REVIEW ARTICLE

Functionalities of electrochemical fluoroquinolone sensors and biosensors

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Abstract

Fluoroquinolones (FQs) are a class of broad-spectrum antimicrobial agents that are used to treat variety of infectious diseases. This class of antibiotics was being used for patients exhibiting early symptoms of a human respiratory disease known as the COVID-19 virus. As a result, this outbreak causes an increase in drug-resistant strains and environmental pollution, both of which pose serious threats to biota and human health. Thus, to ensure public health and prevent antimicrobial resistance, it is crucial to develop effective detection methods for FQs determination in water bodies even at trace levels. Due to their characteristics like specificity, selectivity, sensitivity, and low detection limits, electrochemical biosensors are promising future platforms for quick and on-site monitoring of FQs residues in a variety of samples when compared to conventional detection techniques. Despite their excellent properties, biosensor stability continues to be a problem even today. However, the integration of nanomaterials (NMs) could improve biocompatibility, stability, sensitivity, and speed of response in biosensors. This review concentrated on recent developments and contemporary methods in FQs biosensors. Furthermore, a variety of modification materials on the electrode surface are discussed. We also pay more attention to the practical applications of electrochemical biosensors for FQs detection. In addition, the existing challenges, outlook, and promising future perspectives in this field have been proposed. We hope that this review can serve as a bedrock for future researchers and provide new ideas for the development of electrochemical biosensors for antibiotics detection in the future.

Keywords Fluoroquinolones · Antibiotics · COVID-19 · Biosensors · Detection · Nanomaterials

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Introduction

Antibiotics can be described as either natural or synthetic compounds with useful antibacterial activities that are usually employed in human and veterinary medicine to treat various infectious diseases (Khan 2020; Cardoso et al. 2021). Overuse of antibiotic drugs could lead to bacteria resistance, creating challenges to societies and health centers due to increased patient numbers and costly treatment (Yadav et al. 2021). Antibiotics are categorized according to their mechanism of action or chemical structure and are arranged into classes that include quinolones, ß-lactams, sulphonamides, macrolides, and tetracyclines (Hamnca et al. 2017; Ding et al. 2021). Table 1 shows the common antibiotics and their properties. Among these antibiotics, quinolones such as Fluoroquinolones (FQs) have gained significant interest due to their widespread application in households, hospitals, and veterinary for the treatment of infectious diseases (Teglia et al. 2019). Over the past four years, there has been an increase in the use of FQs due to the COVID-19 pandemic as

Table 1 Detailed description of different antibiotics and their general characteristics

Type of antibiotics	Functional groups	Target microbes	Mechanism of action	Example	Chemical formula	Side effects	Application	Ref
Tetracycline	Four hydrocarbon rings (cyclins)	Both gram-positive and negative bacteria	Inhibition in protein synthesis through binding with ribosome	Tetracycline Oxytetracycline Doxycycline	$C_{22}H_{24}N_2O_8$ $C_{22}H_{24}N_2O_9$ $C_{22}H_{24}N_2O_8$	Hepatotoxic	Human, veterinary, human,	(Liu et al. 2018)
Sulphonamides	The Sulfonyl group (O=S=O) is connected to an amine group (−NH2)	Both gram-positive and negative	Inhibition in folic acid synthesis	Sulphanilamide Sulfamethoxazole Sulfadiazine	$C_6H_8N_2O_2S$ $C_{11}H_{11}N_3O_2S$ $C_{12}H_{14}N_4O_4S$	Diarrhea, vomiting, and nausea	Veterinary, veterinary, human	(Zhou et al. 2022)
Fluoroquinolones	Bicyclic core structure	Gram-negative bacteria	Inhibition of bacterial DNA Gyrase	Ciprofloxacin Norfloxacin Levofloxacin	$C_{17}H_{18}FN_3O_3$ $C_{16}H_{18}FN_3O_3$ $C_{18}H_{20}FN_3O_4$	Hepatic toxicity, haemolytic anemia	Human, veterinary, human, human,	(Bhatt and Chatterjee 2022)
β-lactams	Lactam ring 3-C and N ring	Both gram-positive and gram-negative	Inhibition of peptidoglycan layer	Penicillin Amoxicillin Cephalosporins	$C_{16}H_{18}N_2O_4S$ $C_{16}H_{19}N_3O_5S$ $C_{16}H_{21}N_3O_8S$	Rashes, fever	Human, veterinary	(Maciel et al. 2023)
Macrolides	14;15;16 membered macrocyclic lactone ring	Streptococcal/pneumococcal	Inhibition in bacterial protein biosynthesis	Erythromycin Clarithromycin Roxithromycin	$C_{37}H_{67}NO_{13}$ $C_{38}H_{69}NO_{13}$ $C_{41}H_{76}N_2O_{15}$	Gastrointestinal disturbances	Human, veterinary	(Nguyen et al. 2023)

there is no evidence of any specific recommended treatment measures for patients with confirmed COVID-19 (Miranda et al. 2020; Ebrahimi and Akhavan 2022). As a result, FQs are frequently detected in different environmental compartments due to an incomplete metabolism in the target organism and inefficient wastewater treatment (Cuprys et al. 2018; Gou et al. 2021), leading to accumulation of these drugs in human bodies through drinking water, which in turn poses serious detrimental health effects to both humans and the environment (Gaudin 2017; Kraemer et al. 2019; Lan et al. 2017). Hence, to prevent further antibiotic contamination, national governments should limit antibiotic use in livestock and aquaculture (Ters 2022). In this outlook, we are yet to find the report exploiting safe concentration for commonly used antibiotics in water regulated by national governments to ensure safety for living organisms. Thus, there is a need for the development of new reliable approaches for detecting antibiotics and their metabolites in the environment to ensure public health safety.

According to the published literature and national studies, the concentrations of pharmaceutical products in surface and groundwater impacted by wastewater discharges are typically less than 0.1 µg L^{-1} (or 100 ng L^{-1}) as shown in Table 2, whereas the concentrations in treated drinking water are usually well below 0.05 µgL^{-1} (Maycock and Watts 2011). There are not many thorough, systematic research on the presence of pharmaceutical compounds in drinking water. Hence, assessing possible dangers to human health from exposure to trace amounts of these compounds in drinking water is difficult due to the lack of data on the topic (Epa 2008). As a result, there is no evidence yet on the standard safety of these antibiotics in water.

Several techniques have been reported for FQs detection in different samples, including high-performance liquid chromatography (HPLC) (Abedalwafa et al. 2019), liquid chromatography–mass spectrometry (LC–MS) (Lim and Ahmed 2016), capillary electrophoresis (CE) (Zhang et al. 2020), and immunoassay (Acaroz et al. 2020). Although these methods are sensitive, they are often costly and time-consuming and usually require specialized/skilled personnel to operate, which in turn limits their potential application. For these reasons, conventional methods are not suitable for routine and rapid analysis of large numbers of samples (Wu et al. 2016; Kharewal et al. 2020). Consequently, new approaches are needed to overcome the limitations of the traditional methods.

Recently, with the rapid increase in nanotechnology, electrochemical methods on specific biometric elements have been extensively used for FQs detection owing to their advantages such as low cost, rapid response, high sensitivity, easy operation, and suitability for on-site monitoring (Jahanbani and Benvidi 2016). Electrochemical biosensors have emerged as an alternative strategy for antibiotics detection. Biosensors are a group of state-of-the-art analytical devices that use a biorecognition material in close contact with a transducer. The recognizing elements

Table 2 Summary of concentrations levels of FQs in different streams

Fluoroquinolones	Streams	Concentrations	Refs
Ciprofloxacin	Tap water	6.0–679.7 ng L^{-1}	(Yiruhan et al. 2010)
Levofloxacin	River	42 ng L^{-1}	(Speltini et al. 2015)
Ofloxacin	Wastewater	9 ng L^{-1}	(He et al. 2015)
Enrofloxacin	Water sample	0.003 µg L^{-1}	(Zhang et al. 2013)
Norfloxacin	Water sample	3.02–23.90 ng mL^{-1}	(Madikizela et al. 2022)
Enrofloxacin	River and lake samples	0.22 µg L^{-1}	(He et al. 2015)
Ciprofloxacin	Water	127 µg L^{-1}	(Ajibola et al. 2021)

such as enzymes, antibodies, and DNA are the most used when developing biosensor (López et al. 2017; Yazdanparast et al. 2019). The binding affinity of a recognition element with a target analyte plays a critical role on biosensor performance. The greatest challenges associated with biosensor development involve the efficient capturing of biorecognition signals and the transformation of these signals into either electrochemical, electrical, and optical signal. However, one of the recent trends to overcome such drawbacks related to biosensor fabrication is through the integration of sensing technology and nanomaterials (NMs) with properties such as high surface-to-volume ratio, good conductivities, shock-bearing abilities, and color tunability (Kumar and Neelam 2016; Lawal 2018). These NMs have a high capacity for charge transfer and influence the biosensor to produce high sensitivity and lower detection limit (LOD). Herein, this review reports the recent advances in electrochemical biosensing systems for FQs detection water sample. To this end, the electrochemical biosensor for FQs detection and their development were briefly introduced. The review also discusses the challenges encountered by the existing electrochemical biosensor and how their performance can be improved further. Therefore, the concepts introduced in this review are expected to motivate new findings toward electrochemical detection of FQs in future.

Fluoroquinolones (FQs) as environnemental pollutants

Fluoroquinolones (FQs) are a synthetic group of antimicrobial agents, which are derived from quinolone nalidixic acid by the addition of a fluorine atom at carbon 6 and piperazine at carbon 7 position (Zahra et al. 2021). FQs are considered as broad-spectrum antibiotics due to their bactericidal effect against various pathogenic bacteria. They destroy the bacteria or inhibit their growth by inhibiting their DNA gyrase replication favored by their chemical structure (Rasheed et al. 2023). Since the discovery of using FQs for the treatment of living organism, a number of FQs are being prescribed for their broad-spectrum mode of action toward Gram-negative, Gram-positive bacteria, and mycoplasma (Zhang et al. 2018). However, the extensive use of FQs leads to an accumulation

of these compounds in aquatic and terrestrial environments in large quantities, which could probably cause allergic reactions in humans and the emergence of food-borne bacteria (Lu et al. 2021a). Releasing effluents from different manufacturing sectors is one of the most significant pathways for these drugs to enter the aquatic ecosystem (Bhatt and Chatterjee 2022). On the other hand, humans and animals partially metabolize FQs, and about 10–70% of these drugs are excreted and released into the sewage and subsequently enter the wastewater treatment plants (WWTPs) (Sodhi and Singh 2021; Sodhi et al. 2021). FQs and their metabolites are highly toxic and the continuous discharge of these drugs into the water bodies can pose potential risks to aquatic organisms and marine biodiversity even at lower concentrations (Ramesh et al. 2021). In addition, when the antibiotics interact with bacteria in water bodies, new pathogenic species are being formed that are resistant to these compounds (Leibovici et al. 2016; Cristea et al. 2017; Majdinasab et al. 2017). According to World Health Organization (WHO), the increase in antibacterial resistance has become a national and international issue that threatens society's health by spreading antibiotic-resistant bacterial infections (Flaherty and Cummins 2017). FQs are classified as first-generation, second-generation, third generation, and fourth-generation agents to describe their evolution based on the antibacterial spectrum. However, the most used FQs antibiotics belong to the second and third generation. Thus, the occurrence of FQs in surface water and wastewater has drawn great attention. Figure 1 shows the different types of FQs antibiotics.

The analytical method used for FQs antibiotics detection

The monitoring and screening of FQs in water is imperative as it is the first stage to dealing with environmental pollution generated by these antibiotics. Several conventional technologies have been employed and reported for the detection of FQs in water bodies. This includes spectrofluorometry, spectrophotometry, photochemistry, and chromatography technique (Xia et al. 2013; Akram et al. 2015; Shokoufi et al. 2020; Mao et al. 2021). However, these methods have shown some limitations as they require a qualified person
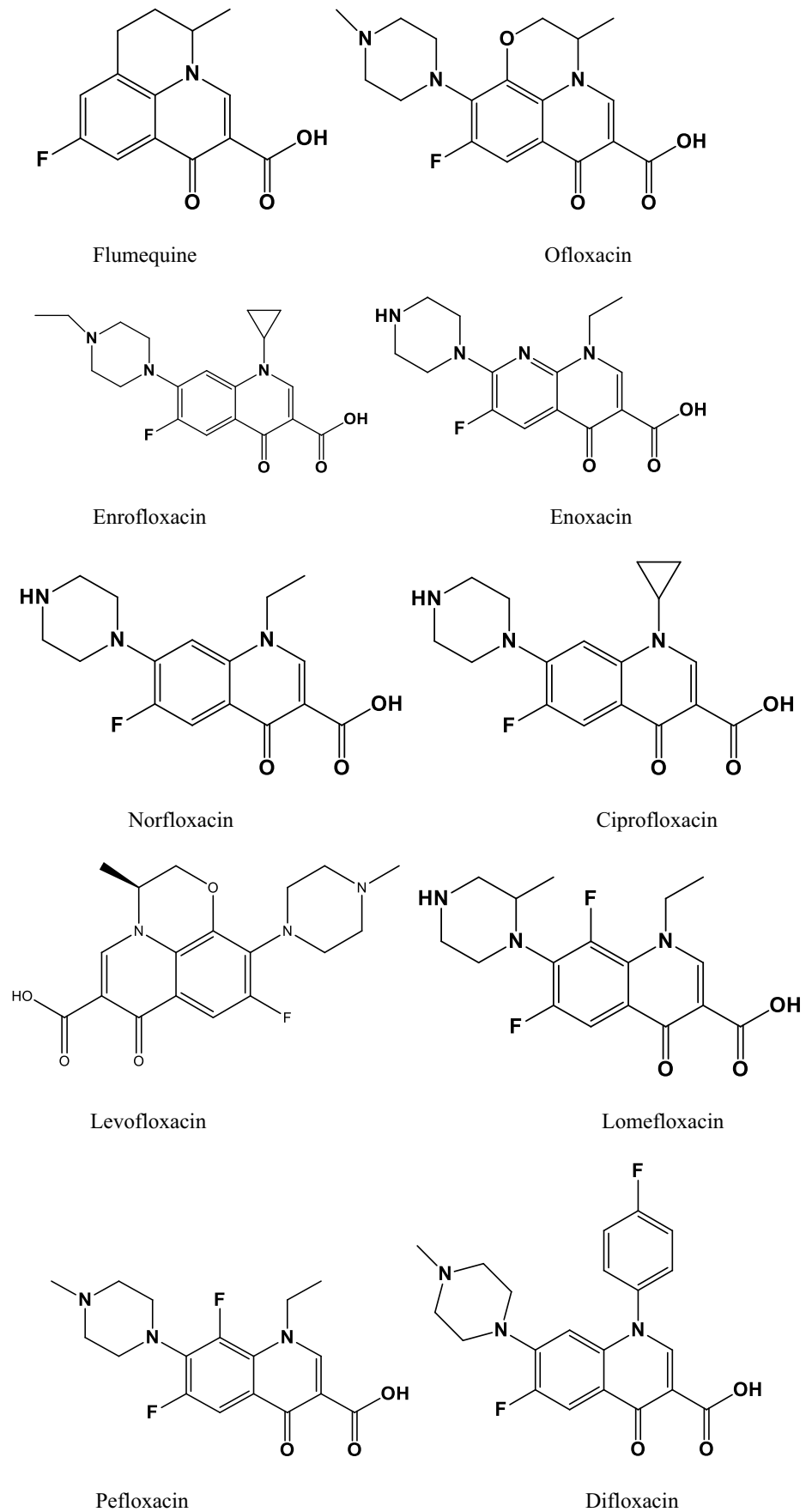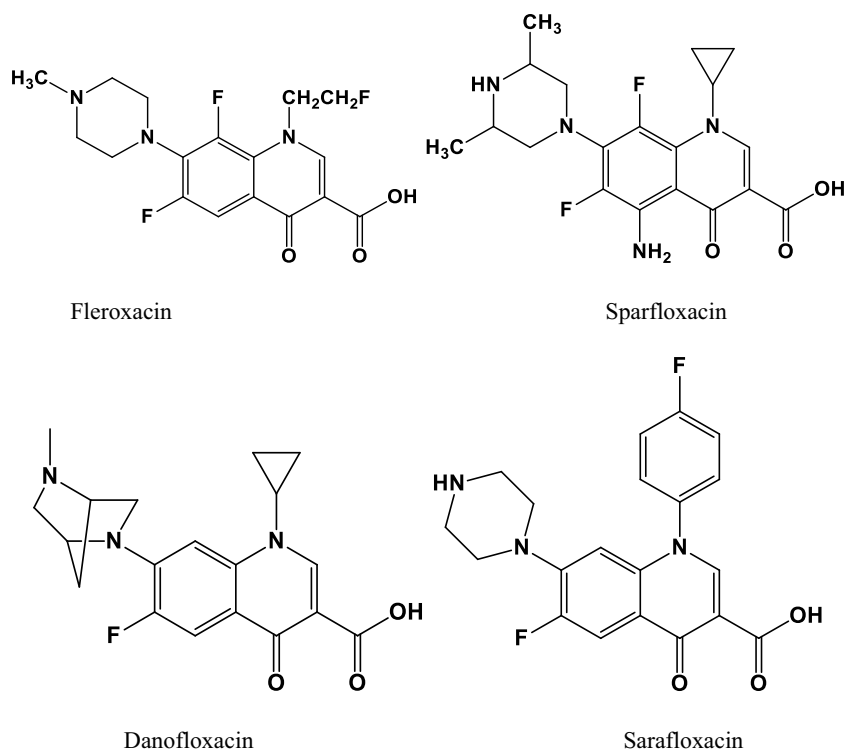
Fig. 1 Structures of fluoroquinolone antibiotics

Flumequine

Ofloxacin

Enrofloxacin

Enoxacin

Norfloxacin

Ciprofloxacin

Levofloxacin

Lomefloxacin

Pefloxacin

Difloxacin

Fig. 1 (continued)

Fleroxacin

Sparfloxacin

Danofloxacin

Sarafloxacin

to perform the analysis, are time-consuming, costly, and require different sample pre-treatments, restraining their potential use for quick, on-site, and real-time analytes detections. Table 3 shows the summary of the different traditional method that has been used for FQs detection with their advantages and disadvantages. When compared with various reported approaches, electrochemical methods, especially electrochemical biosensors have considerable benefits with their outstanding features such as less time consumption, cost-effectiveness, amenability to miniaturization, easy handling techniques, quick response, ability for on-site analysis, high sensitivity, and selectivity (Sun et al. 2023). Currently, significant attention has been drawn to electrochemical biosensor development for FQs detection. The next section will discuss more about the development of electrochemical biosensors.

Electrochemical biosensors for FQs

The need for the development and exploitation of analytical devices for the quantification, detection, and monitoring of antibiotics in water bodies has led to the development of sensing methods. The are various types of sensing techniques that have been successfully established for the detection of contaminants of emerging concern in food and water sample, including electrochemical sensors and biosensors, optical sensors, etc. (Kaur et al. 2020). Among these, electrochemical biosensors have currently

attracted significant interest from various researchers as new promising sensing methods that can be employed in food analysis, health care, environmental monitoring, and drug delivery (Kumar and Neelam 2016; Shetti et al. 2019). They exhibit properties such as excellent sensitivity, rapid analysis time, and the possibility of miniaturization (Labib et al. 2016). The electrochemical biosensor comprises of biological recognition component (enzymes, DNA, antibodies and cells, etc.) that is directly connected to a chemical or physical transducer, which converts a chemical or biological signal into a measurable electrical signal (Akhavan et al. 2012; Dhar et al. 2019; Singh et al. 2021; Wang et al. 2023). In this type of biosensor, the electrochemical reaction takes place on the surface of the transducer between the bioreceptor and analyte producing detectable electrochemical signals with respect to voltage, current, impedance, and capacitance. The performance of electrochemical biosensor is influenced by a number of variables, including electrode type, electrolyte solution, and pH (Liu et al. 2019a). Among these, solution pH is one of the most important since, at various pH levels, not only the activity of an electrode is affected, but also the surface charges of the drug species vary, which has an impact on the behavior of the electrode surface during detection. (Wammer et al. 2013; Khosravikia and Rahbar-Kelishami 2022). Based on the electroanalytical technique that is used to measure chemical and biochemical interactions, biosensors are categorized as either potentiometric, impedimetric, amperometric or coulometric, conductometric and

Table 3 Summary of traditional technique used for FQs

Technique	Principle	Advantages	Disadvantages	Ref
Spectrophotometry	Here, light is passed through a sample and the fraction of light that passes through the sample is measured. The amount of light absorbed is called absorbance and the light passed through the sample is called transmittance	• Sensitive • Low-cost • Rapid analysis	• Low reproducibility • Less accurate • Limited applications	(Bonfilio et al. 2010; Kuntzleman and Jacobson 2016; Redasani et al. 2018)
Photochemistry	A photochemical reaction is triggered by the absorption of light and leads to an observable chemical change. After excitation by absorption of a photon of energy, a nuclear wave function is promoted from the electronic and nuclear ground state to an excited state. Thereby, creating a wave packet that evolves in time. This motion then directs the molecule toward a different geometry in the excited state	• Minimum undesirable decomposition • Low production of by-products	• Possible rapid termination of photoreactions • High unit capital input costs • High cost of photons and the light absorption	(Pape 1975)
Spectrofluorimety	Here, a fluorescence light is passed through a sample and the fraction of light that passes through the sample is measured. Fluorescence makes it more sensitive than spectrophotometry	• Highly sensitive • Quantification of some drugs in biological matrices	• Likelihood of analyzing only luminescent compounds • Complex analysis • Time-consuming analysis • Failure of analysis of related substances	(Macii and Biver 2021)
Chromatography	In chromatography, the mobile phase (eluent) is passed through the column using gravity flow or a pump. The sample with several components is then introduced into one end of the column followed by elution with the mobile phase in the direction toward the other end. Different components will then move at different rates through the column depending on their partition or distribution coefficients between the mobile and the stationary phases. The separated components are collected at the other end of the column and detected	• Simplicity • Sensitivity • Accuracy • Reproducibility	• Requirement of high-cost equipment • Requirement for highly trained technicians • The need to be handled with care • Generation a lot of waste	(Mallik et al. 2016)

voltammetric (Hernandez-Vargas et al. 2018; Jalalian et al. 2018). Figure 2 shows the typical structure of biosensor comprising of three components, i.e., detector, traducer, and electronic component. The most critical characteristics of a biosensor development depend on its sensitivity and specificity. The specificity of biosensors is affected by the coupling efficiency between biological and transducer elements, whereas sensitivity is mainly influenced by the bioreceptor (Hernandez-Vargas et al. 2018). Recently, many researchers have based their focus on blending of nanostructured materials when development biosensor to enhance the sensitivity and detection limit. Numerous nanomaterials (NMs) and their composites such as gold nanoparticles (Au NPs), carbon nanotubes (CNTs), graphene (Gr) (Akhavan et al. 2014), and graphene–metal/metal oxide nanocomposites (Sethuraman et al. 2016) have been employed as perfect biosensor transducers, which offers great improvement in sensitivity by increasing electrochemical signal production and decreasing background noise (Shan et al. 2020). However, one of the most important factors for achieving an effective process during drug substrate detection is the electroosmotic flow through the nanopores/nanochannels within the NMs used for biosensor modification (Khosravikia 2023). In principle, the ion flow through the pore is changed when the analyte enters the pore under the applied potential, and this change is reflected over time in the current recording (Zhang et al. 2023). On other hand, there are certain challenges with the integration of NMs in electrochemical sensing because electrocatalyst materials (i.e., nanomaterials) slip off the electrode surface, affecting the performance of the biosensor (Baig et al. 2019; Liu and Mandler 2020). Although many researchers have solved these issues by employing nafion to stop these materials from falling off the electrode surface (Feleni et al. 2019, 2020; Wenninger et al. 2021), more study on this topic has to be done to enhance the surface kinetics of the electrodes. Review articles on electrochemical methods for the detection of antibiotics have been reported by a number of researchers (Tran et al. 2022; Ding et al. 2021; Seth and Rathinasabapathi 2022; Hong et al. 2023) and Table 4 shows the summary of biosensors used for FQs detections. This section discusses types of electrochemical biosensors that have been reported in literature.

Enzymatic-based biosensor for FQs

Enzymes are biomolecules whose major constituents are amino acids and usually act as biocatalysts which are efficient to increase the biological reaction rate (Kurbanoglu et al.

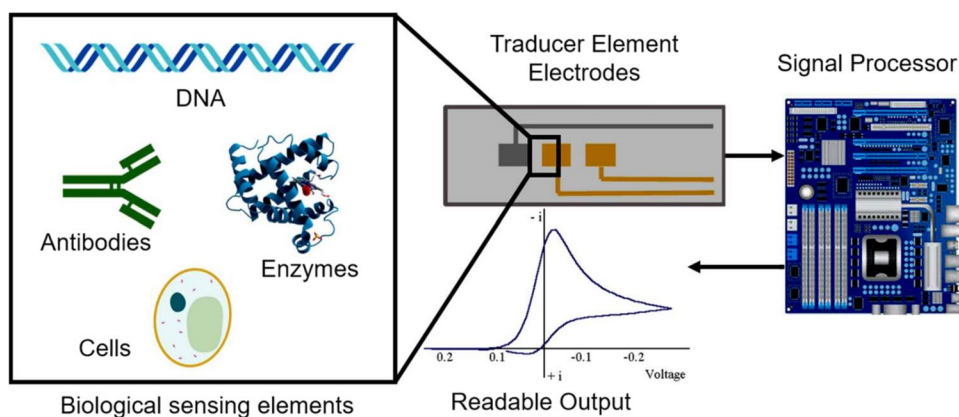**Fig. 2** Schematic representation of an electrochemical biosensor (Hernandez-Vargas et al. 2018)

Table 4 Summary of the biosensors used for FQs

Biosensor type	Analyte	Nanomaterials	Bioreceptors	Linear range (μM)	LOD (μM)	Ref
Optical	FQs	AuNRs	Antibody (Ab2)	0.13–29.91	0.31	(Dai et al. 2023)
Amperometric	Norfloxacin	CH-Y$_2$O$_3$	Antibody	1×10^{-6}–10	3.87×10^{-7}	(Yadav et al. 2020)
Electrochemical	Ciprofloxacin	nLa$_2$O$_3$ NPs	Antibody (Ab)	0.001–0.5	0.001	(Chaudhary et al. 2021)
Electrochemical	Ciprofloxacin	-	Aptamer	8.0×10^{-4}–0.4	2.63×10^{-4}	(Abnous et al. 2014)
Electrochemical	Ciprofloxacin	-	Aptamer	3×10^{-4}–0.45	1.0×10^{-5}	(Taghdisi Heidarian et al. 2021)
Fluorescent	Ciprofloxacin	-	Aptamer	0.01–0.2 10–120	0.051	(Jadhav et al. 2020)
Electrochemical	Ciprofloxacin	-	DNA	40–80	24	(Nawaz et al. 2006)
Electrochemical	Enrofloxacin	AuNPs/Ni-MOF	c-DNA	1×10^{-2}–1×10^{3}	5.6×10^{-3}	(Lv et al. 2022)

2020). Biosensors that have enzyme molecules immobilized on transducing surfaces (electrodes) as biorecognition elements are referred to as enzymatic-based biosensors (Campaña et al. 2019). This type of biosensor operates on two main mechanisms, namely substrate detection and enzyme inhibition depending on the target analyte. The working principle of an enzyme-based biosensor relies on the catalytic reaction and binding abilities of the target analyte detection (Rocchitta et al. 2016). The are several possible mechanisms which are involved during the recognition process of an analyte. One of the mechanisms involves the metabolism of the analyte by the enzyme where the enzyme concentration is estimated by measuring the catalytic transformation of the analyte by the enzyme (Das et al. 2019). The other working principle is based on enzyme inhibition or activation by the target analyte to reduce enzyme activity. This process is based on the determination of enzyme activity in the presence and absence of inhibitor compounds (Asal et al. 2018). The decrease in product concentration provides the detection of inhibitory targets that inhibit the activity of certain enzymes. Enzyme-based biosensors can be developed on the basis of enzyme specificity (Cordeiro et al. 2018). These types of biosensors usually incorporate electrochemical, optical, and calorimetric transducers. Among them, electrochemical is the most used in literature. Enzyme-based biosensors have been widely used in different applications like the detection of industrial toxins and food contamination (Kurbanoglu et al. 2020), and viral, fungal, and bacterial disease detection (Kłos-Witkowska 2015). The most common family of enzymes with a well-recognized ability for the detection of different substances including pharmaceuticals are oxidases and peroxidases and have been widely used during enzyme-based biosensors development (Soylemez et al. 2019). The lifetime of an enzyme-based biosensor is dependent on the type of enzyme used as a recognition element.

Photoelectrochemical (PEC) aptasensor for FQs

Biosensors that utilize aptamers as biorecognition component are known as aptasensors (Januarie et al. 2022). Aptamers are artificial functional single-stranded (ss) DNA or RNA molecules with the potential for precise recognition of specific and various targets, from small molecules to proteins and whole cells (Taghdisi Heidarian et al. 2021). Compared to antibodies, aptamers have several important characteristics such as low production cost, high stability in different physical and chemical form, long-term storage, easy modification, small size, and lack of immunogenicity and toxicity (Jin et al. 2019; Majdinasab et al. 2020). Fabrication of aptasensors is conventionally achieved through direct modification of a biofunctionalized sensor surface with aptamers using appropriate linkers or non-covalent modification of functionally activated surfaces with aptamers. NMs such as carbon fibers and Au NPs are mostly used during the development of aptasensors to enhance their sensitivity (He and Yan 2018; Li et al. 2018).

In recent years, aptamer-based biosensors have emerged as a robust detection approach for antibiotic residues. For instance, Yang et al. (2021) developed a photoelectrochemical (PEC) aptasensor for Ciprofloxacin (CIP) detection based on $Bi_{24}O_{31}C_{110}$/BiOCl heterojunction. The PEC aptasensor achieved high sensitivity with a wide detection range $(5.0 \sim 1.0 \times 104$ ng $L^{-1})$ and low limit of detection (LOD) of $(1.67$ ng L^{-1}, S/N = 3). Their method is straightforward and simple to follow. The PEC aptasensor was applied for the detection of CIP in water. Another photoelectrochemical aptasensor was developed by Zhang et al. (2021); they developed two materials with excellent PEC performance: three-dimensional nitrogen-doped graphene-loaded copper indium disulfide $(CuInS_2$/3DNG) and Bi^{3+-}doped black anatase titania nanoparticles decorated with reduced graphene oxide $(Bi^{3+}$/B-TiO_2/rGO). The aptasensor was based on applying different bias potentials to the two materials near one ITO electrode, the cathodic current generated by $CuInS_2$/3DNH and the anodic current generated by Bi^{3+}/B-TiO_2/rGO was clearly distinguished without interfering with each other. Then, Enrofloxacin (ENR) and CIP aptamers were respectively modified onto the surface of $CuInS_2$/3DNH and Bi^{3+}/B-TiO_2/rGO to construct a PEC aptasensor for sensitive detection of ENR and CIP. The aptasensor exhibit wide linear ranges of 0.01 to 10,000 ng mL^{-1} for ENR and 0.01 to 1000 ng mL^{-1} for CIP, with relatively low LOD 3.3 pg mL^{-1} for ENR and CIP in milk samples. In a study conducted by You et al. (2022), they developed a PEC aptasensor based on Ti_3C_2/Bi_4VO_8Br/TiO_2 nanocomposite. The constructed PEC aptasensor presented an "on–off-on" detection signal and completed the specific detection of CIP in milk. With the increase of target detection concentration, the PEC aptasensor presented a detection range of 1 to 1500 nM and LOD of 0.3 nM. In Wu et al. (2022) study, they developed a self-powered microfluidic PEC aptasensor that uses photoactive AgBr/$CuBi_2O_4$ (ACO) composites as the photocathode matrix for ultrasensitive detection of CIP and ofloxacin (OFL). The $ZnIn_2S_4$-decorated CdS nanorod arrays (CZIS) as the photoanode was used instead of a platinum counter electrode to provide electrons. The CIP detection was accomplished through the steric hindrance effect in the photoanode due to the combination of aptamer$_{(CIP)}$ and CIP. To increase the cathodic photocurrent intensity for OFL determination, a controlled release of luminol was first used. Luminol molecules were successfully embedded in the porous structure of silicon dioxide nanospheres (PSiO$_2$) by the electrostatic adsorption between PSiO$_2$ and aptamer $_{(OFL)}$. The aptasensor exhibits wide linear ranges for CIP 0.001 to 100 ng mL^{-1} and 0.0005 to 100 ng mL^{-1} for OFL detection. The LOD for CIP was 0.06 pg mL^{-1} and 0.022 pg mL^{-1} for OFL. Despite many advantages of aptamer, the interaction between aptamer and small molecules is more time-consuming and less specific compared to antibodies.

## Electrochemical immunosensor for FQs

Immunosensor is referred to as a biosensor that utilized an antibody as a biorecognition element. They have emerged as a powerful tool in clinical diagnostics, environmental monitoring, and food safety applications due to their extreme specificity. Immunosensors take advantage of high affinity of antibodies to antigens for the determination of specific analytes using an appropriate signal transducer. The working principle is reliant on detecting, processing, and displaying the signal produced by the formation of an antibody-antigen (Ab-Ag) complex. Figure 3 describes the possible mechanism for immunoassay binding configurations. Immunosensors play an important role in the detection of hazardous substances in foods. Aymard et al. (2022) constructed a dual electrochemical immunosensor for the detection of ENR in meat samples. Anti-quinolone antibody was immobilized onto screen-printed dual carbon electrodes via carbodiimide coupling. The detection principle was based on the competitive binding of this conjugate and free ENR on immobilized antibodies. The immunosensor was used to detect ENR at concentrations ranging from 0.005 μg. mL^{-1} to 0.01 μg. mL^{-1} and achieved the LOD of 0.003 μg. mL^{-1}. The immunosensor was stable for at least 1 month at 4 °C and displayed a good specificity for other FQs drugs. Shinko et al. (2022) developed a piezoelectric immunosensor based on multi-walled carbon nanotubes (MWCNTs) for the detection of FQs in milk samples. They used MWCNTs in the formation of a stable piezoelectric sensor detection layer to increase the active specific surface area which is

necessary for receptor molecule binding. The immunosensor achieved the LOD of 9 ng mL^{-1} and 8 ng mL^{-1} for levofloxacin (LEV) and CIP, respectively. Similarly, Bizina et al. (2022) developed a piezoelectric immunosensor with a recognition layer based on magnetic carbon nanocomposites for CIP detection in milk and meat sample. The receptor coating of the sensor was formed by the action of magnetic field on magnetic particles located on the surface of CNTs modified with a CIP conjugate. The immunosensor exhibits LOD of 2 ng mL^{-1} with a wide linear range from 5 to 400 ng mL^{-1}. The use of magnetic carbon nanocomposites in the creation of a recognition layer ensured the reduction of a sensor preparation time. Lamarca et al. (2020) designed an impedimetric immunosensor to determine CIP in wastewater samples. They immobilized anti-CIP antibody on the surface of a printed carbon electrode. The observed Rct changes presented a linear relationship from CIP concentrations of 10^{-5} to 1.0 mg mL^{-1}, with LOD and LOQ of 2.50×10^{-6} and 7.90×10^{-6} mg mL^{-1}, respectively. The immunosensor presented high selectivity and repeatability, as well as a good recovery rate in wastewater samples (97%). Interference of the immunosensor with other compounds was not observed.

Nanomaterial-based biosensors

Although enzymatic-based biosensor, aptasensor, and immunosensor are well established for the detection of various analytes, some challenges such as low stability, low sensitivity, and long detection time may still exist

Fig. 3 Possible immunoassay binding configurations are suitable for biosensing applications. Shown are the progressive reaction steps leading to the final binding structures for **A** sandwich structure formation using a fluorophore-labeled secondary antibody, **B** competitive style immunoassays using labeled antibodies/antigens, **C** extended sandwich structure formation using a fluorophore-labeled tertiary antibody, and **D** sandwich structure formation on a quantum dot (microparticle) surface using a secondary FRET-paired fluorophore (Mohammed and Desmulliez 2011)
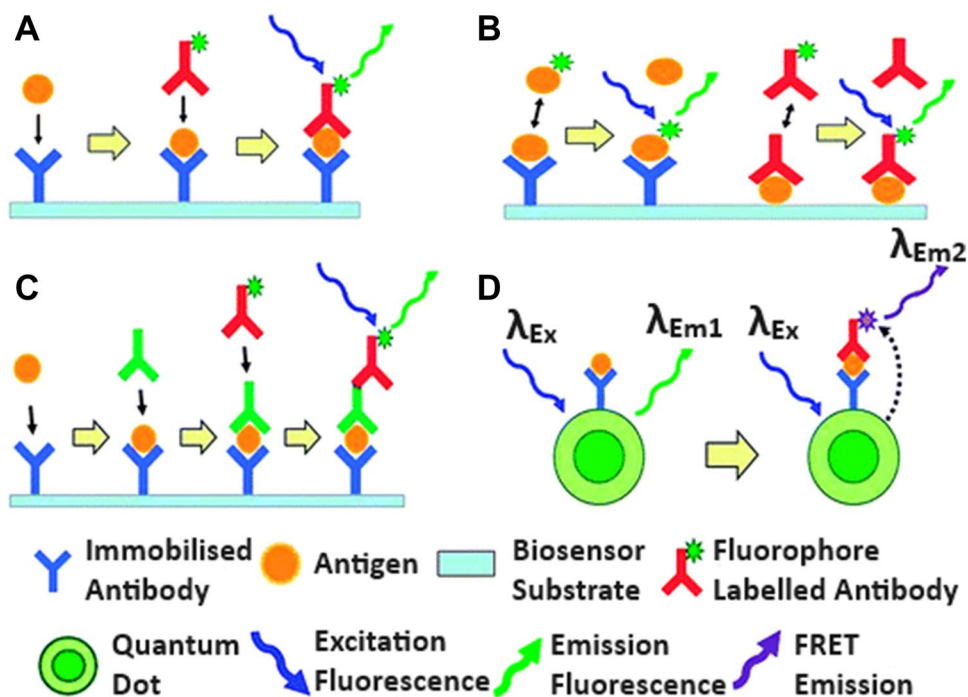
(Majdinasab et al. 2020). However, with the rapid development in nanotechnology, the application of NMs in sensing technology has become one of the most exciting forefront fields in analytical chemistry driven by their unique properties that offer excellent prospects for designing novel sensing systems and enhancing the performance of the bioanalytical assay (Ahmadipour et al. 2020; Chiam et al. 2022; Xia et al. 2012). Furthermore, NMs have the potential to increase the direct electron transfer (DET) and response time on a sensing system. For these reasons, nanomaterials-based biosensors have gained significant interest to many researchers owing to their distinctive properties such as high sensitivity, selectivity, low cost, and easy operation (Li et al. 2019). Since the performance of electrochemical biosensors largely depends on the performance of working electrodes (WEs), whereas the performance of WEs relies on the nature of the material used to modify the electrode (Wang et al. 2021), these NMs improve electron transfer among electrodes and detection species and behave as biocompatible frameworks for biomolecule control in electrochemical biosensors. A wide variety of NMs with different sizes, shapes, and compositions including carbon nanomaterials, metal nanoparticles, magnetic nanoparticles, quantum dots, and nanocomposites have been successfully used to develop electrochemical biosensors for antibiotics detection in food and water samples (Lan et al. 2017; Joshi and Kim 2020) and Table 5 shows the performance comparison of different nanomaterial-based electrochemical sensors for FQs. Herein, this section will mainly discuss nanomaterials for biosensor development.

Carbon-based nanomaterials

Carbon-based nanomaterials (CNMs) offer various unique advantages when compared to many other NMs. They exhibit high surface-to-volume ratios, high electrical conductivity, long-term chemical stability, and enhanced mechanical strength. These characteristics enable CNMs to have lower detection limits and higher sensitivities (Qian et al. 2021). As a member of NMs, CNMs including carbon nanotubes (CNTs), graphene (Gr), graphene quantum dots (GQD), and carbon nanofibers (CNFs) have received great attention due to their exceptional physical, chemical, and electrical properties which has resulted in their widespread application during the development electrochemical biosensors for environmental monitoring, etc. (Power et al. 2018). Recently, most materials that are employed as electrocatalysts for the detection of FQs antibiotics are incorporated with CNMs to form advanced nanocomposites. Among them, CNTs and Gr are the most used CNMs in biosensors for antibiotics detection. Thus, the next section discusses the CNMs that are commonly used for electrochemical biosensors development.

Carbon nanotubes

Carbon nanotubes (CNTs) have been extensively used in various fields due to their unique electronic, optical, and catalytic properties (Ardani et al. 2022). The functionalization of CNTs with guest species either at their outer surfaces or in their nanochannels largely expands CNTs properties and applications (Jalal et al. 2019). Because CNTs have abundant surface area and surface characteristics, they can be physically or chemically altered to introduce a variety of materials, including biomacromolecules, active small molecules, and other materials, to their outer surfaces (Wang et al. 2012). As one-dimensional, seamless, and hollow graphitic NMs, CNTs are made of the sp2-hybridized carbon atoms bonding to each other through C–C σ interaction. CNTs were discovered by Iijima in 1991 (Iijima 1991). Since their discovery, CNTs have attracted considerable attention to the development of electrochemical sensors owing to their excellent conductivity and high tunability (Lawal 2016). CNTs offers the possibility of highly sensitive electrochemical sensors because of their electrical properties that enable the improvement of their analytical response (Cernat et al. 2015). Depending on the specific molecular structure and chemical composition of pharmaceutical compounds, CNTs may be used to promote the electron transfer of many reactions and facilitate the adsorption of organic molecules (Camilli and Passacantando 2018). Moreover, CNTs may produce synergetic effects that promote sensing (Jung et al. 2015; Mallakpour and Khadem 2016). To date, CNTs-based biosensors have been extensively used for the detection of FQs antibiotics. Liu et al. (2019a, b) designed an electrochemical sensor based on functionalized multi-walled carbon nanotubes (fMWCNTs) decorated with molecularly imprinted polymer (MIP) for the detection of norfloxacin (NOR). The porous structure of the fMWCNT 3D framework effectively increases the specific surface area, and the copolymer of fMWCNTs and MIP shows a synergistic effect for the electrocatalytic reaction of NOR on the modified sensor. The authors obtained wide linear ranges of 0.003 to 0.391 μM and 0.391 to 3.125 μM with LOD of 1.58 nM, and excellent selectivity in distinguishing NOR according to its structural analogs and possible interferences. The recoveries from pharmaceutical formulations ranging from 97.36 to 109.58% and the recoveries from rat plasma samples ranging from 83.00 to 115.67% were achieved. Another sensor for monitoring CIP was the fusion of nanocellulose and polypyrrole (NNC-PPY), incorporated with single-walled carbon nanotubes (SWCNTs) via a drop-casting method designed by Shalauddin et al. (2022) with a dynamic linear range of 1 to 50 μM and a LOD of 0.196 nM. Furthermore, the sensor exhibits a high sensitivity of 18.610 μA μM^{-1} cm^{-2}, and the fabricated sensor was implemented successfully for the determination of CIP from water samples, biological fluids and pharmaceutical preparations. Sabeti et al. (2021) designed an electrochemical sensor based on a modified-glassy carbon electrode using f-MWCNTs and dopamine for the determination

Table 5 Performance comparison of different nanomaterial-based electrochemical sensors for FQs

Targeted analyte	Sensor	Electrode	Electro-chemical technique	Real sample	Linear range (μM)	LOD (μM)	Recovery (%)	Ref
Norfloxacin	Ni/NiO/C/ β-CD/RGO/ GCE	[a]GCE	[e]CV	Water	0.4–80	0.01	-	(Cui et al. 2019)
Total FQs content	γ-CD-GQDs-CHI/SPCE	[b]SPCE	[f]DPV	Broths, bouillon cubes and milkshakes	4–250	1.2	90 to 106	(Bartolomé et al. 2023)
Norfloxacin	AuNPs-NOR-MIP/AuNPs/ SPCE	SPCE	CV	Pharmaceu-ticals and aquaculture samples	0.00015 − 0.03113	0.15	-	(Vu et al. 2022)
Ciprofloxacin	N-prGO/CPE	[c]CPE	CV DPV	pharmaceuti-cal	0.1–10	39		(Rahimpour et al. 2021)
Ofloxacin Norfloxacin	ERGO/GCE	GCE	CV DPV	Medicine and aquaculture wastewater	1–40 1–60	0.19 0.56	98.01 102.77	(Wang et al. 2022)
Enrofloxacin	TAPB-PDA-COFs/ AuNPs/GCE	GCE	[g]SWV	Water samples and milk samples	0.05–10 10–120	0.041	96.7–102.2	(Lu et al. 2021b)
Ciprofloxacin	AuNPs/AC/ GCE	GCE	CV DPV	Milk	0.5–25	0.20	78.6–110.2	(Gissawong et al. 2021)
Ofloxacin Pefloxacin Gatifloxacin	P-L-CuO: Tb^{3+} NS/ GCE	GCE	DPV	Milk	0.01 and 800.0	1.9 2.3 1.2		(Taherizadeh et al. 2023)
Ciprofloxacin	Pt − RGO/ GCE	GCE	DPV	Tap and river water	10–25	1.53		(Pham et al. 2022)
Ciprofloxacin	TiO$_2$/PVA-GCE	GCE	DPV CV	Rainwater	10–120	0.04		(Zhao et al. 2021)
Pefloxacin	AuNPs/RGO/ SWCNT/ GCE	GCE	CV DPV	Milk	5.0×10^{-7}–2.0×10^{-5}	1.6×10^{-8}		(Shi et al. 2020)

[a]*GCE*, glassy carbon electrode; [b]*SPCEs*, screen-printed carbon electrode; [c]*CPE*, carbon printed electrode; [d]*AuE*, gold electrode; [e]*CV*, cyclic voltammetry; [f]*DPV*, differential pulse voltammetry; [g]*SWV*, square wave voltammetry

of CIP. The dopamine is electropolymerized to form a layer of polydopamine on the surface of functionalized CNTs. Two linear dynamic ranges from 0.075 to 10 μM and from 10 to 100 μM were obtained for CIP detection with LOD of 0.04 μM, and repeatability and reproducibility of 3.2 and 3.3%, respectively. Afterwards, the sensor's selectivity against common interfering agents was checked out, and the sensor proved to be highly selective for CIP detection. The sensor was tested using urine samples for CIP detection. The sensor proved to be a trustable tool for CIP measurement in clinical and industrial applications.

Graphene

Graphene (Gr), is a two-dimensional (2D) CNMs, with a sheet of sp^2 bonded carbon atoms that are arranged into a rigid honeycomb lattice, exhibiting the highest mechanical strength among the known materials, extraordinary electron transfer capabilities, excellent electrical conductivity,

ultra-large specific surface area, unprecedented pliability and permeability, and favorable biocompatibility (Wang et al. 2016). Gr has become a novel and promising material for nanoelectronics due to its electrocatalytic activity, and it has been investigated as an electrode material for sensing devices. Gr has large surface area, good conductivity, and strong mechanical properties, but the major disadvantage lies in its poor dispersion. Pan et al. (2021) developed an electrochemical biosensor by the modification of a screen-printed carbon electrode (SPCEs) with graphene oxide (GO) for CIP detection based on the complexation of CIP with Mn^{2+} in the milk sample. The fabricated sensor achieved the linear range from 1.0 to 8.0 μM with LOD of 0.30 μM. The CIP recoveries in the milk samples ranged of 81.0 to 95.4% with relative standard deviations (RSDs) below 4.6%. Liu et al. (2023) designed an electrochemical sensor for the detection of OFL in water by depositing β-cyclodextrin (β-CD) and samarium oxide nanoparticles (Sm$_2$O$_3$ NPs)

onto a laser-induced graphene (LIGr) electrode. The sensor obtains a wide linear range of 0.01 to 1.0 μmol L^{-1} and 1.0 to 120 μmol L^{-1} with low LOD of 0.005 μmol L^{-1} and good anti-interference ability and stability. This sensor was successfully applied in tap water for OFL detection.

Metal nanoparticles

Besides the CNMs, metal and metal oxide nanoparticles have been widely used in electrochemical sensing materials for a long time due to beneficial features such as their small size; unique chemical, physical, and electronic properties, flexibility in fabricating novel and improved sensing devices, and good sensitivity to the ambient conditions and the ability to immobilize bioreceptors without affecting their bioactivity (Shrivastava et al. 2016). In addition, they offer exclusive physical, chemical, and electronic properties that make them suitable as transducer components of an electrochemical biosensor. Moreover, their surfaces are easy to functionalize. Metal nanoparticles are promising immobilization matrix for aptamers, proteins, antibodies, and enzymes (Joshi and Kim 2020). Among all metal nanoparticles, (Au NPs) have been widely explored to improve the LOD in electrochemical biosensing. Very often, AuNPs are associated with carbon materials such as CNTs and Gr in a synergetic effect to enhance the electrocatalytic effect of the working electrode (Rotariu et al. 2016). Thus, considerable effort has been devoted to metal nanoparticle–based electrochemical biosensors for antibiotics detection.

Magnetic nanoparticles

In recent years, magnetic nanoparticles (MNPs) have received increasing attention toward the development of biosensor and their applications. The magnetic properties of MNPs are associated with the core and shell, which is active in biomolecule recognition, binding, and catalytic processes (Asab et al. 2020). MNPs display superparamagnetic properties at high temperatures. Superparamagnetic is when the net magnetic dipoles are zero (Mohammed et al. 2017). Most applications that use magnetic nanoparticles depend on the use of magnetic fields to manipulate their properties, which depends on the effectiveness of the particle magnetic moment and the field gradient. Moreover, MNPs can be integrated into the transducer materials, attracting analytes in the samples by an external magnetic field (Ventura-Aguilar et al. 2023). Compared to the non-MNPs-based biosensor, the biosensing strategy based on MNPs offers various advantages that include, improved sensitivity, lower detection limit, less noise, and quicker analysis (Calcaterra et al. 2022).

Quantum dots

Quantum dots (QDs) are quasi-zero-dimensional semiconductor nanostructures that bind excitons in three spatial directions, and their quantum confinement effects result in good photoelectric properties. QDs are a type of novel fluorescent nanomaterial consisting of inorganic nuclei with organic molecules in the nanoscale range of 1–10 nm applied to the surface of the nucleus (Rajendiran et al. 2019; Li et al. 2020). These materials usually consist of carbon, silicon, cadmium selenide, cadmium sulfide, or indium arsenide and emit fluorescence when excited by a light source (Zhou et al. 2018). QDs possess unique chemical properties and excellent optical properties, including extended fluorescence lifetime, adjustable particle sizes, superior signal brightness, emission of multiple fluorescence colors, confined emission spectra, and broad excitation spectra (Ding et al. 2022). Currently, QDs have been recognized as an ideal material for the development of biosensors for antibiotic detection. According to the literature, QDs have been flourishing as promising tools in the development of biosensors for FQs detection.

Nanocomposite

To overcome the limitations of individual NMs and homogenous preparations, a range of highly efficient approaches to synthesize various nanocomposites have been developed. Nanocomposite-based electrochemical biosensors have different applications in the field of environmental monitoring. Composite nanomaterials are composed of different functional components, and have garnered significant interest from materials scientists due to their combined physicochemical properties and great potential applications in the areas of electronics, photonics, catalysis, biotechnology, and nanotechnology (Hussain et al. 2017; Khasawneh et al. 2021). Generally, these nanocomposites exhibit a core/shell or a binary nanostructure which can be modified with different charges, reactive groups, or functional moieties on the surface with enhanced stability and compatibility (Pang et al. 2022). The successful application of such nanocomposites is highly dependent on their nanostructure, composition, stability, and dispersity of the particles under a range of different conditions. Furthermore, metal-based NMs can be combined with CNTs, Gr, rGO, polymers, etc., to develop nanocomposite material (Ahmadipour et al. 2021) and used to immobilize enzymes, antibodies, aptamers, etc. (Kucherenko et al. 2019). Therefore, many researchers have focused on the fabrication of different nanocomposite materials to develop novel multi-functional materials that possess serendipitous properties. Suanchan et al. (2021) developed a nanocomposite optosensing probe based on hierarchical porous carbon and graphene quantum dots incorporated with selective polymer for the detection of trace OFL. The probe showed a good linear range from 0.10 to 25 μg L^{-1} for OFL with LOD of 0.066 μg L^{-1}. The probe was applied to detect

OFL in milk achieving recoveries in the range of 92 to 99% with an RSD < 7%. In another study by Li et al. (2022), an ultrasensitive label-free molecularly imprinted polymer (MIP) voltammetric sensor for the selective determination of NOR, based on Au nanoparticle-functionalized black phosphorus nanosheet nanocomposite (BPNS-AuNP) covered by a polypyrrole-imprinted film was developed. The BPNS-AuNPs were found to improve the ambient stability and electrocatalytic activity, providing a large surface area for locating a higher number of specific recognition sites. The fabricated MIP/BPNS-AuNP/GCE sensor showed excellent sensing performance toward NOR, with a wide linear range from 0.1 nM to 10 μM, with an extremely low LOD of 0.012 nM. Similarly, Jalal et al. (2019) also developed an electrochemical sensor based on a nanocomposite of MWCNTs, magnetite nanoparticle (Fe_3O_4), and polyethylenimine (PEI) for highly sensitive detection of CIP drug in biological samples and pharmaceutical formulations. Due to the high conductivity of CNTs and moderate conductivity of the polymer along with rich active sites of amine functional groups, the PEI@Fe_3O_4@CNTs nanocomposite displayed excellent electro-catalytic effect on the electro-oxidation of CIP. The electrochemical responses of the modified electrode were proportional to the drug concentrations in the range of 0.03–70.0 μmol L^{-1} with a limit of detection of 3.0 nmol L^{-1}. Furthermore, the sensor was applied to determine CIP in the drug tablets, urine, and serum samples with acceptable recoveries of 97 to 108% and satisfactory precisions (1–3%RSD). Ghanbari et al. (2019) developed an electrochemical sensor for LEV detection based on poly (L-Cysteine) @ AuNPs @ reduced graphene oxide nanocomposite. The sensor exhibits the linear response in two concentration windows of 1.0×10^{-11} M and 1.0×10^{-4}, with LOD of 3.0×10^{-12} M. The glassy carbon electrode (GCE) modified through coating with a film of poly(l-cys)/AuNPs/rGO/GCE was found to offer high stability, reproducibility, and repeatability, as well as selectivity and was successfully used in the analysis of the LEV in synthetic blood serum, with recovery values of around 99%. In another study conducted by Bano et al. (2022), a novel PPy/Bi_2MoO_6/chitosan nanocomposites was prepared for electrochemical detection of CIP and benzene. The as-prepared sensor has shown a distinct increase in electrocatalytic and electrochemical activity. Furthermore, experimental results have confirmed high sensitivity due to the increased surface area and electron mobility of the electrocatalyst. The linear concentration falls into two distinct ranges for CIP with low LOD value and high sensitivity 0.01 to 1500 μM.

General conclusions, challenges, and future perspective

FQs are important class of antibiotics that has received widespread in clinical application. The overuse of these drugs in medicinal treatment has become problematic due to the negative effects they pose to the environment. Thus, to reduce the excessive presence of FQs in water ways, research on the development of effective detection strategy is significant to keep the environment safe. However, due to the complexity of wastewater sample, the residual detection of FQs at trace level remains difficult. Therefore, the present review was compiled to report the recent advancements in FQs detection strategies in water samples. Compared with other reported technologies, electrochemical methods are relatively simple and portable. They are promising analytical tools for FQs detection owing to their admirable properties such as low cost, high sensitivity, selectivity, and specificity. On the other hand, NMs have been successfully utilized in developing ultrasensitive electrochemical biosensors for antibiotic detection as highlighted in this review. Although these electrochemical biosensing methods have some advantages over traditional methods, there are still some challenges associated with the detection of real water samples. Electrochemical biosensors are usually designed to detect one or two analytes at a time, while there are thousands of pollutants in the environment. In addition, the electrodes that are currently produced cannot simultaneously detect all the pollutants of interest. The presence of other pollutants can interfere with targeted antibiotics. Based on the above discussion, we can conclude that the electrochemical method for the detection of antibiotics is simple and cheap, but further improvement is needed in terms of anti-interference ability and sensitivity. Furthermore, we anticipate that developing electrochemical biosensors with NMs is a powerful tool in environmental monitoring, food safety, and medical diagnosis, as well as other fields. Lastly, we believe that nanomaterial-based electrochemical biosensors for FQs can offer higher sensitivity, higher speed and integration that will increase portability and automation. However, the issue of NMs being leached off the electrode is still of great concern and alternative measures need to be developed. Hence, future research on electrochemical detection methods for antibiotics could be based on these aspects.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

References

Abedalwafa MA, Li Y, Ni C et al (2019) Colorimetric sensor arrays for the detection and identification of antibiotics. Anal Methods 11:2836–2854. https://doi.org/10.1039/c9ay00371a

Abnous K, Danesh NM, Alibolandi M et al (2014) A novel electrochemical aptasensor for ultrasensitive detection of fluoroquinolones based on single-stranded DNA-binding protein. Toxicol Appl Pharmacol 280:100–106. https://doi.org/10.1016/j.snb.2016.08.100

Acaroz U, Dietrich R, Knauer M et al (2020) Development of a generic enzyme-immunoassay for the detection of fluoro(quinolone)-residues in foodstuffs based on a highly sensitive monoclonal antibody. Food Anal Methods 13:780–792. https://doi.org/10.1007/s12161-019-01695-1

Ahmadipour M, Arjmand M, Ahmad ZA et al (2020) Photocatalytic degradation of organic dye by sol–gel-synthesized CaCu3Ti4O12 powder. J Mater Eng Perform 29:2006–2014. https://doi.org/10.1007/s11665-020-04712-1

Ahmadipour M, Azlan A, Ling A et al (2021) Journal of Environmental Chemical Engineering Photodegradation of rhodamine B-dye pollutant using CaCu 3 Ti 4 O 12 -multiwall carbon nanotube nanocomposites. J Environ Chem Eng 9:105185

Ajibola AS, Amoniyan OA, Ekoja FO et al (2021) QuEChERS Approach for the analysis of three fluoroquinolone antibiotics in wastewater: concentration profiles and ecological risk in two Nigerian hospital wastewater treatment plants. Arch Environ Contam Toxicol 80:389–401. https://doi.org/10.1007/s00244-020-00789-w

Akhavan O, Ghaderi E, Rahighi R et al (2014) Spongy graphene electrode in electrochemical detection of leukemia at single-cell levels. Carbon N Y 79:654–663. https://doi.org/10.1016/j.carbon.2014.08.058

Akhavan O, Ghaderi E, Rahighi R (2012) Toward single-DNA electrochemical biosensing by graphene nanowalls. ACS Nano 4:2904–2916. https://doi.org/10.1021/nn300261t

Akram M, Anwar J, Alshemarya AZ et al (2015) Quantitative determination of ciprofloxacin and levofloxacin antibacterials by spectrophotometeric and high performance liquid chromatography. Malaysian J Fundam Appl Sci 11:2–5. https://doi.org/10.11113/mjfas.v11n1.329

Ardani MR, Pang AL, Pal U et al (2022) Ultrasonic-assisted polyaniline-multiwall carbon nanotube photocatalyst for efficient photodegradation of organic pollutants. J Water Process Eng 46:102557. https://doi.org/10.1016/j.jwpe.2021.102557

Asab G, Zereffa EA, Abdo Seghne T (2020) Synthesis of silica-coated Fe3O4 nanoparticles by microemulsion method: characterization and evaluation of antimicrobial activity. Int J Biomater 2020. https://doi.org/10.1155/2020/4783612

Asal M, Özen Ö, Şahinler M et al (2018) Recent developments in enzyme, DNA and Immuno-Based Biosensors. Sensors (switzerland) 18:1924. https://doi.org/10.3390/s18061924

Aymard C, Kanso H, Serrano MJ et al (2022) Development of a new dual electrochemical immunosensor for a rapid and sensitive detection of enrofloxacin in meat samples. Food Chem 370:1–8. https://doi.org/10.1016/j.foodchem.2021.131016

Baig N, Sajid M, Saleh TA (2019) Recent trends in nanomaterial-modified electrodes for electroanalytical applications. TrAC - Trends Anal Chem 111:47–61. https://doi.org/10.1016/j.trac.2018.11.044

Bano S, Ganie AS, Khan RIA et al (2022) Designing and application of PPy/Bi2MoO6/chitosan nanocomposites for electrochemical detection of ciprofloxacin and benzene and evaluation of hydrogen evolution reaction. Surf Interfaces 29:101786. https://doi.org/10.1016/j.surfin.2022.101786

Bartolomé M, Soriano ML, Villaseñor MJ et al (2023) γ-Cyclodextringraphene quantum dots-chitosan modified screen-printed electrode for sensing of fluoroquinolones. Microchim Acta 190:60. https://doi.org/10.1007/s00604-023-05646-w

Bhatt S, Chatterjee S (2022) Fluoroquinolone antibiotics : occurrence, mode of action, resistance, environmental detection, and remediation – a comprehensive review. Environ Pollut 315:120440. https://doi.org/10.1016/j.envpol.2022.120440

Bizina EV, Farafonova OV, Zolotareva NI et al (2022) A piezoelectric immunosensor based on magnetic carbon nanocomposites for the determination of ciprofloxacin. J Anal Chem 77:458–465. https://doi.org/10.1134/S1061934822040049

Bonfilio R, de Araújo MB, Salgado HRN (2010) Recent applications of analytical techniques for quantitative pharmaceutical analysis: a review. WSEAS Trans Biol Biomed 7:316–338

Calcaterra A, Polli F, Lamelza L et al (2022) Resorc[4]arene-modified gold-decorated magnetic nanoparticles for immunosensor development. Bioconjug Chem 34:529–537. https://doi.org/10.1021/acs.bioconjchem.2c00605

Camilli L, Passacantando M (2018) Advances on sensors based on carbon nanotubes. Chemosensors 6:1–17. https://doi.org/10.3390/chemosensors6040062

Campaña AL, Florez SL, Noguera MJ et al (2019) Enzyme-based electrochemical biosensors for microfluidic platforms to detect pharmaceutical residues in wastewater. Biosensors 9:41. https://doi.org/10.3390/bios9010041

Cardoso AR, Carneiro LPT, Cabral-Miranda G et al (2021) Employing bacteria machinery for antibiotic detection: using DNA gyrase for ciprofloxacin detection. Chem Eng J 409:128135. https://doi.org/10.1016/j.cej.2020.128135

Cernat A, Tertiş M, Săndulescu R et al (2015) Electrochemical sensors based on carbon nanomaterials for acetaminophen detection: A review. Anal Chim Acta 886:16–28. https://doi.org/10.1016/j.aca.2015.05.044

Chaudhary N, Yadav AK, Sharma JG, Solanki PR (2021) Designing and characterization of a highly sensitive and selective biosensing platform for ciprofloxacin detection utilizing lanthanum oxide nanoparticles. J Environ Chem Eng 9:106771. https://doi.org/10.1016/j.jece.2021.106771

Chiam SL, Pung SY, Yeoh FY et al (2022) Highly efficient oxidative degradation of organic dyes by manganese dioxide nanoflowers. Mater Chem Phys 280:125848. https://doi.org/10.1016/j.matchemphys.2022.125848

Cordeiro CA, Sias A, Koster T et al (2018) In vivo "real-time" monitoring of glucose in the brain with an amperometric enzyme-based biosensor based on gold coated tungsten (W-Au) microelectrodes. Sensors Actuators B Chem 263:605–613. https://doi.org/10.1016/j.snb.2018.02.116

Cristea C, Tertis M, Galatus R (2017) Magnetic nanoparticles for antibiotics detection. Nanomaterials 7:119. https://doi.org/10.3390/nano7060119

Cui X, Cao D, Djellabi R et al (2019) Enhancement of Ni/NiO/graphitized carbon and β-Cyclodextrin/reduced graphene oxide for the electrochemical detection of norfloxacin in water sample. J Electroanal Chem 851:113407. https://doi.org/10.1016/j.jelechem.2019.113407

Cuprys A, Pulicharla R, Brar SK et al (2018) Fluoroquinolones metal complexation and its environmental impacts. Coord Chem Rev 376:46–61. https://doi.org/10.1016/j.ccr.2018.05.019

Dai Z, Tan J, Zhou K et al (2023) Optical fiber SPR biosensor with frequency multiplexing compensated laser heterodyne feedback for ultrasensitive detection of fluoroquinolones. Sensors Actuators B Chem 393:134335. https://doi.org/10.1016/j.snb.2023.134335

Das P, Fatehbasharzad P, Colombo M et al (2019) Multifunctional magnetic gold nanomaterials for cancer. Trends Biotechnol 37:995–1010. https://doi.org/10.1016/j.tibtech.2019.02.005

Dhar D, Roy S, Nigam VK (2019) Advances in protein/enzyme-based biosensors for the detection of pharmaceutical contaminants in the environment. Elsevier Inc 2019:207–229. https://doi.org/10.1016/B978-0-12-814679-8.00010-8

Ding R, Chen Y, Wang Q et al (2021) Recent advances in quantum dots-based biosensors for antibiotic detection. J Pharm Anal 12:355–364. https://doi.org/10.1016/j.jpha.2021.08.002

Ding R, Chen Y, Wang Q et al (2022) Recent advances in quantum dots-based biosensors for antibiotics detection. J Pharm Anal 12:355–364. https://doi.org/10.1016/j.jpha.2021.08.002

Ebrahimi M, Akhavan O (2022) Nanomaterials for photocatalytic degradations of analgesic, mucolytic and anti-biotic/viral/inflammatory drugs widely used in controlling SARS-CoV-2. Catalysts 12:667. https://doi.org/10.3390/catal12060667

Epa (2008) Approaches to screening for risk from pharmaceuticals in drinking water and prioritization for further evaluation. XLI:292–300.

Feleni U, Sidwaba U, Makelane H et al (2019) Core – shell palladium telluride quantum biosensor for detecting indinavir drug. J Nanosci Nanotechnol 19:1–8. https://doi.org/10.1166/jnn.2019.16866

Feleni U, Sidwaba U, Ntshongontshi N et al (2020) Biocompatible palladium telluride quantum dot-amplified biosensor for HIV drug. Electrocatalysis 11:68–76. https://doi.org/10.1007/s12678-019-00563-0

Flaherty EO, Cummins E (2017) Human and Ecological Risk Assessment : An International Antibiotic resistance in surface water ecosystems : presence in the aquatic environment, prevention strategies, and risk assessment. Hum Ecol Risk Assess 23:299–322. https://doi.org/10.1080/10807039.2016.1247254

Gaudin V (2017) Advances in biosensor development for the screening of antibiotic residues in food products of animal origin – A comprehensive review. Biosens Bioelectron 90:363–377. https://doi.org/10.1016/j.bios.2016.12.005

Ghanbari MH, Khoshroo A, Sobati H et al (2019) An electrochemical sensor based on poly (L-Cysteine)@AuNPs @ reduced graphene oxide nanocomposite for determination of levofloxacin. Microchem J 147:198–206. https://doi.org/10.1016/j.microc.2019.03.016

Gissawong N, Srijaranai S, Boonchiangma S et al (2021) An electrochemical sensor for voltammetric detection of ciprofloxacin using a glassy carbon electrode modified with activated carbon, gold nanoparticles and supramolecular solvent. Microchim Acta 188:208. https://doi.org/10.1007/s00604-021-04869-z

Gou Y, Chen P, Yang L et al (2021) Degradation of fluoroquinolones in homogeneous and heterogeneous photo-Fenton processes: a review. Chemosphere 270:129481. https://doi.org/10.1016/j.chemosphere.2020.129481

Hamnca S, Phelane L, Iwuoha E et al (2017) Electrochemical determination of neomycin and norfloxacin at a novel polymer nanocomposite electrode in aqueous solution. Anal Lett 50:1887–1896. https://doi.org/10.1080/00032719.2016.1261876

He BS, Yan SS (2018) Electrochemical aptasensor based on aptamer-complimentary strand conjugate and thionine for sensitive detection of tetracycline with multi-walled carbon nanotubes and gold nanoparticles amplification. Anal Methods 10:783–790. https://doi.org/10.1039/c7ay02728a

He K, Soares AD, Adejumo H et al (2015) Detection of a wide variety of human and veterinary fluoroquinolone antibiotics in municipal wastewater and wastewater-impacted surface water. J Pharm Biomed Anal 106:136–143. https://doi.org/10.1016/j.jpba.2014.11.020

Hernandez-Vargas G, Sosa-Hernández JE, Saldarriaga-Hernandez S et al (2018) Electrochemical biosensors: a solution to pollution detection with reference to environmental contaminants. Biosensors 8:1–21. https://doi.org/10.3390/bios8020029

Hong J, Su M, Zhao K et al (2023) A minireview for recent development of nanomaterial-based detection of antibiotics. Biosensors 13:327. https://doi.org/10.3390/bios13030327

Hussain MM, Rahman MM, Asiri AM (2017) Ultrasensitive and selective 4-aminophenol chemical sensor development based on nickel oxide nanoparticles decorated carbon nanotube nanocomposites for green environment. J Environ Sci (china) 53:27–38. https://doi.org/10.1016/j.jes.2016.03.028

Iijima S (1991) Helical microtubules of graphitic carbon. Nature 354:56–58

Jadhav VR, Bagul TD, Aswale SR (2020) Job crafting and employee innovation : peer rev. Ijnrd 7:1–3

Jahanbani S, Benvidi A (2016) Comparison of two fabricated aptasensors based on modified carbon paste/oleic acid and magnetic bar carbon paste/Fe3O4@oleic acid nanoparticle electrodes for tetracycline detection. Biosens Bioelectron 85:553–562. https://doi.org/10.1016/j.bios.2016.05.052

Jalal NR, Madrakian T, Afkhami A et al (2019) Polyethylenimine@Fe3O4@carbon nanotubes nanocomposite as a modifier in glassy carbon electrode for sensitive determination of ciprofloxacin in biological samples. J Electroanal Chem 833:281–289. https://doi.org/10.1016/j.jelechem.2018.12.004

Jalalian SH, Karimabadi N, Ramezani M et al (2018) Electrochemical and optical aptamer-based sensors for detection of tetracyclines. Trends Food Sci Technol 73:45–57. https://doi.org/10.1016/j.tifs.2018.01.009

Januarie KC, Uhuo OV, Iwuoha E et al (2022) Recent advances in the detection of interferon-gamma as a TB biomarker. Anal Bioanal Chem 414:907–921. https://doi.org/10.1007/s00216-021-03702-z

Jin H, Gui R, Gao X et al (2019) An amplified label-free electrochemical aptasensor of γ-interferon based on target-induced DNA strand transform of hairpin-to-linear conformation enabling simultaneous capture of redox probe and target. Biosens Bioelectron 145:111732. https://doi.org/10.1016/j.bios.2019.111732

Joshi A, Kim K (2020) Biosensors and Bioelectronics Recent advances in nanomaterial-based electrochemical detection of antibiotics : challenges and future perspectives. Biosens Bioelectron 153:112046. https://doi.org/10.1016/j.bios.2020.112046

Jung D, Kim J, Lee GS (2015) Enhanced humidity-sensing response of metal oxide coated carbon nanotube. Sensors Actuators, A Phys 223:11–17. https://doi.org/10.1016/j.sna.2014.12.023

Kaur G, Kaur A, Kaur H (2020) Review on nanomaterials / conducting polymer based nanocomposites for the development of biosensors and electrochemical sensors. Polym Technol Mater 00:1–18. https://doi.org/10.1080/25740881.2020.1844233

Khan MZH (2020) Recent biosensors for detection of antibiotics in animal derived food. Crit Rev Anal Chem 0:1–11. https://doi.org/10.1080/10408347.2020.1828027

Kharewal T, Verma N, Gahlaut A et al (2020) Biosensors for penicillin quantification : a comprehensive review. Biotechnol Lett 42:1829–1846. https://doi.org/10.1007/s10529-020-02970-6

Khasawneh OFS, Palaniandy P, Palaniandy P et al (2021) Removal of acetaminophen using Fe2O3-TiO2nanocomposites by photocatalysis under simulated solar irradiation: Optimization study. J Environ Chem Eng 9:104921. https://doi.org/10.1016/j.jece.2020.104921

Khosravikia M (2023) Quantitative model for predicting the electroosmotic flow in dual-pole nanochannels. Electrophoresis 44:733–743. https://doi.org/10.1002/elps.202300006

Khosravikia M, Rahbar-Kelishami A (2022) A simulation study of an applied approach to enhance drug recovery through electromembrane extraction. J Mol Liq 358:119210. https://doi.org/10.1016/j.molliq.2022.119210

Kłos-Witkowska A (2015) Enzyme-based fluorescent biosensors and their environmental, clinical and industrial applications. Polish J Environ Stud 24:19–25. https://doi.org/10.15244/pjoes/28352

Kraemer SA, Ramachandran A, Perron GG (2019) Antibiotic pollution in the environment: From microbial ecology to public policy. 180:1–24. https://doi.org/10.3390/microorganisms7060180

Kucherenko IS, Soldatkin OO, Kucherenko DY et al (2019) Advances in nanomaterial application in enzyme-based electrochemical biosensors: a review. Nanoscale Adv 1:4560–4577. https://doi.org/10.1039/c9na00491b

Kumar H, Neelam R (2016) Enzyme-based electrochemical biosensors for food safety: a review. Nanobiosensors Dis Diagnosis 20:29–39. https://doi.org/10.2147/ndd.s64847

Kuntzleman TS, Jacobson EC (2016) Teaching Beer's Law and absorption spectrophotometry with a smart phone: a substantially simplified protocol. J Chem Educ 93:1249–1252. https://doi.org/10.1021/acs.jchemed.5b00844

Kurbanoglu S, Erkmen C, Uslu B (2020) Frontiers in electrochemical enzyme based biosensors for food and drug analysis. TrAC - Trends Anal Chem 124:115809. https://doi.org/10.1016/j.trac.2020.115809

Labib M, Sargent EH, Kelley SO (2016) Electrochemical methods for the analysis of clinically relevant biomolecules 116:9001-90.https://doi.org/10.1021/acs.chemrev.6b00220

Lamarca RS, De FRAD, Zanoni MVB et al (2020) Simple, fast and environmentally friendly method to determine ciprofloxacin in wastewater samples based on an impedimetric immunosensor. RSC Adv 10:1838–1847. https://doi.org/10.1039/c9ra09083e

Lan L, Yao Y, Ping J et al (2017) Recent advances in nanomaterial-based biosensors for antibiotics detection. Biosens Bioelectron 91:504–514. https://doi.org/10.1016/j.bios.2017.01.007

Lawal AT (2018) Progress in utilisation of graphene for electrochemical biosensors. Biosens Bioelectron 106:149–178. https://doi.org/10.1016/j.bios.2018.01.030

Lawal AT (2016) Synthesis and utilization of carbon nanotubes for fabrication of electrochemical biosensors. Mater Res Bull 73:308–350. https://doi.org/10.1016/j.materresbull.2015.08.037

Leibovici L, Paul M, Garner P et al (2016) Addressing resistance to antibiotics in systematic reviews of antibiotic interventions. J Antimicrob Chemother 71:2367–2369. https://doi.org/10.1093/jac/dkw135

Li F, Wang X, Sun X et al (2018) Multiplex electrochemical aptasensor for detecting multiple antibiotics residues based on carbon fiber and mesoporous carbon-gold nanoparticles. Sensors Actuators B Chem 265:217–226. https://doi.org/10.1016/j.snb.2018.03.042

Li G, Qi X, Wu J et al (2022) Ultrasensitive, label-free voltammetric determination of norfloxacin based on molecularly imprinted polymers and Au nanoparticle-functionalized black phosphorus nanosheet nanocomposite. J Hazard Mater 436:129107. https://doi.org/10.1016/j.jhazmat.2022.129107

Li P, Liu S, Cao W et al (2020) Low-toxicity carbon quantum dots derived from gentamicin sulfate to combat antibiotic resistance and eradicate mature biofilms. Chem Commun 56:2316–2319. https://doi.org/10.1039/c9cc09223d

Li Z, Wang L, Li Y et al (2019) Carbon-based functional nanomaterials: preparation, properties and applications. Compos Sci Technol 179:10–40. https://doi.org/10.1016/j.compscitech.2019.04.028

Lim SA, Ahmed MU (2016) A simple DNA-based electrochemical biosensor for highly sensitive detection of ciprofloxacin using disposable graphene. Anal Sci 32:687–693. https://doi.org/10.2116/analsci.32.687

Liu L, Mandler D (2020) Using nanomaterials as building blocks for electrochemical deposition: a mini review. Electrochem Commun 120:106830. https://doi.org/10.1016/j.elecom.2020.106830

Liu T, Xue Q, Jia J et al (2019a) New insights into the effect of pH on the mechanism of ofloxacin electrochemical detection in aqueous solution. Phys Chem Chem Phys 21:16282–16287. https://doi.org/10.1039/c9cp03486b

Liu X, Huang D, Lai C et al (2018) Recent advances in sensors for tetracycline antibiotics and their applications. TrAC - Trends Anal Chem 109:260–274. https://doi.org/10.1016/j.trac.2018.10.011

Liu Z, Jin M, Lu H et al (2019b) Molecularly imprinted polymer decorated 3D-framework of functionalized multi-walled carbon nanotubes for ultrasensitive electrochemical sensing of Norfloxacin in pharmaceutical formulations and rat plasma. Sensors Actuators B Chem 288:363–372. https://doi.org/10.1016/j.snb.2019.02.097

Liu Z, Wang Q, Xue Q et al (2023) Highly efficient detection of ofloxacin in water by samarium oxide and β-cyclodextrin-modified laser-induced graphene electrode. Microchem J 186:108353. https://doi.org/10.1016/j.microc.2022.108353

López MS, Redondo-gómez E, López-ruiz B (2017) Talanta Electrochemical enzyme biosensors based on calcium phosphate materials for tyramine detection in food samples. Talanta 175:209–216. https://doi.org/10.1016/j.talanta.2017.07.033

Lu D, Qin M, Liu C et al (2021a) Ionic liquid-functionalized magnetic metal-organic framework nanocomposites for efficient extraction and sensitive detection of fluoroquinolone antibiotics in environmental water. ACS Appl Mater Interfaces 13:5357–5367. https://doi.org/10.1021/acsami.0c17310

Lu S, Wang S, Wu P et al (2021b) A composite prepared from covalent organic framework and gold nanoparticles for the electrochemical determination of enrofloxacin. Adv Powder Technol 32:2106–2115. https://doi.org/10.1016/j.apt.2021.04.025

Lv L, Zhang B, Tian P et al (2022) A "signal off" aptasensor based on AuNPs/Ni-MOF substrate-free catalyzed for detection Enrofloxacin. J Electroanal Chem 911:116251. https://doi.org/10.1016/j.jelechem.2022.116251

Maciel EVS, Vargas-Medina DA, Lancas FM (2023) Analyzes of β-lactam antibiotics by direct injection of environmental water samples into a functionalized graphene oxide-silica packed capillary extraction column online coupled to liquid chromatography tandem mass spectrometry. Talanta Open 7:100185. https://doi.org/10.1016/j.talo.2023.100185

Macii F, Biver T (2021) Spectrofluorimetric analysis of the binding of a target molecule to serum albumin: tricky aspects and tips. J Inorg Biochem 216:111305. https://doi.org/10.1016/j.jinorgbio.2020.111305

Madikizela LM, Nomngongo PN, Pakade VE (2022) Synthesis of molecularly imprinted polymers for extraction of fluoroquinolones in environmental, food and biological samples. J Pharm Biomed Anal 208:114447. https://doi.org/10.1016/j.jpba.2021.114447

Majdinasab M, Mishra RK, Tang X et al (2020) Detection of antibiotics in food: new achievements in the development of biosensors. TrAC - Trends Anal Chem 127:115883. https://doi.org/10.1016/j.trac.2020.115883

Majdinasab M, Yaqub M, Rahim A et al (2017) An overview on recent progress in electrochemical biosensors for antimicrobial drug residues in Animal-Derived food. Sensors (switzerland) 17:1947. https://doi.org/10.3390/s17091947

Mallakpour S, Khadem E (2016) Carbon nanotube–metal oxide nanocomposites: Fabrication, properties and applications. Chem Eng J 302:344–367. https://doi.org/10.1016/j.cej.2016.05.038

Mallik B, Chakravarti B, Chakravarti DN (2016) Principles of chromatography. Curr Protoc Essent Lab Tech 2016:6.1.1–6.1.23. https://doi.org/10.1002/cpet.7

Maycock DS, Watts CD (2011) Pharmaceuticals in Drinking Water. Encycl Environ Heal 472–484. https://doi.org/10.1016/B978-0-444-52272-6.00457-8

Mao K, Zhang H, Pan Y et al (2021) Biosensors for wastewater-based epidemiology for monitoring public health. Water Res 191:116787. https://doi.org/10.1016/j.watres.2020.116787

Miranda C, Silva V, Capita R et al (2020) Implications of antibiotics use during the COVID-19 pandemic: present and future. J Antimicrob Chemother 75:3413–3416. https://doi.org/10.1093/jac/dkaa350

Mohammed L, Gomaa HG, Ragab D et al (2017) Magnetic nanoparticles for environmental and biomedical applications: a review. Particuology 30:1–14. https://doi.org/10.1016/j.partic.2016.06.001

Mohammed MI, Desmulliez MPY (2011) Lab-on-a-chip based immunosensor principles and technologies for the detection of cardiac biomarkers: a review. Lab Chip 11:569–595. https://doi.org/10.1039/c0lc00204f

Nawaz H, Rauf S, Akhtar K et al (2006) Electrochemical DNA biosensor for the study of ciprofloxacin-DNA interaction. Anal Biochem 354:28–34. https://doi.org/10.1016/j.ab.2006.04.004

Nguyen VBC, Ayankojo AG, Reut J et al (2023) Molecularly imprinted co-polymer for class-selective electrochemical detection of macrolide antibiotics in aqueous media. Sensors Actuators B Chem 374:132768. https://doi.org/10.1016/j.snb.2022.132768

Pan M, Guo P, Liu H et al (2021) Graphene oxide modified screen-printed electrode for highly sensitive and selective electrochemical detection of ciprofloxacin residues in milk. J Anal Sci Technol 12:1–7. https://doi.org/10.1186/s40543-021-00309-y

Pang AL, Arsad A, Ahmadipour M et al (2022) High efficient degradation of organic dyes by polypyrrole-multiwall carbon nanotubes nanocomposites. Polym Adv Technol 33:1402–1411. https://doi.org/10.1002/pat.5609

Pape M (1975) Industrial applications of photochemistry. Pure Appl Chem 41:535–558. https://doi.org/10.1351/pac197541040535

Pham TSH, Hasegawa S, Mahon P et al (2022) Graphene nanocomposites based electrochemical sensing platform for simultaneous detection of multi-drugs. Electroanalysis 34:435–444. https://doi.org/10.1002/elan.202100485

Power AC, Gorey B, Chandra S, Chapman J (2018) Carbon nanomaterials and their application to electrochemical sensors: A review. Nanotechnol Rev 7:19–41. https://doi.org/10.1515/ntrev-2017-0160

Qian L, Durairaj S, Prins S, Chen A (2021) Nanomaterial-based electrochemical sensors and biosensors for the detection of pharmaceutical compounds. Biosens Bioelectron 175:112836. https://doi.org/10.1016/j.bios.2020.112836

Rajendiran K, Zhao Z, Pei DS et al (2019) Antimicrobial activity and mechanism of functionalized quantum dots. Polymers (basel) 11:1670. https://doi.org/10.3390/polym11101670

Ramesh M, Sujitha M, Anila PA et al (2021) Responses of Cirrhinus mrigala to second-generation fluoroquinolone (ciprofloxacin) toxicity: assessment of antioxidants, tissue morphology, and inorganic ions. Environ Toxicol 36:887–902. https://doi.org/10.1002/tox.23091

Rasheed AS, Qassim AW, Karabat RR (2023) Determination of ciprofloxacin in pharmaceutical preparations using (ZIC-HILIC) with UV detection. AIP Conf Proc 2457:541–544. https://doi.org/10.1063/5.0118634

Redasani VK, Patel PR, Marathe DY et al (2018) A review on derivative uv-spectrophotometry analysis of drugs in pharmaceutical formulations and biological samples review. J Chil Chem Soc 63:4126–4134. https://doi.org/10.4067/s0717-97072018000304126

Rahimpour R, Sabeti B, Chekin F (2021) Electrochemical sensor based on nitrogen doped porous reduced graphene oxide to detection of ciprofloxacin in pharmaceutical samples. Russ J Electrochem 57:654–662. https://doi.org/10.1134/S1023193520120186

Rocchitta G, Spanu A, Babudieri S et al (2016) Enzyme biosensors for biomedical applications: strategies for safeguarding analytical performances in biological fluids. Sensors (switzerland) 16:780. https://doi.org/10.3390/s16060780

Rotariu L, Lagarde F, Jaffrezic-Renault N et al (2016) Electrochemical biosensors for fast detection of food contaminants - trends and perspective. TrAC - Trends Anal Chem 79:80–87. https://doi.org/10.1016/j.trac.2015.12.017

Sabeti M, Ensafi AA, Zarean Mousaabadi K et al (2021) A selective electrochemical sensor based on a modified-glassy carbon electrode using f-MWCNTs-polydopamine for ciprofloxacin detection. IEEE Sens J 21:19714–19721. https://doi.org/10.1109/JSEN.2021.3100251

Seth S, Rathinasabapathi P (2022) A short review on detection of antibiotics in milk using nanomaterial-based biosensor. Food Anal Methods 15:2181–2192. https://doi.org/10.1007/s12161-022-02291-6

Sethuraman V, Muthuraja P, Anandha Raj J et al (2016) A highly sensitive electrochemical biosensor for catechol using conducting polymer reduced graphene oxide–metal oxide enzyme modified electrode. Biosens Bioelectron 84:112–119. https://doi.org/10.1016/j.bios.2015.12.074

Shalauddin M, Akhter S, Jeffrey Basirun W et al (2022) A metal free nanosensor based on nanocellulose-polypyrrole matrix and single-walled carbon nanotube: experimental study and electroanalytical application for determination of paracetamol and ciprofloxacin. Environ Nanotechnol Monit Manag 18:100691. https://doi.org/10.1016/j.enmm.2022.100691

Shan H, Li X, Liu L et al (2020) Recent advances in nanocomposite-based electrochemical aptasensors for the detection of toxins. J Mater Chem B 8:5808–5825. https://doi.org/10.1039/d0tb00705f

Shetti NP, Bukkitgar SD, Reddy KR et al (2019) Nanostructured titanium oxide hybrids-based electrochemical biosensors for healthcare applications. Colloids Surf B Biointerfaces 178:385–394. https://doi.org/10.1016/j.colsurfb.2019.03.013

Shi X, Zuo Y, Jia X et al (2020) A novel molecularly imprinted sensor based on gold nanoparticles/reduced graphene oxide/single-walled carbon nanotubes nanocomposite for the detection of pefloxacin. Int J Electrochem Sci 15:9683–9697. https://doi.org/10.20964/2020.10.38

Shinko EI, Farafonova OV, Shanin IA et al (2022) Determination of the fluoroquinolones levofloxacin and ciprofloxacin by a piezoelectric immunosensor modified with multiwalled carbon nanotubes (MWCNTs). Anal Lett 55:1164–1177. https://doi.org/10.1080/00032719.2021.1991364

Shokoufi N, Vosough M, Rahimzadegan-Asl M et al (2020) Fiberoptic-coupled spectrofluorometer with array detection as a process analytical chemistry tool for continuous flow monitoring of fluoroquinolone antibiotics. Int J Anal Chem 2020. https://doi.org/10.1155/2020/2921417

Shrivastava S, Jadon N, Jain R (2016) Next-generation polymer nanocomposite-based electrochemical sensors and biosensors: a review. TrAC - Trends Anal Chem 82:55–67. https://doi.org/10.1016/j.trac.2016.04.005

Singh A, Sharma A, Ahmed A et al (2021) Recent advances in electrochemical biosensors: applications, challenges, and future scope. Biosensors 11:1–31. https://doi.org/10.3390/bios11090336

Sodhi KK, Kumar M, Dhaulaniya AS et al (2021) Enhanced ciprofloxacin removal by plant growth-promoting Microbacterium sp. WHC1 in presence of Eichhornia crassipes root exudates. Environ Sustain 4:143–153. https://doi.org/10.1007/s42398-020-00153-7

Sodhi KK, Singh DK (2021) Insight into the fluoroquinolone resistance, sources, ecotoxicity, and degradation with special emphasis on ciprofloxacin. J Water Process Eng 43:102218. https://doi.org/10.1016/j.jwpe.2021.102218

Soylemez S, Kaya HZ, Udum YA et al (2019) A multipurpose conjugated polymer: electrochromic device and biosensor construction for glucose detection. Org Electron 65:327–333. https://doi.org/10.1016/j.orgel.2018.11.001

Speltini A, Sturini M, Maraschi F et al (2015) Graphene-derivatized silica as an efficient solid-phase extraction sorbent for preconcentration of fluoroquinolones from water followed by liquid-chromatography fluorescence detection. J Chromatogr A 1379:9–15. https://doi.org/10.1016/j.chroma.2014.12.047

Suanchan K, Chansud N, Sa-nguanprang S et al (2021) A nanocomposite optosensing probe based on hierarchical porous carbon and graphene quantum dots incorporated in selective polymer for the detection of trace ofloxacin. Colloids Surf A Physicochem Eng Asp 628:127376. https://doi.org/10.1016/j.colsurfa.2021.127376

Sun Y, Waterhouse GIN, Qiao X et al (2023) Determination of chloramphenicol in food using nanomaterial-based electrochemical and optical sensors-a review. Food Chem 410:135434. https://doi.org/10.1016/j.foodchem.2023.135434

Taghdisi Heidarian SM, Tavanaee Sani A, Danesh NM et al (2021) A novel electrochemical approach for the ultrasensitive detection of fluoroquinolones based on a double-labelled aptamer to surpass complementary strands of aptamer lying flat. Sensors Actuators B Chem 334:129632. https://doi.org/10.1016/j.snb.2021.129632

Taherizadeh M, Jahani S, Moradalizadeh M et al (2023) Synthesis of a dual-functional terbium doped copper oxide nanoflowers for high-efficiently electrochemical sensing of ofloxacin, pefloxacin and gatifloxacin. Talanta 255:124216. https://doi.org/10.1016/j.talanta.2022.124216

Teglia CM, Perez FA, Michlig N et al (2019) Occurrence, distribution, and ecological risk of fluoroquinolones in rivers and wastewaters. Environ Toxicol Chem 38:2305–2313. https://doi.org/10.1002/etc.4532

Ters LET (2022) Monoculture plantations fuel fires amid heat waves A low-carbon future for China ' s tech industry Standards needed for antibiotics in water. Science 377:1498–1498

Tran TTT, Do MN, Dang TNH et al (2022) A state-of-the-art review on graphene-based nanomaterials to determine antibiotics by electrochemical techniques. Environ Res 208:112744. https://doi.org/10.1016/j.envres.2022.112744

Ventura-Aguilar RI, Bautista-Baños S, Mendoza-Acevedo S et al (2023) Nanomaterials for designing biosensors to detect fungi and bacteria related to food safety of agricultural products. Postharvest Biol Technol 195:112116. https://doi.org/10.1016/j.postharvbio.2022.112116

Vu OT, Nguyen QH, Nguy Phan T et al (2022) Highly sensitive molecularly imprinted polymer-based electrochemical sensors enhanced by gold nanoparticles for norfloxacin detection in aquaculture water. ACS Omega 8:2887–2896. https://doi.org/10.1021/acsomega.2c04414

Wammer KH, Korte AR, Lundeen RA et al (2013) Direct photochemistry of three fluoroquinolone antibacterials: norfloxacin, ofloxacin, and enrofloxacin. Water Res 47:439–448. https://doi.org/10.1016/j.watres.2012.10.025

Wang Q, Xue Q, Chen T et al (2021) Recent advances in electrochemical sensors for antibiotics and their applications. Chinese Chem Lett 32:19–29. https://doi.org/10.1016/j.cclet.2020.10.025

Wang S, Liu Y, Zhu A et al (2023) In Vivo Electrochemical biosensors: recent advances in molecular design, electrode materials, and electrochemical devices. Anal Chem 95:388–406. https://doi.org/10.1021/acs.analchem.2c04541

Wang T, Fu Y, Bu L et al (2012) Facile synthesis of Prussian blue-filled multiwalled carbon nanotubes nanocomposites: exploring filling/electrochemistry/mass-transfer in nanochannels and cooperative biosensing mode. J Phys Chem C 116:20908–20917. https://doi.org/10.1021/jp306492a

Wang Y, Cui Y, Wang H et al (2022) Ofloxacin and norfloxacin simultaneous detection by ERGO/GCE and its application in medicine and aquaculture wastewater. Res Chem Intermed 49:741–761. https://doi.org/10.1007/s11164-022-04892-6

Wang Z, Yu J, Gui R et al (2016) Carbon nanomaterials-based electrochemical aptasensors. Biosens Bioelectron 79:136–149. https://doi.org/10.1016/j.bios.2015.11.093

Wenninger N, Bračič U, Kollau A et al (2021) Development of an electrochemical sensor for nitric oxide based on carbon paste electrode modified with Nafion, gold nanoparticles and graphene nanoribbons. Sensors Actuators B Chem 346:130532. https://doi.org/10.1016/j.snb.2021.130532

Wu D, Du D, Lin Y (2016) Trends in Analytical Chemistry Recent progress on nanomaterial-based biosensors for veterinary drug residues in animal-derived food. Trends Anal Chem 83:95–101. https://doi.org/10.1016/j.trac.2016.08.006

Wu T, Du Y, Dai L et al (2022) A direct Z-scheme AgBr/CuBi2O4 photocathode for ultrasensitive detection of ciprofloxacin and ofloxacin by controlling the release of luminol in self-powered microfluidic photoelectrochemical aptasensors. Anal Chem 94:10651–10658. https://doi.org/10.1021/acs.analchem.2c00889

Xia D, Yan J, Hou S (2012) Fabrication of nanofluidic biochips with nanochannels for applications in DNA analysis. Small 8:2787–2801. https://doi.org/10.1002/smll.201200240

Xia Q, Yang Y, Liu M (2013) Spectrofluorimetric determination of fluoroquinolones in honey with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone in the presence of β-cyclodextrin. J Fluoresc 23:713–723. https://doi.org/10.1007/s10895-013-1166-1

Yadav AK, Dhiman TK, Lakshmi GBVS et al (2020) A highly sensitive label-free amperometric biosensor for norfloxacin detection based on chitosan-yttria nanocomposite. Int J Biol Macromol 151:566–575. https://doi.org/10.1016/j.ijbiomac.2020.02.089

Yadav AK, Verma D, Solanki PR (2021) Electrophoretically deposited L-cysteine functionalized MoS2@MWCNT nanocomposite platform: a smart approach toward highly sensitive and label-free detection of gentamicin. Mater Today Chem 22:100567. https://doi.org/10.1016/j.mtchem.2021.100567

Yang M, Chen Y, Yan P et al (2021) A photoelectrochemical aptasensor of ciprofloxacin based on Bi24O31Cl10/BiOCl heterojunction. Microchim Acta 188(188):1–8. https://doi.org/10.1007/s00604-021-04952-5

Yazdanparast S, Benvidi A, Abbasi S, Rezaeinasab M (2019) Enzyme-based ultrasensitive electrochemical biosensor using poly (L -aspartic acid)/ MWCNT bio-nanocomposite for xanthine

detection : A meat freshness marker. Microchem J 149:10400. https://doi.org/10.1016/j.microc.2019.104000

Yiruhan WQJ, Mo CH et al (2010) Determination of four fluoroquinolone antibiotics in tap water in Guangzhou and Macao. Environ Pollut 158:2350–2358. https://doi.org/10.1016/j.envpol.2010.03.019

You F, Wen Z, Yuan R et al (2022) Selective and ultrasensitive detection of ciprofloxacin in milk using a photoelectrochemical aptasensor based on Ti3C2/Bi4VO8Br/TiO2 nanocomposite. J Electroanal Chem 914:116285. https://doi.org/10.1016/j.jelechem.2022.116285

Zahra A, Luo Z, Ali R et al (2021) Advances in gold nanoparticles-based colorimetric aptasensors for the detection of antibiotics : an overview of the past decade. Nanomaterials 11:840. https://doi.org/10.3390/nano11040840

Zhang W, Yang F, Wang H et al (2020) Determination of four residues of fluoroquinolones with similar structure in fish by modified QuEChERS protocol coupled to capillary electrophoresis (CE) with end-column electrochemiluminescence (ECL). Int J Electrochem Sci 15:6802–6814. https://doi.org/10.20964/2020.07.55

Zhang X, Lin M, Dai Y et al (2023) Stochastic sensing of dynamic interactions and chemical reactions with nanopores/nanochannels. Analytical Chem 95:10465–10475. https://doi.org/10.1021/acs.analchem.3c00543

Zhang XH, Deng Y, Zhao MZ et al (2018) Highly-sensitive detection of eight typical fluoroquinolone antibiotics by capillary electrophoresis-mass spectroscopy coupled with immunoaffinity extraction. RSC Adv 8:4063–4071. https://doi.org/10.1039/c7ra12557g

Zhang Z, Liu JF, Feng TT et al (2013) Time-resolved fluoroimmunoassay as an advantageous analytical method for assessing the total concentration and environmental risk of fluoroquinolones in surface waters. Environ Sci Technol 47:454–462. https://doi.org/10.1021/es303858a

Zhang Z, Liu Q, Zhang M et al (2021) Simultaneous detection of enrofloxacin and ciprofloxacin in milk using a bias potentials controlling-based photoelectrochemical aptasensor. J Hazard Mater 416:125988. https://doi.org/10.1016/j.jhazmat.2021.125988

Zhao J, Huang P, Jin W (2021) Electrochemical sensor based on TiO2/polyvinyl alcohol nanocomposite for detection of ciprofloxacin in rainwater. Int J Electrochem Sci 16:1–10. https://doi.org/10.20964/2021.10.01

Zhou J, Yun X, Wang J et al (2022) A review on the ecotoxicological effect of sulphonamides on aquatic organisms. Toxicol Reports 9:534–540. https://doi.org/10.1016/j.toxrep.2022.03.034

Zhou JW, Zou XM, Song SH, Chen GH (2018) Quantum dots applied to methodology on detection of pesticide and veterinary drug residues. J Agric Food Chem 66:1307–1319. https://doi.org/10.1021/acs.jafc.7b05119