₂ to the electrode and enhance light absorption through plasmonic effects. These results are in good agreement with those found by B. Y. Balarabe [43].

3.1.2. FTIR Characterization

Fourier-transform infrared (FTIR) spectroscopy was employed to identify the functional groups present in the samples based on their characteristic vibrational frequencies. All four FTIR spectra exhibited similar profiles, suggesting the presence of comparable functional groups across the samples, which are attributed to the phytochemical constituents of *Punica granatum* (Figure 2A). A broad absorption band around 3258 and 2936 cm^{−1} is attributed to O–H stretching vibrations from carboxylic acids, as well as C–H stretching vibrations typical of alkanes. A peak observed near 1708 cm^{−1} indicates the presence of C=O stretching vibrations, suggesting carbonyl-containing groups such as ketones, aldehydes, and carboxylic acids. The band at 1587 cm^{−1} is associated with C=C stretching in aromatic rings and N–H bending vibrations of primary amines. A distinct peak at 1437 cm^{−1} corresponds to C–H rocking in alkanes and may also indicate symmetric N=O

stretching in nitro compounds. Absorption at 1308 cm^{-1} is characteristic of C–O stretching, typically found in alcohols, carboxylic acids, esters, and ethers. Additionally, a band at 1193 cm^{-1} is indicative of C–N stretching vibrations in aliphatic amines. A peak around 1021 cm^{-1} can be attributed to N–H wagging in primary and secondary amines, as well as C–H out-of-plane bending in aromatic compounds.

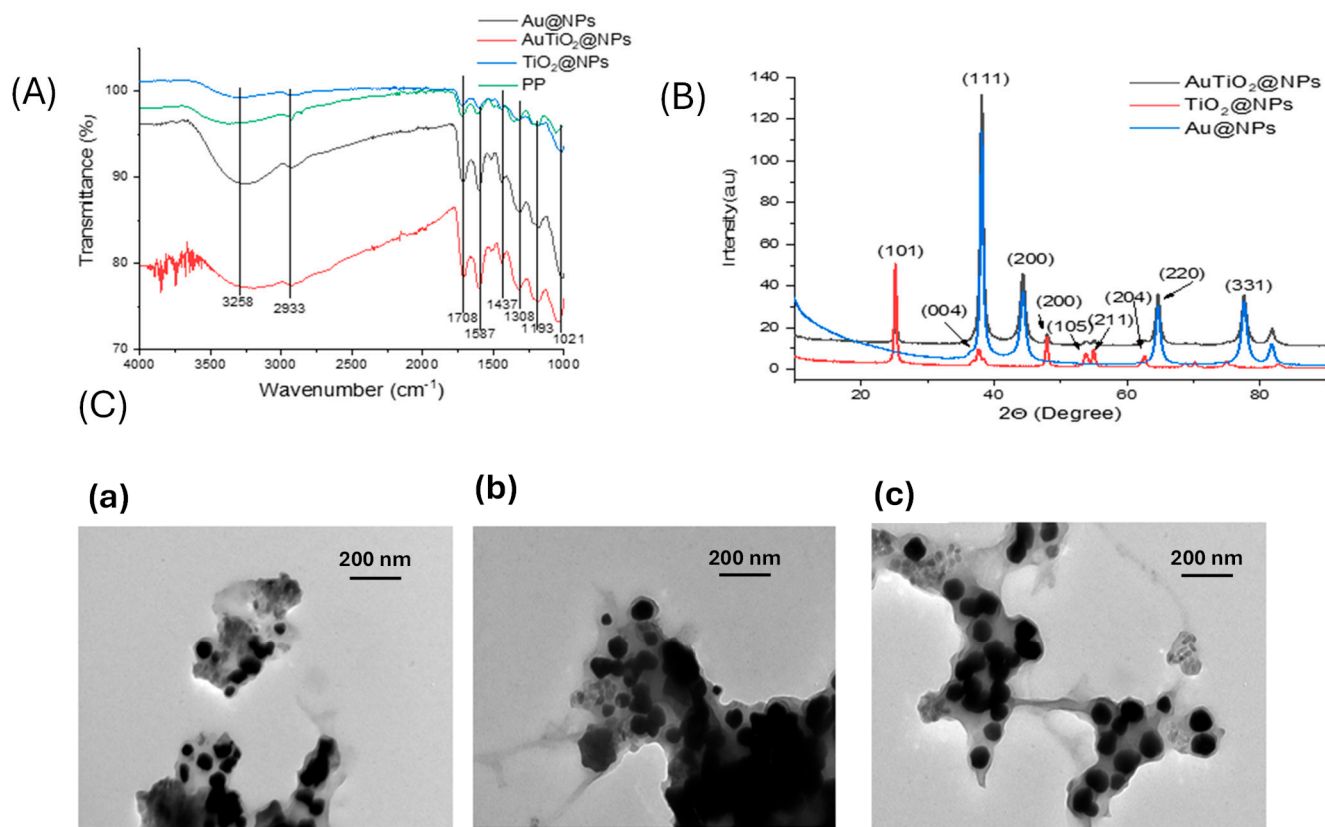


Figure 2. (A) FTIR spectra of *Punica granatum* (PP), Au@NPs, TiO₂@NPs and AuTiO₂@NPs in the range of wavenumber varied from 1000 to 4000 cm^{-1} ; (B) XRD of Au@NPs, TiO₂@NPs and AuTiO₂@NPs; (C) TEM spectra of: (a) Au@NPs; (b) TiO₂@NPs; and (c) AuTiO₂@NPs.

The observed functional groups are consistent with those reported in previous studies, confirming the presence of various organic compounds derived from *Punica granatum* [22,44]. The enhanced FTIR absorption intensity observed in the nanoparticle samples, compared to the *Punica granatum* extract alone, can be attributed to an increase in the vibrational dipole moment of these functional groups following nanoparticle synthesis. This enhancement results from strong interactions between the phytochemicals and the nanoparticle surfaces, leading to more pronounced IR-active vibrations, especially in the case of bimetallic nanoparticles.

3.1.3. X-Ray Diffraction

For evaluating the crystalline and phase structures of the prepared nanomaterials, Figure 2B presents the X-ray diffraction (XRD) pattern of the synthesized TiO₂ nanoparticles. The diffraction analysis revealed well-defined peaks at 2θ values of 25.5° , 37.7° , 48.1° , 53.8° , 54.9° , and 62.5° , which correspond to the (101), (004), (200), (105), (211), and (204) crystallographic planes, respectively. These reflections are in good agreement with the standard diffraction data for the anatase phase of TiO₂, as reported in previous studies [45] and confirmed by the Joint Committee on Powder Diffraction Standards (JCPDS) card No. 84-1285. The dominance of the (101) peak indicates that this plane is the

most thermodynamically stable and preferentially oriented during crystal growth. The absence of peaks related to the rutile or brookite phases suggests high phase purity of the anatase TiO_2 . This phase is particularly desirable due to its higher surface area and better charge carrier mobility. The XRD pattern of Au@NPs displays characteristic diffraction peaks at 2θ values of 38.2° , 44.3° , 64.2° and 77.9° , corresponding to the (111), (200), and (331) planes of face-centered cubic gold (Au), in accordance with the JCPDS card no. 04–0784. The XRD spectrum of $\text{AuTiO}_2\text{@NPs}$ exhibits all the diffraction peaks associated with Au@NPs , along with those of $\text{TiO}_2\text{@NPs}$, confirming the formation of a composite material. The presence of distinct diffraction peaks from both Au and TiO_2 indicates the coexistence of their respective crystalline phases in the final $\text{AuTiO}_2\text{@NPs}$ nanostructure, at the same angle as in the pure phase. These results confirm the successful incorporation of Au nanoparticles into the TiO_2 matrix, in agreement with the findings reported by Z. Duan et al. [46].

3.1.4. Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM)

The TEM image of Au@NPs (Figure 2C(a)) reveals well-dispersed, spherical gold nanoparticles with an average particle diameter of approximately 40 ± 5 nm. The particles exhibit a narrow size distribution and are predominantly monodisperse, confirming the high degree of uniformity achieved during synthesis. *Punica granatum* extract improves nucleation, avoids agglomeration, and improves stability, as already observed in green synthesis in the presence of other extracts [47].

In contrast, the TEM image of $\text{TiO}_2\text{@NPs}$ (Figure 2C(b)) displays spherical nanoparticles with a slightly broader size distribution compared to the gold nanoparticles, with an average diameter of 50 ± 7 nm. Although the TiO_2 nanoparticles are generally uniform in shape, a slight degree of aggregation is observed, which is typical for TiO_2 -based materials. The distinct contrast between the particles and the background confirms the crystalline nature of TiO_2 . Furthermore, the smooth surfaces of the particles suggest the predominance of the anatase phase, consistent with the XRD results.

The TEM image of $\text{AuTiO}_2\text{@NPs}$ (Figure 2C(c)) reveals a composite nanostructure with an average particle size of 60 ± 6 nm, where gold nanoparticles are closely integrated within the TiO_2 matrix, forming a core-shell or hybrid configuration. This morphology indicates the successful incorporation of Au into the TiO_2 framework. No significant aggregation of either component is observed, demonstrating the good stability and dispersion of the composite.

3.2. Sensor Design

3.2.1. Surface Characterization

Building on the physicochemical properties of the synthesized nanomaterials of Au@NPs , $\text{TiO}_2\text{@NPs}$, and $\text{AuTiO}_2\text{@NPs}$ nanoparticles and to ensure a more comparative investigation concerning the properties of monometallic and bimetallic nanoparticles in the enhancement of electrochemical signal, three different electrochemical sensors were developed by functionalizing screen-printed electrodes (SPGEs) with these nanomaterials. The electrochemical behavior of the electrodes, both before and after surface modification, was evaluated in a 0.1 M phosphate-buffered saline (PBS, pH 7.4) solution containing 5 mM of the redox couple $[\text{Fe}(\text{CN})_6]^{3-}/^{4-}$. To assess the electron transfer capability and electrical conductivity of the modified electrodes, cyclic voltammetry (CV) was performed (Figure 3). The cyclic voltammograms revealed an increase in peak current for the different surface modifications with the green nanoparticle electrode compared to the bare SPGE, indicating enhanced electron transfer kinetics.

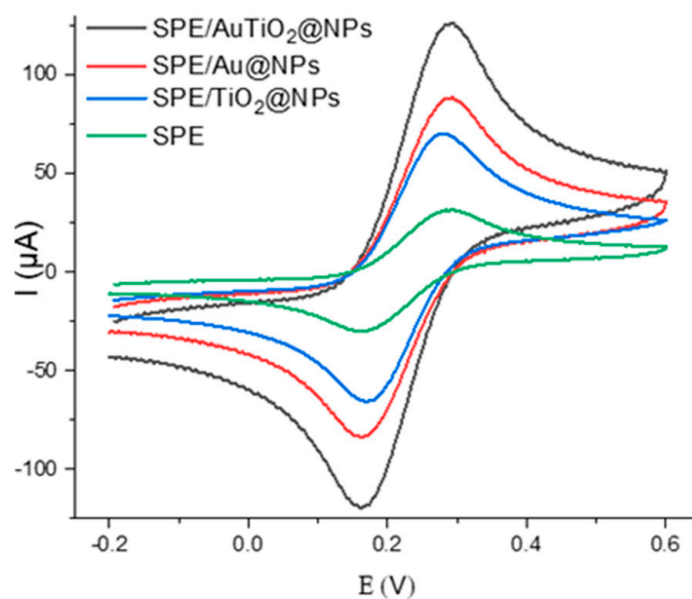


Figure 3. Cyclic voltammetry voltammograms of the gold surface before and after modification with Au@NPs, TiO₂@NPs, and AuTiO₂@NPs. All measurements are performed in 5 mM of [Fe(CN)₆]^{3−/4−} in PBS buffer (0.1 M).

Electrochemical measurements reveal that the peak current follows the trend AuTiO₂@NPs > Au@NPs > TiO₂@NPs, the bimetallic AuTiO₂ composite exhibiting the highest electrochemical response. This enhancement can be explained by the synergistic mechanism between gold and titanium dioxide at the nanoscale. Gold nanoparticles provide high electrical conductivity and excellent catalytic activity, which accelerate electron transfer [48].

3.2.2. Effect of the Supporting Electrolyte on the Electrochemical CIP Signal

To enhance the output signal of CIP oxidation, various buffers were tested, including PBS, acetate, borate, and Tris, alongside surface modifications using Au@NPs, TiO₂@NPs, and AuTiO₂@NPs. The results indicate that the electrochemical response of CIP is significantly superior when the surface is modified with AuTiO₂@NPs across all tested electrolytes. This enhancement can be attributed to the synergistic effects between gold and titanium dioxide at the nanoscale. Gold nanoparticles (AuNPs) contribute high electrical conductivity and excellent catalytic activity, enabling rapid electron transfer. On the other hand, TiO₂, as a semiconductor, exhibits a strong adsorption capacity for polar and charged molecules like CIP, particularly through surface hydroxyl groups that facilitate hydrogen bonding and electrostatic interactions. Among the different surface modifications tested, PBS emerges as the optimal supporting electrolyte for electrochemical CIP detection. CIP, an amphoteric fluoroquinolone antibiotic, exhibits pH-dependent electrochemical behavior, with its electroactive form predominating near physiological pH (6.5–7.5) [49–51]. PBS maintains a stable pH in the range of 7.0–7.4, where both ionizable groups of CIP, the carboxyl and piperazinyl moieties, are optimally protonated/deprotonated to contribute to well-defined redox activity, thereby enhancing detection sensitivity. In contrast, other buffers such as acetate (pH 3.6–5.6) tend to protonate CIP excessively, suppressing its redox response [49–51]. Borate buffer (pH 8.0–10.0), on the other hand, may lead to full deprotonation of CIP and altered adsorption behavior on the sensor surface [49–51]. Tris buffer is also less suitable, as it is known to interact with metal oxide surfaces and can inhibit electron transfer [52]. PBS, by comparison, is electrochemically inert and does not interfere with the active sites of Au or TiO₂. Its high ionic strength supports efficient charge

transport, while its chemical stability minimizes surface passivation. PBS was then selected for CIP detection.

3.2.3. CIP Detection

The sensing performance of various sensors toward ciprofloxacin (CIP) was evaluated using square wave voltammetry (SWV). The sensors were incubated in CIP solutions at different concentrations for 30 min before measurement. To avoid overcrowding the figure, we present only the SWV voltammograms recorded at varying CIP concentrations in the case of a sensor functionalized with AuTiO₂@NPs, as the oxidation profiles for CIP were similar across the different sensors. All measurements were performed in triplicate, showing a relative standard deviation (RSD) below 5%. An electrochemical signal for CIP was observed at 0.18 V (Figure 4a) [53].

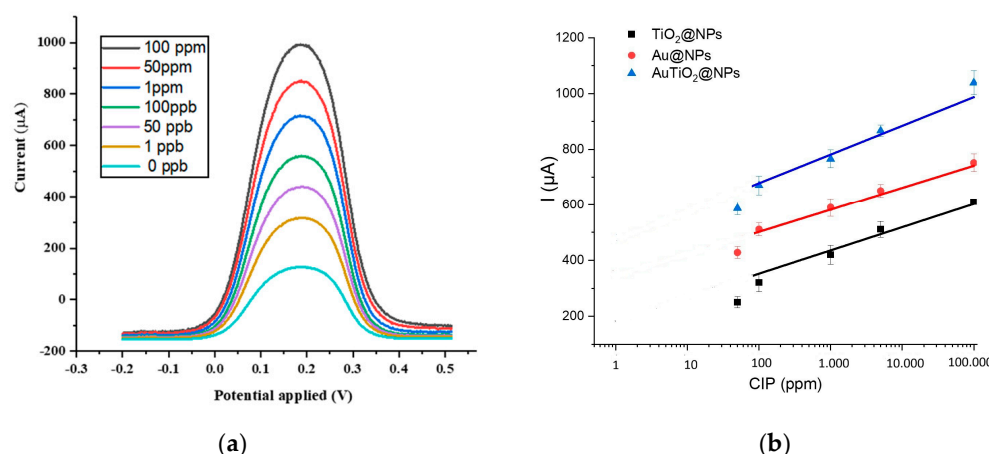


Figure 4. (a) SWV voltammograms variation versus different CIP concentrations for the sensor functionalized AuTiO₂@NPs. Measurements are recorded in PBS buffer (pH = 7.4), and (b) Current variation versus different concentration variation for the sensor functionalized Au@NPs, TiO₂@NPs, and AuTiO₂@NPs.

As the CIP concentration increased, a corresponding rise in the oxidation current was recorded.

For better visualization, the current intensity variation for different sensors versus different CIP concentrations is presented in Figure 4b. A linear relationship was observed in the case of the different sensors, demonstrating the sensor's capability for quantitative detection. Limits of detection (LOD), linear range, and sensitivity values for the different sensors are presented in Table 1.

Table 1. Sensitivities, linear ranges and LODs of Au@NPs, TiO₂@NPs, and AuTiO₂@NPs based sensors.

Nanomaterial	Sensitivity (μA/ppm)	Linear Range (μM)	LOD	R ²
TiO ₂ @NPs	79.69 ± 6.63	3 × 10 ^{−1} to 3 × 10 ²	0.8 ppb 2.4 × 10 ^{−9} M,	0.97
Au@NPs	83.39 ± 6.39	3 × 10 ^{−1} to 3 × 10 ²	0.8 ppb 2.4 × 10 ^{−9} M	0.97
AuTiO ₂ @NPs	102.96 ± 6.39	3 × 10 ^{−1} to 3 × 10 ²	0.2 ppb 0.64 × 10 ^{−9} M	0.98

The combination of two metallic nanoparticles enhances the electrical conductivity and electrochemical activity of the sensor, leading to a lower LOD and higher sensitivity compared to the individual components.

The sensors developed in this study (Au@NPs, TiO₂@NPs, and AuTiO₂@NPs) exhibit highly competitive performance compared to previously reported systems: large linear dynamic range and low detection limits, the SPGE/AuTiO₂@NPs showing the most promising analytical characteristics (Table 2).

Table 2. Comparison with previously published electrochemical sensors for ciprofloxacin detection (receptor type, linear range, and LOD).

Receptor Nature	Receptor	Range (μM)	LOD (nM)	Refs
Biological receptors	dsDNA	0.1 to 100	10 ²	[54]
Molecularly imprinted polymer	MIP/rGO/GCE	0.001 to 0.5	0.052	[55]
Chemical nanomaterials	AuNPs/AC/GCE	0.5×10^3 to 25×10^3	0.20	[56]
	eCNF/CNT/NiCo/GCE	-	6.0×10^3	[57]
	Ca ₂ CuO ₃ NS/GCE	0.05 to 0.8	0.012	[58]
	TiO ₂ /PVA/GCE	10 to 120	40	[59]
	EGr/GC	-	1	[60]
	V ₂ O ₅ /SPE	-	0.01	[61]
	ERGO/PANI/PARS/SPCE	0.01 to 69.8	2.1	[62]
Green nanomaterials	AgNPs/C black/GCE	3×10^3 – 1.3×10^5	480	[34]
	TiO ₂ @ NPs/SPE	3×10^{-1} to 3×10^2	2.41	The present work
	Au@NPs/SPE		1.81	
	AuTiO ₂ @ NPs/SPE		0.64	

3.2.4. Stability and Repeatability

The operational and storage stability of the modified electrodes was systematically investigated. Operational stability was examined through repeated electrochemical measurements, where the AuTiO₂@NP-based sensor maintained over 95% of its initial current response after 20 continuous measurement cycles, demonstrating strong resistance to surface fouling and signal degradation. Long-term stability was evaluated by storing the modified electrodes at room temperature and periodically recording their electrochemical response toward CIP. After 14 days of storage, the sensor retained approximately 92% of its original response, indicating satisfactory stability and durability. The good stability can be attributed to the strong interaction between the bimetallic nanoparticles and the electrode surface, as well as the stabilizing effect of the *Punica granatum* extract used during green synthesis.

The repeatability of the developed electrochemical sensors was evaluated by performing consecutive measurements of ciprofloxacin (CIP) at a fixed concentration under identical experimental conditions using the same modified electrode. For the AuTiO₂@NP-modified electrode, the peak current response showed minimal variation over 20 successive SWV measurements, retaining more than 95% of the initial signal intensity. The relative standard deviation (RSD) of the recorded peak currents was below 3.5%, indicating excellent repeatability and reliable sensor response. To further assess fabrication reproducibility, five independently prepared AuTiO₂@NP-modified electrodes were tested toward CIP detection. The obtained current responses exhibited good consistency, with an RSD of less than 4%, confirming the robustness of the electrode modification procedure.

3.2.5. Selectivity Measurements

The selectivity of the Au@NPs, TiO₂@NPs, and AuTiO₂@NPs sensors against antibiotics such as norfloxacin (similar to ciprofloxacin), amoxicillin, tetracycline, sulfamethoxazole, and chloramphenicol was evaluated at a fixed concentration of 1 ppb (Figure 5). The sensors exhibited good selectivity, with the AuTiO₂@NPs-functionalized sensor. Norfloxacin, a quinolone antibiotic, differs from ciprofloxacin primarily in the side chain at position 7 (piperazine in ciprofloxacin vs. a methyl group in norfloxacin) and the presence of a cyclopropyl group in ciprofloxacin. These structural differences result in norfloxacin having a relatively higher oxidation potential compared to ciprofloxacin, which enhances the sensor's selectivity towards CIP in the applied potential range.

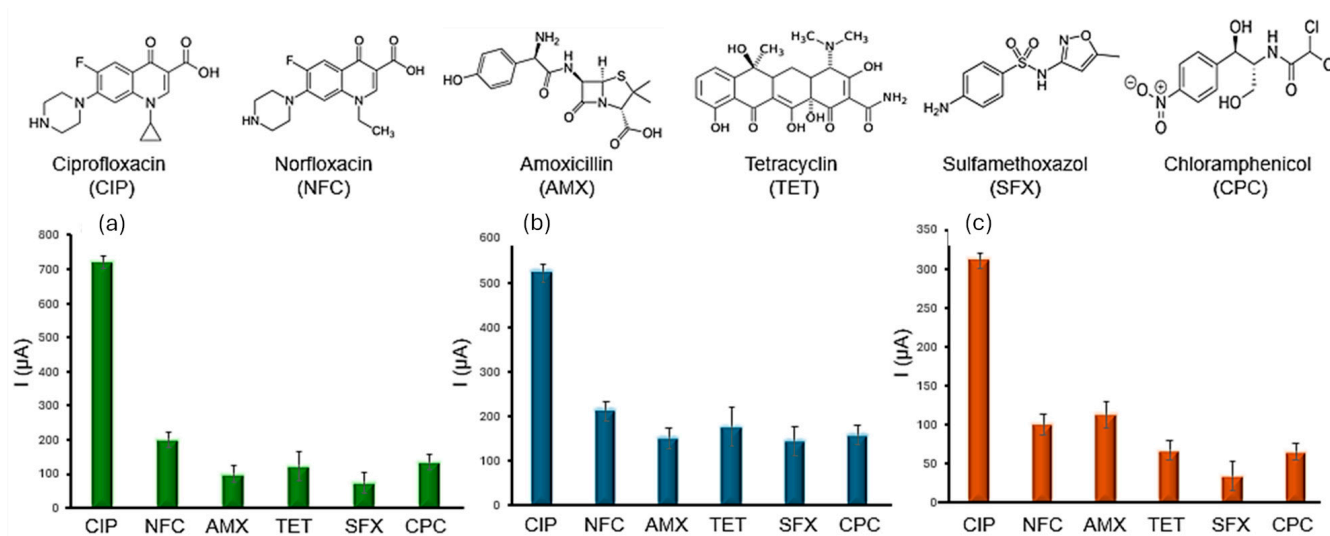


Figure 5. Sensor selectivity measurements: (a) Response toward interfering antibiotics for the sensor modified with Au@NPs; (b) Response toward interfering antibiotics for the sensor modified with TiO₂@NPs; (c) Response toward interfering antibiotics for the sensor modified with AuTiO₂@NPs. All measurements were recorded in PBS buffer (pH 7.4) at a fixed concentration of 1 ppb for each molecule.

Amoxicillin (a β -lactam antibiotic), tetracycline, sulfamethoxazole, and chloramphenicol (aromatic structures with nitrogen-containing groups) require higher potentials for detection. Overall, the different sensors, particularly the AuTiO₂@NPs sensor, demonstrate the highest selectivity and sensitivity across a broad range of antibiotics. This enhanced performance is attributed to the combined catalytic and conductive properties of the AuTiO₂@NPs, making it the most efficient platform for the electrochemical sensing of ciprofloxacin (CIP).

3.2.6. Validation in Real Samples

Table 3 compares the analytical performance of the three nanoparticle-modified sensors, Au@NPs, TiO₂@NPs, and AuTiO₂@NPs, based on recovery rates and reproducibility (RSD%) for ciprofloxacin detection in tap water and wastewater at three concentration levels. In tap water, the bimetallic AuTiO₂@NPs sensor demonstrated the most consistent and accurate recovery values across all concentrations (98%) with low RSDs (1.1–3.8%), indicating excellent analytical precision and matrix tolerance. In a more complex matrix such as wastewater, the AuTiO₂@NPs sensor again maintained strong performance, achieving recoveries between 101% and 108% with RSDs below 4%, indicating good robustness under real-world conditions.

Table 3. Sensor’s validation in real samples.

	Sensor Nature	Spiked Concentration (ppm)	Recovered Concentration (ppm)	Recovery (%) ($n = 3$)	RSD (%)
Tapwater	Au@NPs	50	47.2	95	1.8
		100	89.9	90	3.3
		500	479.1	96	1.6
	TiO ₂ @NPs	50	52.4	105	1.8
		100	110.5	116	3.3
		500	520.3	105	2.1
	AuTiO ₂ @NPs	50	49.1	98	3.8
		100	98.4	98	1.3
		500	489.9	98	1.1
Wastewater	Au@NPs	50	51.4	103	1.7
		100	108.5	109	2.2
		500	512.3	102	1.6
	TiO ₂ @NPs	50	53.4	107	1.0
		100	109.5	110	2.9
		500	514.3	103	1.1
	AuTiO ₂ @NPs	50	50.4	101	1.8
		100	107.5	108	3.9
		500	511.3	102	3.6

Bimetallic AuTiO₂@NPs, combining high accuracy, excellent reproducibility, and low matrix effect, confirm the synergistic advantage of the green combination of hybrid nanomaterial in electrochemical detection of ciprofloxacin.

4. Conclusions

The present study provides a pioneering comparative investigation into the green synthesis of monometallic (Au@NPs, TiO₂@NPs) and bimetallic (AuTiO₂@NPs) nanoparticles using *Punica granatum* extract, with a focus on their application in the electrochemical detection of ciprofloxacin (CIP) as a model pharmaceutical contaminant. Electrochemical studies using cyclic voltammetry (CV) and square wave voltammetry (SWV) demonstrated that all nanoparticle-modified electrodes significantly enhanced the analytical response toward CIP compared to the bare SPGE. The sensors exhibited excellent performance, with a lower limit of detection for AuTiO₂@NPs (LOD = 0.2 ppb). The superior performance of the bimetallic AuTiO₂@NPs is attributed to the synergistic combination of gold’s high conductivity and catalytic efficiency with TiO₂’s large surface area and adsorption capability. Importantly, the sensors demonstrated high selectivity and reliable performance in real water samples, highlighting their practical utility for trace-level pharmaceutical monitoring. Overall, these findings emphasize the potential of green-synthesized bimetallic nanoparticle platforms as sensitive, sustainable, and cost-effective tools for environmental electrochemical sensing. Future work could explore extending this green synthetic strategy to other metal or metal oxide systems and integrating these materials into portable, on-site devices for real-time environmental monitoring.

Author Contributions: Conceptualization, A.C. and S.N.; methodology, M.B.E.; software, S.M.A.A.; validation, B.M., and M.B.E.; formal analysis, A.C.; investigation, S.N.; resources, M.B.E.; data curation, L.M.A.; writing—original draft preparation, A.C.; writing—review and editing, H.B.H.; visualization, N.J.-R.; supervision, N.J.-R.; project administration, H.B.H.; funding acquisition, N.J.-R. All authors have read and agreed to the published version of the manuscript.

Funding: The author extends appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research work through the project number ER-2025-2254.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Emmanuel, S.S.; Adesibikan, A.A.; Saliu, O.D.; Opatola, E.A. Greenly biosynthesized bimetallic nanoparticles for ecofriendly degradation of notorious dye pollutants: A review. *Plant Nano Biol.* **2023**, *3*, 100024. [\[CrossRef\]](#)
- Wu, T.; Li, Y.; Zhang, Z.; Zhang, D.; Dragoi, E.N.; Karimi-Maleh, H. 3D Print-Based Polypyrrole/TiVCTx/UiO-66 Composites for Effective Adsorption of Combined Pollutants in Water Media. *J. Nanostruct. Chem.* **2025**, *15*, 16958. [\[CrossRef\]](#)
- Wu, T.; Karimi-Maleh, H.; Li, Y.; Zhang, D.; Zhang, Z.; Zhong, N.; Wen, Y.; Aminabhavi, T.M. 3D printed porous chitosan/metal-organic framework composites as effective adsorbents to remove heavy metals from wastewater. *Chem. Eng. J.* **2024**, *493*, 152780. [\[CrossRef\]](#)
- Chrouda, A. A novel electrochemical sensor based on sodium alginate-decorated single-walled carbon nanotubes for the direct electrocatalysis of heavy metal ions. *Polym. Eng. Sci.* **2023**, *34*, 1807–1816. [\[CrossRef\]](#)
- Lunghi, C.; Valetto, M.R.; Caracciolo, A.B.; Bramke, I.; Caroli, S.; Bottoni, P.; Castiglioni, S.; Crisafulli, S.; Cuzzolin, L.; Deambrosis, P.; et al. Call to action: Pharmaceutical residues in the environment: Threats to ecosystems and human health. *Drug Saf.* **2024**, *48*, 315–320. [\[CrossRef\]](#)
- Samal, K.; Mahapatra, S.; Ali, M.H. Pharmaceutical wastewater as Emerging Contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus* **2022**, *6*, 100076. [\[CrossRef\]](#)
- Cui, C.; Xu, M.; Guan, Q.; Wang, X.; Yang, G.; Zhang, Z.; Du, J. Electrochemical detection of alpha-fetoprotein using graphene-assisted sensors: A novel approach for liver cancer screening. *Alex. Eng. J.* **2025**, *123*, 511–518. [\[CrossRef\]](#)
- Jia, L.; Lei, Z.; Zare, N.; Wu, T.; Ghalkhani, M.; Wan, L.; Xu, Y. Ti₃C₂ MXene-Enhanced Electrochemical Biosensors for Prostate-Specific Antigen (PSA) Detection in Prostate Cancer. *J. Nanostruct. Chem.* **2025**, *15*, 1–10.
- Bounegru, A.V.; Iacob, A.D.; Iticescu, C.; Georgescu, P.L. Electrochemical Sensors and Biosensors for the Detection of Pharmaceutical Contaminants in Natural Waters—A Comprehensive Review. *Chemosensors* **2025**, *13*, 65. [\[CrossRef\]](#)
- Kumar, H.; Kumari, R.; Singh, D.; Mangla, B. Advances in nanomaterials based electrochemical sensors for rapid detection of food additives: A comprehensive review. *TrAC Trends Anal. Chem.* **2024**, *181*, 118011. [\[CrossRef\]](#)
- Mandvi, Singh, P.P.; Ballal, S.; Chahar, M.; Bansal, J.; Kumar, R.; Kumar, S.; Kaushal, S.; Gautam, M.; Singh, R. Construction of a 3D flower-like NiO/Mn₃O₄ heterojunction using Tulsi leaf extract for enhanced photodegradation of thiamethoxam pesticide and organic dyes under direct sunlight. *Mater. Adv.* **2024**, *5*, 8097–8110. [\[CrossRef\]](#)
- Bano, K.; Kaushal, S.; Lal, B.; Joshi, S.K.; Kumar, R.; Singh, P.P. Fabrication of CuO/ZnO heterojunction photocatalyst for efficient photocatalytic degradation of tetracycline and ciprofloxacin under direct sun light. *Environ. Environ. Nanotechnol. Monit. Manag.* **2023**, *20*, 100863. [\[CrossRef\]](#)
- Kaushal, S.; Singh, P.P.; Kaur, N. Metal organic framework-derived Zr/Cu bimetallic photocatalyst for the degradation of tetracycline and organic dyes. *Environ. Nanotechnol. Monit. Manag.* **2022**, *18*, 100727. [\[CrossRef\]](#)
- Gao, Y.; Wang, Y.; Jiang, J.; Wei, P.; Sun, H. Triggered ‘On/Off’ Luminescent Polypeptide Bowl-Shaped Nanoparticles for Selective Lighting of Tumor Cells. *Small* **2025**, *21*, e2411432. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ayesh, A.I.; Qamhieh, N.; Mahmoud, S.T.; Alawadhi, H. Fabrication of size-selected bimetallic nanoclusters using magnetron sputtering. *J. Mater. Res.* **2012**, *27*, 2441–2446. [\[CrossRef\]](#)
- Abdelsayed, V.; Glaspell, G.; Nguyen, M.; Howe, J.M.; El-Shall, M.S. Laser synthesis of bimetallic nanoalloys in the vapor and liquid phases and the magnetic properties of PdM and PtM nanoparticles (M = Fe, Co and Ni). *Faraday Discuss.* **2008**, *138*, 163–180. [\[CrossRef\]](#)
- Bhol, P.; Bhavya, M.B.; Swain, S.; Saxena, M.; Samal, A.K. Modern Chemical Routes for the Controlled Synthesis of Anisotropic Bimetallic Nanostructures and Their Application in Catalysis. *Front. Chem.* **2020**, *8*, 357. [\[CrossRef\]](#)
- Johnson, H.M.; Dasher, A.M.; Monahan, M.; Seifert, S.; Moreau, L.M. Mapping the effects of physical and chemical reduction parameters on local atomic distributions within bimetallic nanoparticles. *Nanoscale* **2022**, *14*, 4519. [\[CrossRef\]](#)
- Hansen, H.E.; Fakhri, D.; Seland, F.; Sunde, S.; Burheim, O.S.; Pollet, B.G. Sonochemical Synthesis of Cu@Pt Bimetallic Nanoparticles. *Molecules* **2022**, *27*, 5281. [\[CrossRef\]](#)
- Nyabadza, A.; McCarthy, É.; Makhesana, M.; Heidarinassab, S.; Plouze, A.; Vazquez, M.; Brabazon, D. A review of physical, chemical and biological synthesis methods of bimetallic nanoparticles and applications in sensing, water treatment, biomedicine, catalysis and hydrogen storage. *Adv. Colloid Interface Sci.* **2023**, *321*, 103010. [\[CrossRef\]](#) [\[PubMed\]](#)

21. Kazemi, S.; Hosseingholian, A.; Gohari, S.; Feirahi, F.; Moammeri, F.; Mesbahian, G.; Moghaddam, Z.; Ren, Q. Recent advances in green synthesized nanoparticles: From production to application. *Mater. Today Sustain.* **2023**, *24*, 100500. [\[CrossRef\]](#)
22. Ün, Ş.Ş.; Ünlü, A.; Ün, İ.; Ok, S. Green synthesis, characterization and catalytic activity evaluation of palladium nanoparticles facilitated by *Punica granatum* peel extract. *Inorg. Nano-Met. Chem.* **2021**, *51*, 1232–1240. [\[CrossRef\]](#)
23. Osman, A.I.; Zhang, Y.; Farghali, M.; Rashwan, A.K.; Eltaweil, A.S.; El-Monaem, E.M.A.; Mohamed, I.M.A.; Badr, M.M.; Ihara, I.; Rooney, D.W.; et al. Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environ. Chem. Lett.* **2024**, *22*, 841–887. [\[CrossRef\]](#)
24. Ramos, R.M.C.R.; Regulacio, M.D. Controllable Synthesis of Bimetallic Nanostructures Using Biogenic Reagents: A Green Perspective. *ACS Omega* **2021**, *6*, 7212–7228. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Idris, D.S.; Roy, A. Synthesis of Bimetallic Nanoparticles and Applications—An Updated Review. *Crystals* **2023**, *13*, 637. [\[CrossRef\]](#)
26. Rani, J.; Goyal, T.; Kaur, A.; Ganesan, S.; Sharma, A.K.; Chauhan, A.S.; Kaushal, S.; Kumar, S. Bimetallic nanoparticles as pioneering eco-friendly catalysts for remediation of pharmaceuticals and personal care products (PPCPs). *Nanoscale Adv.* **2025**, *7*, 3160–3188. [\[CrossRef\]](#)
27. Dlamini, N.G.; Basson, A.K.; Pullabhotla, V.S.R. Synthesis and Characterization of Various Bimetallic Nanoparticles and Their Application. *Appl. Nano* **2023**, *4*, 1–24. [\[CrossRef\]](#)
28. Larrañaga-Tapia, M.; Betancourt-Tovar, B.; Videa, M.; Antunes-Ricardo, M.; Cholula-Díaz, J.L. Green synthesis trends and potential applications of bimetallic nanoparticles towards the sustainable development goals 2030. *Nanoscale Adv.* **2023**, *6*, 51–71. [\[CrossRef\]](#)
29. Jamil, N.; Ali, H.M.S.; Yasir, M.; Hamza, M.; Sagheer, M.; Ahmed, T.; Kanwal, Q.; Bukhari, A.; Al-Ahmary, K.M.; Ahmed, M. Biosynthesized Metallic and Bimetallic Nanoparticles as Effective Biocides for Plant Protection: Plausible Mechanisms and Challenges. *J. Chem.* **2024**, *2024*, 3328223. [\[CrossRef\]](#)
30. Lin, H.; Liu, Y.; Deng, J.; Jing, L.; Wang, Z.; Wei, L.; Wei, Z.; Hou, Z.; Tao, J.; Dai, H. Bimetallic nanoparticles: Advances in fundamental investigations and catalytic applications. *Environ. Sci. Adv.* **2024**, *4*, 33–56. [\[CrossRef\]](#)
31. Selvaraj, A.; Mukundamurthy, K.; Rajmohan, R.; Tamizhdurai, P. Simple one pot green synthesis of silver-palladium bimetallic nanoparticles: A fluorescent turn-off sensor for detection of lead ions in environmental water and its photocatalytic activity. *S. Afr. J. Chem. Eng.* **2025**, *52*, 243–257. [\[CrossRef\]](#)
32. Zhao, L.; Wang, Y.; Zhao, X.; Deng, Y.; Li, Q.; Xia, Y. Green preparation of Ag–Au bimetallic nanoparticles supported on graphene with alginate for non-enzymatic hydrogen peroxide detection. *Nanomaterials* **2018**, *8*, 507. [\[CrossRef\]](#)
33. Bekmezci, M.; Ozturk, H.; Akin, M.; Bayat, R.; Sen, F.; Darabi, R.; Karimi-Maleh, H. Bimetallic Biogenic Pt–Ag Nanoparticle and Their Application for Electrochemical Dopamine Sensor. *Biosensors* **2023**, *13*, 531. [\[CrossRef\]](#)
34. Meireles, L.M.; Silva, R.M.; da Silva, R.C.; Okumura, L.L.; Moreira, R.P.L.; Silva, T.A. Low-cost electrochemical sensor for ciprofloxacin antibiotic based on green-synthesized silver nanoparticles and carbon black. *J. Solid State Electrochem.* **2025**, *29*, 3111–3122. [\[CrossRef\]](#)
35. Farouk, S.M.; Abu-Hussien, S.H.; Abd-Elhalim, B.T.; Mohamed, R.M.; Arabe, N.M.; Hussain, A.A.T.; Mostafa, M.E.; Hemdan, B.; El-Sayed, S.M.; Bakry, A.; et al. Biosynthesis and characterization of silver nanoparticles from *Punica granatum* (pomegranate) peel waste and its application to inhibit foodborne pathogens. *Sci. Rep.* **2023**, *13*, 19469. [\[CrossRef\]](#)
36. Saminathan, U.; Ramasamy, P.; Chinathambi, A.; Paramasivam, S.; Vadamalai, S.; Chinnaiyan, U.; Singh, R. Synthesis, characterization of silver nanoparticles from *Punica granatum* L. and its in vitro antidiabetic activity. *Nanotechnol. Environ. Eng.* **2022**, *7*, 923–930. [\[CrossRef\]](#)
37. Abdelmigid, H.M.; Alyamani, A.A.; Hussien, N.A.; Morsi, M.M.; Alhumaidi, A. Integrated Approaches for Adsorption and Incorporation Testing of Green-Synthesized TiO₂NPs Mediated by Seed-Priming Technology in *Punica granatum* L. *Agronomy* **2022**, *12*, 1601. [\[CrossRef\]](#)
38. Bawazeer, S.; Rauf, A.; Nawaz, T.; Khalil, A.A.; Javed, M.S.; Muhammad, N.; Shah, M.A. *Punica granatum* peel extracts mediated the green synthesis of gold nanoparticles and their detailed in vivo biological activities. *Green Process. Synth.* **2021**, *10*, 882–892. [\[CrossRef\]](#)
39. Dash, S.S.; Bag, B.G. Synthesis of gold nanoparticles using renewable *Punica granatum* juice and study of its catalytic activity. *Appl. Nanosci.* **2014**, *4*, 55–59. [\[CrossRef\]](#)
40. Cao, J.; Xu, B.; Lin, H.; Luo, B.; Chen, S. Chemical etching preparation of BiOI/BiOBr heterostructures with enhanced photocatalytic properties for organic dye removal. *Chem. Eng. J.* **2012**, *185*, 91–99. [\[CrossRef\]](#)
41. Lyu, P.; Espinoza, R.; Nguyen, S.C. Photocatalysis of Metallic Nanoparticles: Interband vs Intraband Induced Mechanisms. *J. Phys. Chem. C* **2023**, *127*, 15685–15698. [\[CrossRef\]](#)
42. Soldo-Olivier, Y.; Abisset, A.; Bailly, A.; De Santis, M.; Garaudée, S.; Lacipiere, J.; Coati, A.; Garreau, Y.; Saint-Lager, M.-C. Localized surface plasmon resonance of Au/TiO₂(110): Substrate and size influence from in situ optical and structural investigation. *Nanoscale Adv.* **2020**, *2*, 2448–2461. [\[CrossRef\]](#)

43. Balarabe, B.Y. Green synthesis of gold-titania nanoparticles for sustainable ciprofloxacin removal and phytotoxicity evaluation on aquatic plant growth. *Hybrid Adv.* **2023**, *4*, 100107. [[CrossRef](#)]
44. Kumar, M.; Dandapat, S.; Ranjan, R.; Kumar, A.; Sinha, M.P. Plant mediated synthesis of silver nanoparticles using *Punica granatum* aqueous leaf extract. *J. Microbiol. Exp.* **2018**, *6*, 175–178. [[CrossRef](#)]
45. Ahmad, M.M.; Mushtaq, S.; Al Qahtani, H.S.; Sedky, A.; Alam, M.W. Investigation of TiO₂ nanoparticles synthesized by sol-gel method for effectual photodegradation, oxidation and reduction reaction. *Crystals* **2021**, *11*, 1456. [[CrossRef](#)]
46. Duan, Z.; Huang, Y.; Zhang, D.; Chen, S. Electrospinning Fabricating Au/TiO₂ Network-like Nanofibers as Visible Light Activated Photocatalyst. *Sci. Rep.* **2019**, *9*, 8008. [[CrossRef](#)]
47. Mahdi, H.S.; Parveen, A.; Bahadur, J.; Singh, S.; Azam, A. A facile biosynthesis approach for development of eco-friendly stable gold nanoparticles. *Mater. Lett.* **2026**, *406*, 139859. [[CrossRef](#)]
48. Duya, C.O.; Okumu, F.O.; Matoetoe, M.C. The electrochemical properties of bimetallic silver-gold nanoparticles nano film's. *Heliyon* **2024**, *10*, e36974. [[CrossRef](#)]
49. Samee, W.; Tadtong, S.; Eiamart, W.; Singwiset, P.; Yingyomsarn, S.; Nunthanavanit, P. Impact of Vehicle Composition on Solubility, Autoclave Sterilization Stability, and Antibacterial Activity of Ciprofloxacin Hydrochloride Ear Drops. *Int. J. Mol. Sci.* **2025**, *26*, 4458. [[CrossRef](#)]
50. Bizi, M.; El Bachra, F.E. Evaluation of the ciprofloxacin adsorption capacity of common industrial minerals and application to tap water treatment. *Powder Technol.* **2020**, *362*, 323–333. [[CrossRef](#)]
51. Jalil, M.E.R.; Baschini, M.; Sapag, K. Influence of pH and antibiotic solubility on the removal of ciprofloxacin from aqueous media using montmorillonite. *Appl. Clay Sci.* **2015**, *114*, 69–76. [[CrossRef](#)]
52. YazdanYar, A.; Buswell, L.; Pantaloni, D.; Aschauer, U.; Bowen, P. Interactions of Tris with rutile surfaces and consequences for in vitro bioactivity testing. *Open Ceram.* **2021**, *7*, 100173. [[CrossRef](#)]
53. Chuiprasert, J.; Srinives, S.; Boontanon, N.; Polprasert, C.; Ramungul, N.; Karawek, A.; Boontanon, S.K. Ciprofloxacin Electrochemical Sensor Using Copper-Iron Mixed Metal Oxides Nanoparticles/Reduced Graphene Oxide Composite. *ACS Omega* **2024**, *9*, 23172–23183. [[CrossRef](#)]
54. Lim, S.A.; Ahmed, M.U. A simple DNA-based electrochemical biosensor for highly sensitive detection of ciprofloxacin using disposable graphene. *Anal. Sci.* **2016**, *32*, 687–693. [[CrossRef](#)]
55. Chuiprasert, J.; Srinives, S.; Boontanon, N.; Polprasert, C.; Ramungul, N.; Lertthanaphol, N.; Karawek, A.; Boontanon, S.K. Electrochemical Sensor Based on a Composite of Reduced Graphene Oxide and Molecularly Imprinted Copolymer of Polyaniline–Poly(o-phenylenediamine) for Ciprofloxacin Determination: Fabrication, Characterization, and Performance Evaluation. *ACS Omega* **2023**, *8*, 2564–2574. [[CrossRef](#)]
56. Gissawong, N.; Srijaranai, S.; Boonchiangma, S.; Uppachai, P.; Seehamart, K.; Jantrasee, S.; Moore, E.; Mukdasai, S. An electrochemical sensor for voltammetric detection of ciprofloxacin using a glassy carbon electrode modified with activated carbon, gold nanoparticles and supramolecular solvent. *Microchim. Acta* **2021**, *188*, 208. [[CrossRef](#)] [[PubMed](#)]
57. Smajdor, J.; Paczosa-Bator, B.; Piech, R. Electrochemical Sensor Based on the Hierarchical Carbon Nanocomposite for Highly Sensitive Ciprofloxacin Determination. *Membranes* **2023**, *13*, 682. [[CrossRef](#)]
58. Khodari, M.; Assaf, H.F.; Shamroukh, A.A.; Rabie, E.M. Fabrication of an electrochemical sensor based on eggshell waste recycling for the voltammetric simultaneous detection of the antibiotics ofloxacin and ciprofloxacin. *BMC Chem.* **2023**, *17*, 131. [[CrossRef](#)] [[PubMed](#)]
59. Zhao, J.; Huang, P.; Jin, W. Electrochemical sensor based on TiO₂/polyvinyl alcohol nanocomposite for detection of ciprofloxacin in rainwater. *Int. J. Electrochem. Sci.* **2021**, *16*, 211018. [[CrossRef](#)]
60. Măgeruşan, L.; Pogăcean, F.; Cozar, B.I.; Tripon, S.C.; Pruneanu, S. Harnessing Graphene-Modified Electrode Sensitivity for Enhanced Ciprofloxacin Detection. *Int. J. Mol. Sci.* **2024**, *25*, 3691. [[CrossRef](#)]
61. Tajik, S.; Beitollahi, H.; Zaeimbashi, R.; Sheikhsheaei, M.; Askari, M.B.; Salarizadeh, P. An electrochemical sensor based on V₂O₅ nanoparticles for the detection of ciprofloxacin. *J. Mater. Sci. Mater. Electron.* **2021**, *32*, 17558–17567. [[CrossRef](#)]
62. Elanchezian, M.; Lee, S.; Yoon, T.H.; Singh, M.; Lee, D.; Won, K. Disposable electrochemical sensors based on reduced graphene oxide/polyaniline/poly(alizarin red S)-modified integrated carbon electrodes for the detection of ciprofloxacin in milk. *Microchim. Acta* **2024**, *191*, 507. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.