



Review

Nanomaterial-Based Biosensors: Sensing Mechanisms, Performance Determinants, and Applications

Sugandika Maparathne , Rafiqul Islam , Melissa Ariza Gonzalez , Ruwanthi Amarasekara , Refia Atik , Pailinrut Chinwangso and T. Randall Lee *

Department of Chemistry and the Texas Center for Superconductivity, University of Houston, Houston, TX 77204, USA

* Correspondence: trlee@uh.edu

Abstract

Nanomaterial-based biosensors have advanced analytical methodologies by enhancing signal transduction, interfacial reactivity, and molecular recognition across diverse sensing platforms. In parallel, the diversity of nanomaterial compositions, architectures, and interfacial designs has expanded the range of available sensing strategies and performance outcomes. This review addresses limitations through a structure–property–function framework that links nanomaterial characteristics to sensing behavior, performance determinants, and application-specific requirements. Within this framework, nanomaterials are classified according to their dominant functional roles in biosensing, including plasmonic, electroactive, fluorescent and quantum-confined, porous, and hybrid architectures. The influence of morphology, surface chemistry, conductivity, and interfacial design on electrochemical, optical, and hybrid transduction mechanisms is critically examined, and key performance parameters, including sensitivity, selectivity, limit of detection, response time, stability, and reproducibility, are discussed in relation to material properties and sensing configuration. Recent advances in clinical biomarker detection, pathogen and nucleic acid analysis, and environmental and food safety monitoring are also evaluated to illustrate how nanomaterial design is tailored to different analytical contexts. Current limitations related to reproducibility, interface engineering, long-term stability, and scalable device integration are highlighted, together with future directions for the rational development of robust and application-oriented biosensor platforms.

Keywords: biosensors; biorecognition elements; sensing mechanisms; nanomaterials; surface functionalization; sensitivity



Academic Editors: Dmitri Simberg and Peng Huang

Received: 26 February 2026

Revised: 1 May 2026

Accepted: 28 May 2026

Published: 2 June 2026

Copyright: © 2026 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

Biosensors are analytical devices that integrate biological recognition elements with electronic components to generate a quantifiable signal [1]. Since their introduction, biosensors have evolved into versatile platforms for applications in clinical diagnostics, environmental monitoring, and food safety [1–3]. A typical biosensor consists of a biorecognition element, a transducer, and a signal processing unit, where the transducer converts a biochemical interaction into a measurable signal [4].

The incorporation of nanomaterials has significantly advanced biosensor performance by introducing tunable physicochemical properties, including high surface-to-volume ratios, enhanced electron transfer kinetics, and unique optical characteristics [5]. Metallic nanostructures, carbon-based materials, metal oxides, and quantum-confined systems

have been widely explored to improve sensitivity, selectivity, and response time in both electrochemical and optical sensing platforms. Phenomena such as localized surface plasmon resonance (LSPR), catalytic activity, and quantum confinement effects enable efficient signal amplification and low detection limits [6–8].

Despite extensive progress, the current literature remains largely descriptive, with many studies organized according to material composition rather than functional roles in biosensing. Such approaches often emphasize individual nanomaterial systems without consistently establishing how their physicochemical properties govern sensing mechanisms and analytical performance. As a result, direct comparison across material classes and rational design of biosensor platforms remain challenging.

To address this limitation, this review introduces a structure–property–function framework for nanomaterial-based biosensors. Nanomaterials are classified according to their dominant functional contributions to signal generation, including plasmonic, electroactive, fluorescent, and porous architectures. Within this framework, the relationships between nanomaterial properties, transduction mechanisms, and key performance metrics such as sensitivity, limit of detection, selectivity, and stability are systematically analyzed. Figure 1 illustrates the main components of a biosensor.

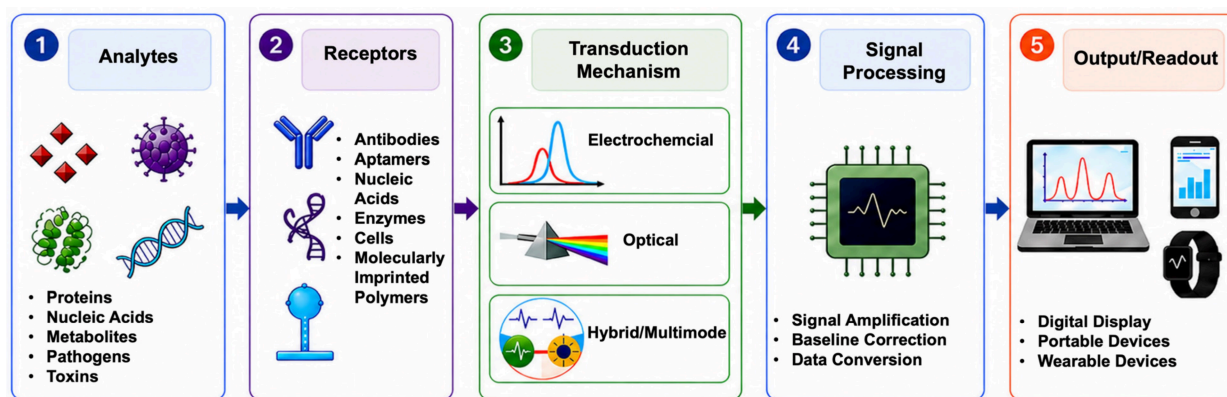


Figure 1. Schematic representation of a biosensing workflow illustrating the progression from target analytes and biorecognition elements to transduction mechanisms, signal processing, and final device-based readout.

2. Functional Classification of Nanomaterials in Biosensing

Nanomaterials can be classified based on their composition into inorganic systems (e.g., noble metals, ceramic nanoparticles, and magnetic nanoparticles), organic systems (e.g., liposomes, polymer nanoparticles, polymeric micelles, polymer–drug conjugates, hydrogel nanoparticles, protein-based nanoparticles, and dendrimers), carbon-based nanomaterials, and hybrid or composite materials [9,10]. These classifications provide limited insight into their functional roles in biosensing systems. Instead, biosensor performance is primarily determined by how nanomaterial physicochemical properties interact with transduction mechanisms. Accordingly, nanomaterials are classified here based on their dominant functional contributions to signal generation and amplification. This approach enables systematic comparison across material classes and establishes a direct structure–property–function relationship.

The functional classification of nanomaterials used in biosensing, along with representative examples, is summarized in Figure 2.

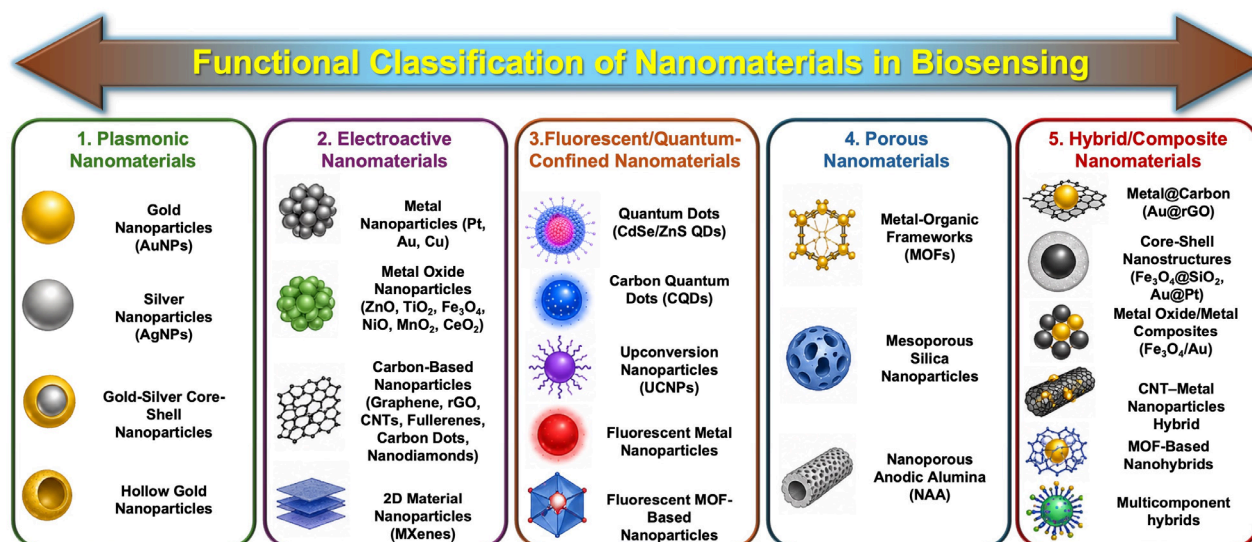


Figure 2. Functional classification of nanomaterials used in biosensing, grouped into plasmonic, electroactive, fluorescent/quantum-confined, porous, and hybrid/composite systems. Representative examples are shown for each category, highlighting their distinct roles in signal transduction and sensing performance.

2.1. Plasmonic Nanomaterials

Plasmonic nanomaterials enable optical signal transduction through localized surface plasmon resonance (LSPR), which arises from collective oscillations of conduction electrons in metallic nanostructures [11]. This phenomenon is highly sensitive to local refractive index changes, enabling label-free detection and real-time monitoring of biomolecular interactions [12].

Gold and silver nanoparticles are widely used plasmonic materials due to their chemical stability, tunable optical properties, and well-defined surface chemistry [5,13]. The LSPR response is strongly dependent on particle size, morphology, and interparticle spacing, which influence spectral position and signal intensity. Aggregation-induced plasmon coupling produces measurable optical shifts and is widely exploited in colorimetric biosensing applications [13].

While plasmonic nanomaterials significantly enhance analytical sensitivity through signal amplification, their selectivity is governed by surface functionalization strategies involving bio recognition elements, such as antibodies, aptamers, or nucleic acids [14,15]. Therefore, interfacial chemistry plays a critical role in determining overall sensor performance. Recent advances in plasmonic nanomaterials have focused on improving sensing sensitivity through structural control and plasmonic coupling effects. Jiang et al. (2025) developed a gold nanoparticle-based biosensor for rapid detection of *Helicobacter pylori*, demonstrating high sensitivity and fast response suitable for clinical diagnostics (Figure 3a) [16]. In addition, Borjikhani et al. developed an LSPR biosensor based on a tapered optical fiber (TOF) functionalized with HAuNPs for cancer biomarker detection [17]. The use of HAuNPs improves sensitivity and yields a reduced full width at half maximum (FWHM), thereby enhancing wavelength resolution (Figure 3b) [17]. Similarly, Zhao et al. (2025) reported Au–Ag core–shell nanostructures for dual SERS/colorimetric detection of *Staphylococcus aureus*, achieving enhanced signal amplification and reduced interference in complex samples, while Demishkevich et al. (2023) showed that tuning nanoparticle morphology significantly improves plasmonic response and detection performance [18,19].

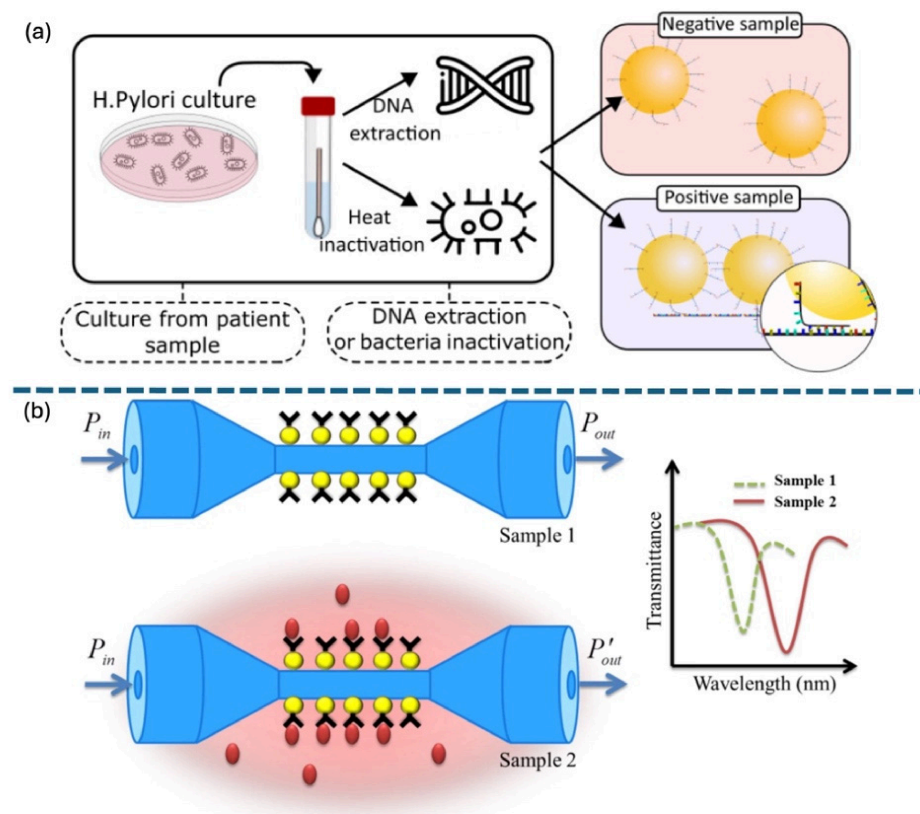


Figure 3. (a) Aggregation-induced plasmonic coupling of colloidal AuNPs for colorimetric detection of *Helicobacter pylori* DNA. Dispersed AuNPs remain separated in negative samples, whereas target-induced aggregation occurs in positive samples. Gold-colored spheres represent AuNPs. (b) Schematic representation of tapered optical fiber (TOF)-based LSPR biosensors functionalized with AuNPs. Yellow spheres represent immobilized AuNPs, black Y-shaped structures denote surface recognition elements, and red species indicate bound target analytes. Binding events alter the local refractive index and produce measurable shifts in the transmission spectrum. Reproduced with permission from Refs. [16,17]. Copyright 2025 American Chemical Society and 2025 Springer Nature.

These studies collectively demonstrate that nanoparticle morphology, composition, and interparticle coupling are key determinants of plasmonic biosensor performance.

2.2. Electroactive Nanomaterials

Electroactive nanomaterials facilitate charge transfer processes at electrode interfaces, thereby enhancing electrochemical signal generation. Their performance is governed by electrical conductivity, catalytic activity, and surface defect structure [20]. This category includes metal nanoparticles, metal oxides, carbon-based nanomaterials, and emerging two-dimensional materials such as MXenes [21].

Metal oxide nanomaterials have attracted considerable attention in biosensor development owing to their distinctive physicochemical properties, including high surface-to-volume ratios, catalytic activity, biocompatibility, and tunable electronic structures enabling both enzymatic and non-enzymatic sensing mechanisms [22–25]. Among them, ZnO, TiO₂, Fe₃O₄, NiO, MnO₂, and CeO₂ are the most extensively investigated metal oxides, offering advantages such as high isoelectric points, good electron mobility, and low toxicity, which make them well suited for biosensing applications [14,24,26].

Carbon-based nanomaterials, including graphene, carbon nanotubes (CNTs), graphene oxide (GO), carbon dots (CDs), fullerenes, and nanodiamonds, have emerged as key components in biosensor development due to their excellent electrical conductivity, high surface-to-volume ratios, mechanical robustness, and ease of surface functionalization [27].

These properties promote efficient electron transfer, enhanced signal transduction, and high-density immobilization of bioreceptors in both enzymatic and non-enzymatic electrochemical biosensors [28].

The surface chemistry of carbon nanomaterials can be readily tailored to enable functionalization with a wide range of biological recognition elements, such as enzymes, antibodies, nucleic acids, and aptamers [29]. This versatility supports the development of sensitive, selective, and rapid biosensors for diverse analytes, including glucose, dopamine, proteins, and nucleic acids [27]. Moreover, integration of carbon nanomaterials with metal nanoparticles or conductive polymers further enhances sensor performance by lowering detection limits, improving operational stability, and expanding detection ranges [30]. Their flexibility and compatibility with various fabrication techniques have facilitated their incorporation into next-generation biosensing formats, such as lab-on-a-chip devices and wearable diagnostic systems, enabling real-time and non-invasive monitoring under physiological conditions [31].

MXenes are a class of two-dimensional transition metal carbides, nitrides, and carbonitrides that have emerged as promising materials for biosensing applications due to their high electrical conductivity, hydrophilicity, surface functionalization capability, and biocompatibility [32,33]. Their layered structure, combined with abundant surface terminations (e.g., $-\text{OH}$, $-\text{O}$, and $-\text{F}$), provides reactive sites for the immobilization of biomolecules such as enzymes, antibodies, and nucleic acids [34,35]. In addition, their high surface-to-volume ratio and strong adsorption capacity enable efficient loading of biorecognition elements, thereby enhancing sensitivity and lowering detection limits in both catalytic and affinity-based biosensing platforms [33,35]. These features facilitate improved electron transfer and efficient signal transduction, which are essential for high-performance electrochemical biosensors.

Recent advances in electroactive nanomaterials have focused on improving charge transfer efficiency, catalytic activity, and simultaneous detection of different analytes. Elshafie et al. (2025) developed a Pt-doped reduced graphene oxide–porphyrin–CNT composite for the simultaneous electrochemical detection of dopamine, serotonin, and norepinephrine, demonstrating high sensitivity and clear signal resolution [36]. Saadh et al. (2025) showed that ZnO and MgO nanocages exhibit strong adsorption and sensing performance for anticancer drug detection, highlighting the influence of nanostructured morphology on electrochemical response [37]. In a separate study, Zermane et al. (2025) developed an electrochemical aptasensor for testosterone detection using a $\text{Ti}_3\text{C}_2\text{T}_x$ MXene– Fe_2O_3 hybrid nanocomposite [32]. The sensor, presented in Figure 4, employed a partially hybridized DNA system, where target binding induced aptamer conformational changes and disrupted duplex formation. The MXene– Fe_2O_3 hybrid enhanced conductivity and catalytic activity, leading to improved sensing performance [32].

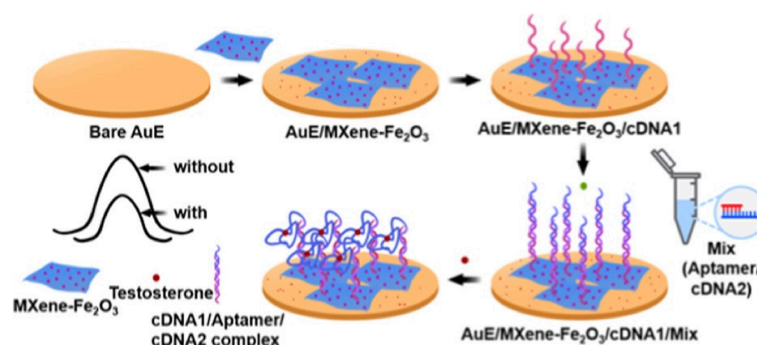


Figure 4. Schematic illustration of the electrochemical testosterone detection mechanism based on an Fe_2O_3 – Ti_3C_2 MXene (iron(III) oxide–titanium carbide MXene) nanocomposite. The figure depicts the immobilization of aptamer-based biorecognition elements on the nanocomposite surface and the

conformational change induced upon target binding, which disrupts duplex formation and modulates the electrochemical signal. The Fe_2O_3 -MXene hybrid enhances electron transfer and catalytic activity due to its high conductivity, surface functionality, and interfacial charge transfer properties, thereby improving signal amplification, sensitivity, and detection performance. Blue sheets denote Fe_2O_3 -MXene hybrids, purple and blue strands represent nucleic acid probes, and red dots indicate testosterone molecules. Arrows indicate the sequence of fabrication and sensing steps. Reproduced with permission from Ref. [32]. Copyright 2025 American Chemical Society.

Collectively, electroactive nanomaterials play a central role in determining sensitivity, response time, and detection limits in electrochemical biosensors.

2.3. Fluorescent and Quantum-Confined Nanomaterials

Fluorescence-based sensing is widely employed in biosensing due to its high sensitivity, rapid response, and operational simplicity [38]. Representative fluorescent nanomaterials include metallic nanoparticles, upconversion nanoparticles, quantum dots (QDs), carbon-based nanomaterials, and MOFs [39]. Fluorescent nanomaterials generate optical signals through photoluminescence processes, often governed by quantum confinement effects. Their emission properties depend on size, composition, and surface states, enabling tunable optical responses [40].

The sensing mechanism is based on changes in the fluorescence properties induced by interactions between the recognition element and the target analyte [39]. These alterations may manifest as fluorescence quenching, enhancement, recovery, ratiometric responses, wavelength shifts, or anisotropy variations, all of which can be quantitatively correlated with analyte concentration [41,42].

Recent advances in fluorescent and quantum-confined nanomaterials have focused on improving signal tunability, multiplexing capability, and analytical sensitivity. Quesada-González and Merkoçi (2025) demonstrated that quantum dot-based biosensors enable highly sensitive and multiplexed detection due to their tunable emission profiles and high photostability [7]. Zhou et al. (2022) reported fluorescent nanomaterial-based biosensors for food safety analysis, showing that emission-based sensing strategies provide rapid and sensitive detection of target analytes in complex matrices [26]. Similarly, Yoo et al. developed a fluorescence-based lateral flow immunoassay for CA19-9 detection using CdSe/ZnS quantum dots embedded in silica nanoparticles [43]. The probes were functionalized with PEG-linked aptamers for specific antigen binding at the test line. Accumulation of the fluorescent nanoparticles produced a signal proportional to CA19-9 concentration, enabling quantitative detection [43]. In addition, Chiu et al. (2025) developed a flexible glucose biosensor using carbon nitride quantum dots (CNQDs) integrated with polyaniline, where immobilized glucose oxidase enabled enzymatic detection in sweat [44]. Glucose oxidation generated an electrochemical signal proportional to concentration. The incorporation of CNQDs improved charge transfer and surface area, enhancing sensor sensitivity and performance [44]. Figure 5 shows a flexible wearable glucose biosensor based on a carbon quantum dots/polyaniline nanocomposite, illustrating the integration of quantum-confined nanomaterials into non-invasive sensing platforms.

These studies collectively demonstrate that emission tunability, photostability, and fluorescence modulation are central to the performance of quantum-confined biosensing platforms.

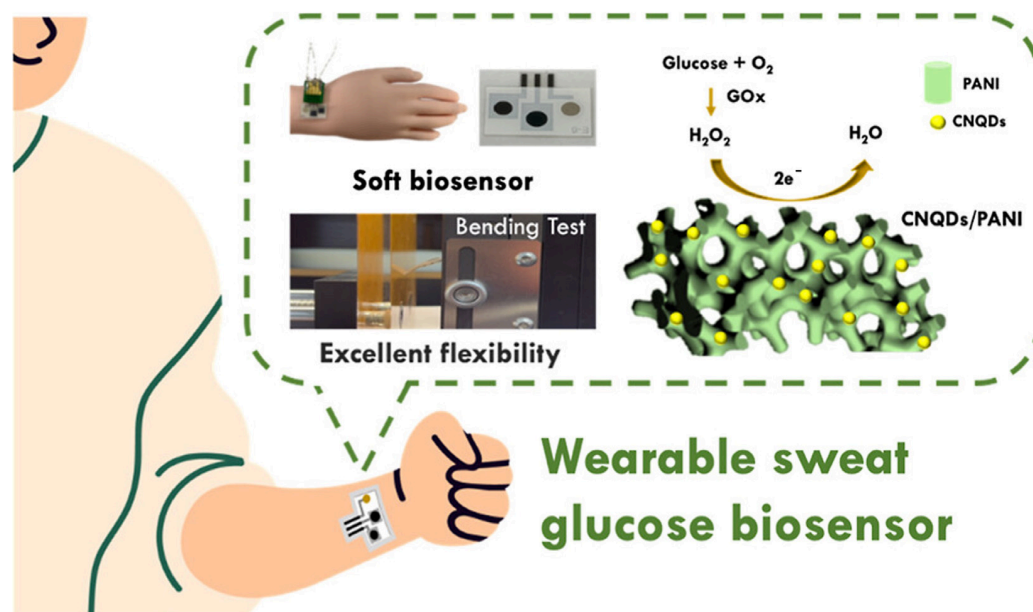


Figure 5. Schematic illustration of a non-invasive, flexible wearable sweat biosensor based on a carbon quantum dots/polyaniline (CQDs/PANI) nanocomposite. The figure depicts enzymatic glucose detection mediated by immobilized glucose oxidase, where glucose oxidation generates a measurable signal proportional to analyte concentration. The CQDs/PANI nanocomposite enhances signal transduction through improved charge transfer, increased surface area, and tunable photoluminescence properties. This integration highlights the role of quantum-confined nanomaterials in enabling sensitive, real-time, and non-invasive biosensing in wearable platforms. Reproduced with permission from Ref. [44]. Copyright 2025 American Chemical Society.

2.4. Porous and High-Surface-Area Nanostructures

Porous nanomaterials, including metal–organic frameworks (MOFs), nanoporous anodic alumina, and mesoporous silica, enhance biosensor performance by providing large surface areas for biomolecule immobilization and analyte interaction. Their functionality arises primarily from structural architecture rather than intrinsic electronic or optical properties [45–47].

These materials enable high loading densities of biorecognition elements and facilitate analyte diffusion within nanoscale pores. Pore size distribution and surface chemistry influence mass transport and binding kinetics, directly affecting sensitivity and response time. Porous nanostructures are therefore particularly effective in applications requiring high analyte capture efficiency and rapid signal generation [48,49].

Recent advances in porous and high-surface-area nanostructures have focused on increasing analyte accessibility, loading capacity, and signal amplification. Kong et al. (2025) developed an electrochemiluminescence immunoassay system based on PCN-224-Mn and gold–platinum bimetallic nanoflowers for sensitive detection of ochratoxin A, showing that porous architectures can substantially enhance signal output [50]. In addition, Liu et al. (2025) developed a PDMS-based substrate incorporating flower-like ZIF-67@Ag nanoparticles for simultaneous SERS detection of creatinine and urea [51]. The porous MOF structure facilitated analyte enrichment, while embedded AgNPs generated plasmonic hotspots. Combined electromagnetic and charge-transfer effects enabled sensitive and selective Raman signal enhancement [51]. In a related approach, Yuan et al. (2025) developed a biosensing platform using nickel mesh sheets and MIL-88@Pd/Pt nanozymes for multiplexed detection of *Salmonella* [52]. The MOF-supported Pd/Pt nanoparticles exhibited peroxidase-like activity and formed sandwich immunocomplexes with target bac-

teria. Catalytic oxidation of TMB produced a colorimetric signal proportional to bacterial concentration, enabling quantitative detection [52].

These studies collectively indicate that pore architecture, accessible surface area, and analyte transport are major determinants of sensing efficiency in porous nanomaterial-based biosensors.

2.5. Hybrid and Multimodal Nanostructures

Hybrid nanostructures represent a key direction for the development of next-generation biosensors with improved performance and broader applicability. Hybrid nanomaterials combine multiple functional properties within a single platform, enabling enhanced biosensor performance through synergistic effects. Examples include metal–graphene composites, metal oxide–carbon hybrids, and plasmonic–fluorescent systems [53].

CNT-based hybrids with bimetallic nanoparticles have been explored for sensitive antibiotic detection. In a recent study, Lv et al. (2025) reported an Au@Pt–CNT magnetic immunoassay exhibiting enhanced peroxidase-like activity for tetracycline detection [54]. The nanohybrids catalyze TMB oxidation to generate a colorimetric signal proportional to analyte concentration, achieving significantly lower detection limits than conventional assays [54]. Similarly, Wekalao et al. (2025) developed a graphene–metal terahertz metamaterial sensor for detecting water-borne pathogens via refractive index changes [55]. Bacterial binding induced shifts in resonance frequency and THz transmission, providing a measurable optical response. These spectral variations were analyzed to enable sensitive detection [55]. In addition, Lisboa et al. demonstrated the integration of nanoporous graphene (NPG) into bimodal waveguide (BiMW) sensors for the detection of C-reactive protein (CRP), a clinically relevant inflammatory biomarker [56]. NPG acts as an atomically precise and highly reactive scaffold for bioreceptor immobilization. Upon CRP binding, antigen–antibody interactions induce changes in the local refractive index, producing a measurable differential phase shift ($\Delta\Phi$) in the BiMW sensor output [56]. Figure 6 illustrates the nanoporous graphene-integrated bimodal waveguide biosensor used for C-reactive protein detection, highlighting the biofunctionalization strategy and the real-time sensing response.

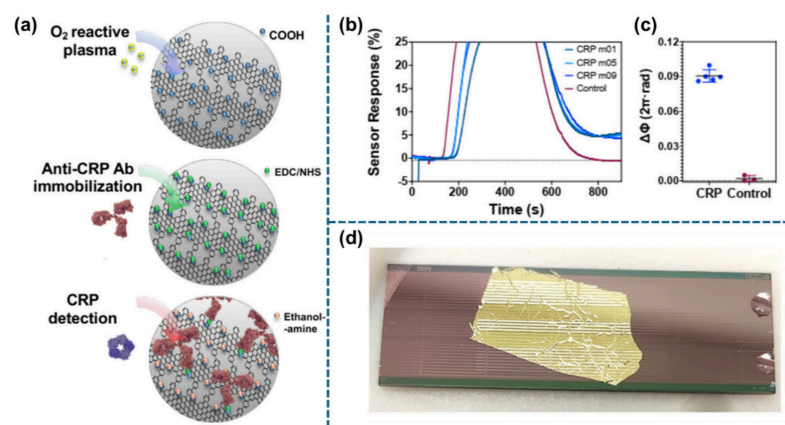


Figure 6. (a) Schematic illustration of nanoporous graphene (NPG) biofunctionalization and covalent immobilization of antibodies via EDC/NHS cross-linking to surface carboxyl groups. (b) Real-time sensor response (sensorgrams) for C-reactive protein (CRP) detection compared with a negative control (BSA), demonstrating specificity. (c) Quantitative comparison of specific and nonspecific responses obtained from the NPG-integrated bimodal waveguide (BiMW) sensor. (d) Photograph of the BiMW device coated with NPG and a thin gold layer in the sensing region. The figure highlights how the high surface area, tunable surface chemistry, and optical properties of NPG enable efficient bioreceptor immobilization and refractive index modulation upon antigen–antibody binding, resulting in measurable phase shifts and enhanced sensitivity in hybrid optical biosensing platforms. Reproduced with permission from Ref. [56]. Copyright 2025 American Chemical Society.

These studies demonstrate that integrating complementary material properties enhances performance beyond that of individual components. Such combinations enable concurrent improvement in sensitivity, selectivity, and stability.

3. Transduction Mechanisms and Performance Determinants

The analytical performance of nanomaterial-based biosensors is determined not only by material composition, but also by the way physicochemical properties are translated into measurable signals. In this context, transduction mechanisms provide the functional link between nanomaterial properties and sensing performance. Electrochemical, optical, and hybrid transduction strategies each exploit distinct interfacial phenomena and therefore differ in their sensitivity, selectivity, response time, and operational stability [57–59].

3.1. Electrochemical Sensors

Electrochemical transduction remains one of the most widely used approaches in biosensing because it enables sensitive, rapid, and quantitative detection using relatively simple instrumentation. In these systems, biochemical interactions occurring at the sensing interface are converted into measurable electrical outputs, such as current, potential, or impedance changes [60].

Conventional electrochemical sensing systems generally consist of sensing electrodes, an electrochemical reaction chamber, and a potentiostat or electrochemical workstation [61]. The most employed electrode configurations are two-electrode (2E) and three-electrode (3E) systems [62]. A 3E configuration comprises a working electrode, a reference electrode, and a counter electrode, whereas the 2E system includes only a working and a reference electrode. The selection of electrode configuration depends on parameters such as electrolyte composition, current magnitude, and the electrochemical technique employed [62].

Various electrode substrates are used in sensor fabrication, including gold electrodes (AuEs), platinum electrodes (PtEs), glassy carbon electrodes (GCEs), screen-printed carbon electrodes (SPCEs), and printed circuit board-based materials [2,63,64]. To enhance electrode performance, surface modifications using conductive and catalytic materials are frequently employed [65]. The counter electrode, typically composed of platinum due to its high conductivity and electrochemical stability, maintains current balance, while the reference electrode, commonly saturated calomel or Ag/AgCl, provides a stable and well-defined potential [65].

The electrical output of electrochemical sensors is influenced by changes in key parameters such as current, voltage, impedance, and photocurrent quenching [62,66]. These variations can be analyzed both quantitatively and qualitatively to determine the presence and concentration of analytes [67]. Commonly employed electrochemical techniques include electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), square-wave voltammetry (SWV), differential pulse voltammetry (DPV), photocurrent sensing voltammetry (PSV), chronoamperometry (CA), and linear sweep voltammetry (LSV) [68].

Unmodified electrodes often exhibit limited sensitivity due to their relatively low surface area. To address this limitation, nanomaterials are incorporated either as electrode modifiers to enhance surface area, facilitate electron transfer, and enable high-density bioreceptor immobilization, or as signal amplification labels conjugated with enzymes or redox-active species [4].

Figure 7 illustrates a representative electrochemical multiplex sensing platform based on a polyaniline–silver nanoparticle nanocomposite, highlighting how coupled redox processes can support the simultaneous detection of glucose and urea.

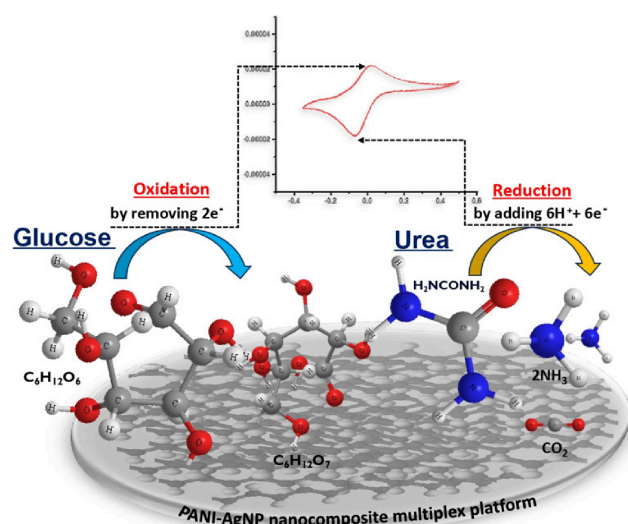


Figure 7. Schematic representation of a polyaniline–silver nanoparticle (PANI–AgNP) nanocomposite for the simultaneous electrochemical detection of glucose and urea, illustrating the associated sensing mechanism. Reproduced with permission from Ref. [69]. Copyright 2025 Springer Nature.

Recent advances on electrochemical biosensors have primarily focused on improving interfacial electron transfer and catalytic signal amplification. An overview of recently reported nanomaterial-based electrochemical sensors detailing their analytical performance on various samples are summarized in Table 1.

Table 1. Recent electrochemical biosensors for bioanalyte detection: key materials, detection parameters, and target analytes.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Cyclic voltammetry (CV)	Fe_3O_4 nanoparticles, PANI–MNPs	Spiked water samples with <i>Escherichia coli</i> O157:H7	Oligonucleotide probes	0.10 ng mL^{-1}	N/A	<i>E. coli</i> O157:H7 genomic DNA	[70]
Differential pulse voltammetry (DPV)	$Cu_2O@TiO_2/MXene$	Milk, water, and soil samples contaminated with <i>Staphylococcus aureus</i>	N/A	1 CFU mL^{-1}	N/A	<i>S. aureus</i>	[25]
Differential pulse voltammetry (DPV)	$Bi_2S_3@CuS/GO$	Detection relies on direct electrochemical oxidation of acetamiprid	N/A	4.1 nM	N/A	Acetamiprid pesticide	[71]
Photocurrent sensing voltammetry (PSV)	PPy–AuNPs/MWCNTs composite and CdS NCs as signal tag	Spiked human serum samples	Rabbit anti-protective antigen (PA) antibody (capture antibody, Ab1) and monoclonal mouse anti-PA antibody (detection antibody, Ab2)	10 pg mL^{-1}	N/A	<i>Bacillus anthracis</i>	[72]
Differential pulse voltammetry (DPV)	MIPs@CNTs	Pharmaceutical tablet formulations and rat plasma samples	Molecularly imprinted polymer (MIP) specific for gefitinib	$0.014 \text{ }\mu\text{M}$	$0.05\text{--}10.0 \text{ }\mu\text{M}$	Gefitinib—an anticancer drug	[64]
Differential pulse voltammetry (DPV)	3DrGO/MWCNTs and UiO-66- NH_2 loaded with ferrocenecarboxylic acid (UiO-66-Fc)	Human serum samples	Primary antibody (Ab1) against CA125 for capture	0.0089 U mL^{-1}	$0.01\text{--}80 \text{ U mL}^{-1}$	Cancer antigen 125 (CA125)	[73]

Table 1. Cont.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Cyclic voltammetry (CV) and amperometry	Core-shell Ag@Au nanocatalysts	Cancer cell lines (HepG2, MCF-7, HeLa) and PBS solutions	N/A	340 nM	1–850 μ M	H ₂ O ₂ secreted from cancer cells	[74]
Differential pulse voltammetry (DPV)	Laser-induced graphene modified with a AuNP-decorated MXene	C-reactive protein (CRP) in PBS and spiked FBS	Anti-CRP monoclonal antibody	1.45 pg mL ^{−1}	10 pg mL ^{−1} –10 μ g mL ^{−1}	CRP	[75]
Linear sweep voltammetry	BPNS–AgNPs	Pharmaceutical drops, spiked milk, and spiked human serum	MIP (polypyrrole, PPy) templated with gatifloxacin	0.2 nM	0.001–1 μ M and 1–50 μ M	Gatifloxacin	[76]
Electrochemical impedance spectroscopy (EIS)	AuNPs, covalent organic framework on carbon nanofiber (COF@CNF)	Human urine (spiking and patient samples)	5'-NH ₂ -modified DNA aptamer (86 nt) targeting sarcosine	0.166 pM	500 fM–50 pM and 50 pM–350 pM	Sarcosine—biomarker for prostate cancer	[77]
Differential pulse voltammetry (DPV)	AuNPs	Clinical human nasopharyngeal swab samples	Thiol-modified ssDNA probe	86.4 amol L ^{−1}	1.0 fM–1.0 nM	Influenza B virus genome	[78]
Square-wave voltammetry (SWV)	GO	Spiked and clinical urine samples	Monoclonal antibody (clone KKKU 505) specific to <i>Opisthorchis viverrini</i> somatic and excretory-secretory antigens	0.08 ng mL ^{−1} (in buffer), 1.5 ng mL ^{−1} (in urine)	0.2–200 μ g mL ^{−1} (in buffer), 0.16–100 μ g mL ^{−1} (in urine)	<i>O. viverrini</i> antigen	[79]
Differential pulse voltammetry (DPV)	AuNPs and Fe ₃ O ₄ /MWCNTs–COOH/Nafion composite	Spiked and clinical human serum samples	DNA aptamer for FT4 and anti-FT4 antibody	0.04 pg mL ^{−1}	0.1–105 pg mL ^{−1}	Free thyroxine (FT4)	[80]
Differential pulse voltammetry (DPV)	AuNPs	Artificial cerebrospinal fluid spiked with tau protein	Biotinylated-DNA aptamer and anti-tau monoclonal antibody	1 fM	0.001–100 pM	Tau protein	[81]
Square-wave voltammetry (SWV)	Ti ₃ C ₂ Tx MXene–Fe ₂ O ₃ nanocomposite	Spiked water samples	DNA aptamer specific to testosterone	1.53 pg mL ^{−1}	0.4–50 ng mL ^{−1}	Testosterone	[32]
Differential pulse voltammetry (DPV)	MXene–CuBTC nanozyme	Spiked buffer and real samples of apple juice, lettuce, and pond water	Anti- <i>L. monocytogenes</i> monoclonal antibody	1.9 $\times$ 10 ¹ CFU mL ^{−1}	1.9 $\times$ 10 ¹ –1.9 $\times$ 10 ⁶ CFU mL ^{−1}	<i>L. monocytogenes</i>	[82]
Photocurrent quenching	Nano-C ₆₀ fullerene and AuNPs	Spiked water samples (tap and lake water)	Pb ²⁺ -specific DNA aptamer (G-rich sequence forming G-quadruplex)	1.67 fM	5.00 fM–500 nM	Lead ion (Pb ²⁺)	[83]
Chronoamperometry (CA)	Carboxylated graphene	Human serum samples	SARS-CoV-2 nucleocapsid protein	1:1601 dilution (v/v)	1:1000–1:200 dilution (v/v)	IgA-SARS-CoV-2 antibodies	[84]
Self-powered sensing	PAN–CNT–COOH nanofiber modified with AuNPs	Myoglobin-specific thiolated aptamer	Myoglobin-specific thiolated aptamer	0.23 ng mL ^{−1}	5–5000 ng mL ^{−1}	Myoglobin	[85]
Differential pulse voltammetry (DPV)	Pt-rGO–P–CNT	Spiked human serum, urine, and buffer	N/A	0.012 μ M (dopamine, serotonin), 0.015 μ M (norepinephrine)	0.1–500 μ M (for all three analytes)	Dopamine, serotonin, norepinephrine	[36]
Differential pulse voltammetry (DPV)	Chitosan@SiO ₂ –APTES composite	Human blood, urine, and pharmaceutical formulations	N/A	0.02 μ M	Paracetamol: 0.025–2.5 μ M	Acetaminophen, paracetamol	[86]
Cyclic voltammetry (CV) and amperometry	Cu-MOF and PEDOT composite	Human sweat	N/A	0.76 μ M	0–180 μ M	Ascorbic acid	[87]

Table 1. Cont.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Differential pulse voltammetry (DPV)	Cu-MOF and MWCNT-COOH	Human serum (diluted 1:100)	N/A	Ascorbic acid: 3.0 μM and dopamine: 0.32 μM	Ascorbic acid: 3–1800 μM and dopamine: 2–180 μM	Ascorbic acid, dopamine	[88]
Cyclic voltammetry (CV) and chronoamperometry (CA)	CuNPs in Fe^{3+} -initiated PHEMA	Human sweat	N/A	9.99 μM	0–0.2 mM and 0.2–4 mM	Glucose	[89]
Cyclic voltammetry (CV)	PtNPs and rGO	Artificial sweat	Lactate oxidase	0.07 mM	0–25 mM	Lactate	[90]
Differential pulse voltammetry (DPV)	$\text{Ti}_3\text{C}_2\text{Tx}$ MXene nanosheets and PtNPs	Human serum samples	Anti-CA15-3 antibody immobilized via streptavidin–biotin interaction	1 nU mL^{-1}	1–100 nU mL^{-1}	CA15-3—breast cancer biomarker	[91]
Cyclic voltammetry (CV)	PANI-AgNP	Human blood samples and PBS	N/A	Glucose: 1.9 μM and urea: 0.021 μM	Glucose: 16–20 mM and urea: 5–9 mM	Glucose and urea	[69]
Chronoamperometry (CA)	AuNPs@ZIF-8-C	Human sweat	N/A	4.99 μM	10–300 μM	Glucose	[92]

N/A—Data not available.

3.2. Optical Transduction

Optical biosensors operate by transducing physicochemical changes into measurable optical signals, including variations in light intensity, wavelength, fluorescence, or refractive index [13]. These platforms offer high sensitivity, rapid response, and compatibility with non-invasive detection, making them suitable for biomedical diagnostics, environmental monitoring, and food safety applications [13]. Nanomaterials play a central role in enhancing optical responses due to their unique electronic and plasmonic properties, which enable efficient light–matter interactions and signal amplification [59].

Advanced optical techniques such as surface-enhanced Raman scattering (SERS) and surface plasmon resonance (SPR/LSPR) further expand sensing capabilities by enabling ultra-sensitive and label-free detection. SERS enhances Raman signals through localized electromagnetic “hot spots,” while SPR and LSPR detect refractive index changes at metal interfaces or nanoparticle surfaces [93,94]. These approaches provide high selectivity and real-time monitoring, particularly when combined with functionalized nanomaterials, supporting their application in complex biological and environmental systems [94].

In contrast, fluorescence-based sensors utilize mechanisms such as quenching, enhancement, or Förster resonance energy transfer (FRET) to achieve highly sensitive and quantitative detection. The incorporation of nanomaterials, including quantum dots, carbon-based nanostructures, and metal nanoparticles, improves photostability, signal intensity, and detection limits [95].

Recent studies emphasize the role of plasmonic and fluorescence signal modulation in enhancing the sensitivity of optical biosensors. A summary of recently reported nanomaterial-based optical sensors, including their analytical performance across diverse sample matrices, is presented in Table 2, highlighting how optical response mechanisms influence sensitivity and analyte scope.

Table 2. Recent developments in optical biosensing platforms: key materials, detection parameters, and target analytes.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Surface-enhanced Raman scattering (SERS)	AuNPs@BC	Ethanol solutions of thiram pesticide	N/A	0.24 ppm	N/A	Thiram (tetramethylthiuram disulfide pesticide)	[63]
Localized surface plasmon resonance (LSPR)	WS ₂ -thin layers, ZnO-NWs	Spiked cabbage and spinach	Butyrylcholine esterase (BChE) enzyme	6.83 µg mL ⁻¹	N/A	Paraoxon (organophosphate pesticide)	[67]
Localized surface plasmon resonance (LSPR)	Spherical gold nanoparticles (SGnPs) and gold nanorods (GnRs) immobilized on the optical fiber	Spiked mushroom homogenates, mushroom wine, and deionized water	Polyclonal anti-amatoxin antibodies	1 µg mL ⁻¹ with SGnP-coated fiber and 0.01 µg mL ⁻¹ with SGnP-GnR fiber (mushroom), 0.001 µg mL ⁻¹ with SGnP-GnR fiber (water)	N/A	Amatoxin	[12]
Fluorescence	SnO ₂ -WO ₃ heterojunction nanosheets	Spiked human urine, river water, and pharmaceutical capsule samples	N/A	7.2 nM	N/A	Nifedipine	[93]
Fluorescence	UCNPs coated with PSS layer	Spiked human serum samples	Hairpin DNA probe specific to miRNA-155	1.14 pM	0.01–3 nM	miRNA-155	[96]
Fluorescence	NAA loaded with RhB dye and capped with specific oligonucleotides	SARS-CoV-2 RNA extracted from patient samples	Complementary to SARS-CoV-2 N gene sequence	50 ± 30 copies mL ⁻¹	60–6000 copies mL ⁻¹	SARS-CoV-2 viral RNA	[47]
Colorimetric and confocal microscopy	SA-AuNPs	Spiked synthetic DNA/RNA targets, patient nasopharyngeal swab samples, and cancer cell line RNA	CRISPR/dCas9 guided by synthetic crRNA-tracrRNA complexes	Colorimetric detection: 100 aM, Light-scattering counting: 1 aM	Colorimetric detection: 100 aM–pM, light-scattering counting: 10 aM–10 fM	SARS-CoV-2 N gene and BCR-ABL fusion genes	[97]
Interferometry	NPG integrated on Si ₃ N ₄ bimodal	CRP in PBS	anti-CRP antibody	3 ng mL ⁻¹	0.05–1 µg mL ⁻¹	CRP	[56]
Fluorescence	NiFe LDH@ZIF-67 MOF/CuO NP nanocomposite, CRP, PBS and FBS	SARS-CoV-2 spike protein S1 in PBS buffer	N/A	1.5 nM (in solution) and 24.5 nM (on mask surface)	1.5–100 nM (in solution) and 24.5–130 nM (on mask surface)	SARS-CoV-2 spike protein S1	[98]
Electrochemiluminescence	MQDs	Spiked FBS	MIP specific to oseltamivir	6.5 × 10 ⁻¹¹ M	1.0 × 10 ⁻¹⁰ –1.0 × 10 ⁻⁶ M	Oseltamivir	[99]
Colorimetry and UV-vis spectroscopy	ssDNA-AuNPs	ssDNA	Thiol-modified ssDNA probes	0.5–2.5 nM	0–10 nM (approximately)	ssDNA targets in buffer	[100]
RGB colorimetry	AuNPs	Synthetic RNA targets and SARS-CoV-2 RNA in nasopharyngeal clinical samples	Cas13a protein with specific crRNA	2.26 fM	N/A	RNA sequences including SARS-CoV-2, Zika virus, and synthetic model targets	[101]
Localized surface plasmon resonance (LSPR)	AuNPs and Al ₂ O ₃ -Ag-Au multilayer	BSA solutions	Anti-BSA antibody	0.3 ng mL ⁻¹	1 ng mL ⁻¹ –10 mg mL ⁻¹	BSA	[102]
Fluorescence	MSN-NH ₂	PBS spiked with IsdA protein	DNA aptamer specific to IsdA	2.34 nM	2.5–100 nM	IsdA from <i>S. aureus</i>	[45]
Surface plasmon resonance (SPR)	Ti ₃ C ₂ MXene nanosheets and citrate-stabilized GNR	Acetylcholine solutions and milk samples	Acetylcholinesterase enzyme	4.42 µM	0–700 µM	Acetylcholine	[103]
Fluorescence	QD ₂ -SiO ₃	Spiked CA19-9 protein solutions	DNA aptamer specific to carbohydrate antigen 19-9	1.74 × 10 ⁻¹ mg mL ⁻¹	1.5 × 10 ⁻² –3.0 × 10 ⁻¹ mg mL ⁻¹	Carbohydrate antigen 19a biomarker for pancreatic cancer	[43]

Table 2. Cont.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Interferometry	NPG	Buffer solutions with spiked CRP	Anti-CRP monoclonal antibody	3 ng mL ⁻¹	10 ⁻⁹ –10 ⁻¹⁵ M	CRP	[104]
Terahertz metamaterial resonance sensing	Graphene–metal nanocomposite	Simulated waterborne bacteria with known refractive indices	N/A	0.028 RIU	1.33–1.3921 RIU	Waterborne pathogens (e.g., <i>E. coli</i> , <i>B. anthracis</i> , <i>Vibrio cholerae</i>)	[55]
Absorbance	Au@Pt/CNTs nanohybrids	Spiked milk and pork	Anti-tetracycline monoclonal antibody	0.74 ng mL ⁻¹ (Au@Pt/CNTs-s), 1.74 ng mL ⁻¹ (Au@Pt/CNTs-o)	1.10–6.57 ng mL ⁻¹ (Au@Pt/CNTs-s), 2.53–12.34 ng mL ⁻¹ (Au@Pt/CNTs-o)	Tetracyclines	[85]
Fluorescence	Py@MSN–Eu	Water, milk, egg, urine, lake water, fruit surfaces	N/A	4.2 nM (in solution), 9.1 nM (in egg)	0–30 µM	Six fluoroquinolones	[105]
Fluorescence	DDSNs and MIONs	Spiked milk samples	Aptamer for ampicillin (Apt2) and oxytetracycline (Apt1)	0.13 ng mL ⁻¹ (oxytetracycline), 0.17 ng mL ⁻¹ (ampicillin)	0.5–100 ng mL ⁻¹ (both targets)	Ampicillin and oxytetracycline	[106]
Absorbance	AlgCu	Sulfite-spiked red wine	N/A	0.78 µM (UV–vis), 4.9 µM (smartphone-based)	2–100 µM	Sulfite (SO ₃ ²⁻)	[107]
Colorimetry	MIL-88@Pd/Pt nanoparticles	Spiked chicken meat	Anti-Salmonella monoclonal and polyclonal antibodies	35 CFU mL ⁻¹	8.0 × 10 ¹ –8.0 × 10 ⁶ CFU mL ⁻¹	<i>Salmonella typhimurium</i>	[52]
Localized surface plasmon resonance (LSPR)	Au–Ag bimetallic nanoparticles embedded in TiO ₂ thin film	Spiked white wine	Monoclonal anti-ochratoxin A antibody	7 pg mL ⁻¹	0.05–2 ng mL ⁻¹	Ochratoxin A	[108]
Surface-enhanced Raman scattering (SERS)	PDMS–flower-like ZIF-67@AgNPs	Artificial blood, urine, and sweat samples spiked with creatinine and urea	N/A	0.004 mg dL ⁻¹ (creatinine), 0.01 mg dL ⁻¹ (urea)	0.005–500 mg dL ⁻¹ (creatinine), 0.05–5000 mg dL ⁻¹ (urea)	Creatinine and urea	[51]
Colorimetry and UV–vis absorption	AuNPs	Clinical cultures and synthetic oligonucleotide spiked samples	Thiolated single-stranded DNA probes targeting 16S rRNA of <i>H. pylori</i>	10 nM (visual), 1 nM (spectrophotometry), 5 × 10 ⁵ copies mL ⁻¹ (clinical DNA)	Up to ~1 µM	<i>H. pylori</i>	[16]
Localized surface plasmon resonance (LSPR)	HAuNPs	Simulated cancer cell environments	N/A	N/A	N/A	Cancer cell presence	[17]
Colorimetry	SP–Au	Exosomes derived from A549 lung cancer cells	CD63 aptamer	10 particles µL ⁻¹	10 ⁻¹⁰ –10 ⁸ particles µL ⁻¹	Colorimetric (oxidation of TMB)	[109]
UV–vis absorption	Metal-doped C60 fullerenes: ZnC59, AlC59, NiC59	Isobutyric acid	N/A	N/A	N/A	Isobutyric acid—volatile organic compound biomarker for COVID-19	[110]
UV–vis absorption	C60 fullerene: BeC59, CaC59, pristine C60	Isobutyric acid	N/A	N/A	N/A	Isobutyric acid	[111]

N/A—Data not available.

3.3. Hybrid Transduction

Hybrid transduction strategies combine multiple sensing mechanisms within a single biosensor platform to improve analytical reliability and broaden functional capability [112]. Dual-response array-based biosensors integrate two transduction mechanisms, whereas multimode systems combine multiple sensing strategies to enhance sensitivity, specificity, and reliability [113]. These platforms commonly integrate optical, electrochemical, and

magnetic sensing strategies, enabling cross-validation of signals and reducing false-positive results [113,114].

Recent studies have demonstrated that this strategy is especially effective when structural, optical, and electrochemical functions are combined. Figure 8 illustrates a representative hybrid electrochemiluminescence sensing platform based on molecularly imprinted MXene quantum dots, highlighting both the fabrication sequence and the signal-off detection mechanism for oseltamivir.

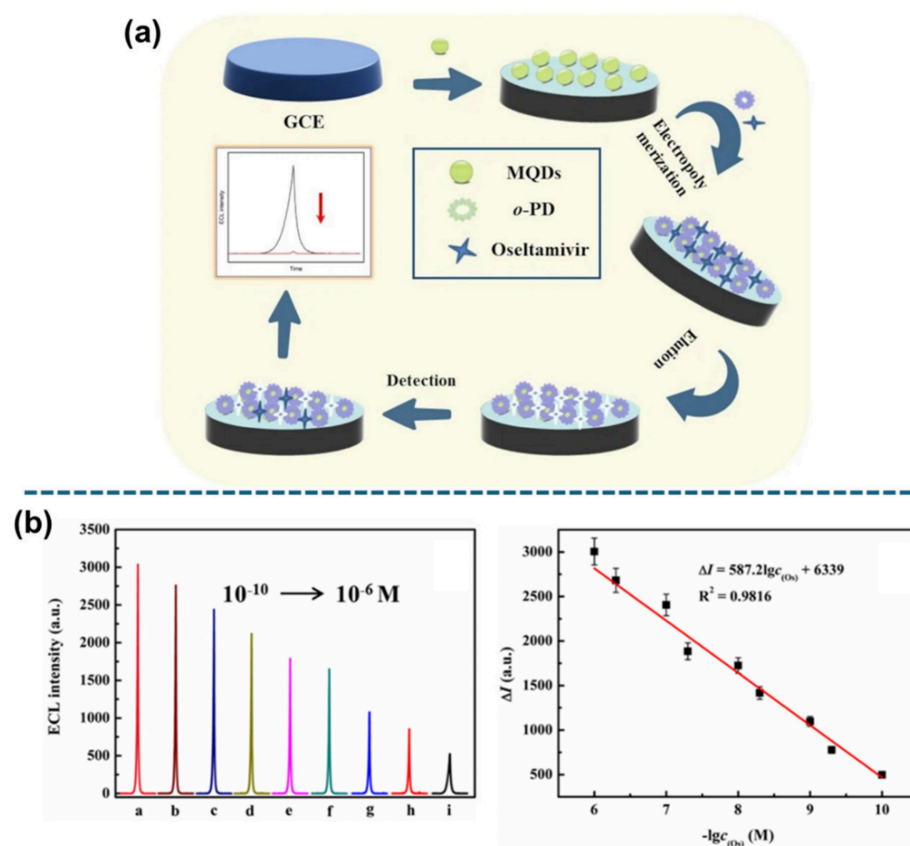


Figure 8. (a) Schematic illustration of the fabrication and sensing mechanism of a molecularly imprinted polymer-based electrochemiluminescence (MIP-ECL) biosensor incorporating MXene quantum dots. The figure depicts the stepwise assembly of the sensing interface and the selective recognition of oseltamivir through molecular imprinting, where target binding modulates the electrochemiluminescence signal (signal-off mechanism). (b) ECL response curves and corresponding calibration plot showing concentration-dependent signal variation. The integration of MXene quantum dots enhances electron transfer, surface reactivity, and signal amplification, demonstrating how hybrid transduction combining molecular recognition and electrochemiluminescence improves sensitivity, selectivity, and analytical performance. Reproduced with permission from Ref. [99]. Copyright 2024 MDPI.

These findings demonstrate that hybrid transduction is an effective strategy for overcoming the limitations of single-mode sensing systems and for improving biosensor performance in complex analytical environments. Representative recent dual- and multimode biosensors are summarized in Table 3 to illustrate how integrating complementary transduction strategies can improve analytical reliability, sensitivity, and functional versatility.

Table 3. Overview of recent nanomaterial-enabled dual/multi-mode biosensors: detection strategies and target analytes.

Detection Mode	Nanomaterial	Sample	Bioreceptor	Limit of Detection (LOD)	Detection Range	Target Analyte	Ref.
Fluorescence and colorimetry	Photonic crystals and AuNPs	Spiked milk, chicken, and SARS-CoV-2 plasmids	crRNA targeting specific genes: <i>invA</i> (for <i>Salmonella</i>), <i>N</i> and <i>Orf1ab</i> genes (for SARS-CoV-2), <i>nuc</i> gene (for <i>S. aureus</i>)	For fluorescence (<i>Salmonella</i> : 1 CFU mL ⁻¹ , SARS-CoV-2 (<i>N</i> gene): 2.97×10^1 copies μL^{-1} , SARS-CoV-2 (<i>Orf1ab</i> gene): 3.26×10^1 copies μL^{-1}) and for colorimetric (<i>Salmonella</i>): 10 ³ CFU mL ⁻¹ , SARS-CoV-2 (<i>N</i> gene): 2.97×10^2 copies μL^{-1} , SARS-CoV-2 (<i>Orf1ab</i> gene): 3.26×10^2 copies μL^{-1})	Same as LOD	<i>Salmonella</i> (<i>invA</i> gene), <i>S. aureus</i> (<i>nuc</i> gene), SARS-CoV-2 (<i>N</i> and <i>Orf1ab</i> genes)	[115]
Fluorescence and SERS	2D Ti ₃ C ₂ MXene decorated with AuNPs	Spiked drinking water and milk samples	Endotoxin-specific aptamer	15.9 pg mL ⁻¹	0.26 ng mL ⁻¹ (fluorescence), 0.04 ng mL ⁻¹ (SERS) and 15.9 pg mL ⁻¹ (ratiometry)	Endotoxin	[39]
Colorimetry and fluorescence	CdTe QDs and Fe ₃ O ₄ magnetic beads	Human serum samples and cell culture supernatant	EpCAM DNA aptamer	1.1 (fluorescence) particles μL^{-1} , N/A (colorimetry)	7.9×10^4 – 2.2×10^6 (fluorescence) particles μL^{-1} , N/A (visual)	Exosomes derived from MCF-7 breast cancer cells	[42]
Colorimetry and fluorescence	FeNi–MOF and OCDs	Spiked samples: chicken, prawn, grass carp	DNA aptamer specific to ofloxacin, monoclonal antibody against ofloxacin	1.1 ng kg ⁻¹ (colorimetric), 0.34 ng kg ⁻¹ (fluorescence), 0.26 ng kg ⁻¹ (smartphone-assisted fluorescence)	1×10^{-7} – 1×10^{-2} mg mL ⁻¹	Ofloxacin	[116]
Colorimetry and fluorescence	ZrFe–MOF@PtNPs	Spiked and real milk, and milk powder samples	Monoclonal antibodies against aflatoxins	0.0636 ng mL ⁻¹ (colorimetric), 0.0062 ng mL ⁻¹ (fluorescence), 0.0179 ng mL ⁻¹ (catalytic)	N/A	Aflatoxins	[117]

N/A—Data not available.

4. Application-Oriented Classification

The practical significance of nanomaterial-based biosensors is most clearly demonstrated through their application in clinically relevant diagnostics, pathogen detection, and environmental and food safety monitoring [118]. These application domains impose different analytical requirements, including sensitivity, selectivity, response time, robustness, and tolerance to complex sample matrices. Accordingly, the performance of a biosensor depends not only on the selected nanomaterial and transduction mechanism but also on how well the sensing platform is matched to the intended use environment [119].

4.1. Clinical Biomarker Detection

Clinical biosensing focuses on the detection of proteins, nucleic acids, metabolites, and disease-associated markers in complex biological fluids and tissues. Recent advances have emphasized improving sensitivity, selectivity, and compatibility with clinically relevant sample matrices using nanomaterial-enabled signal amplification and engineered sensing interfaces. For example, Torati and Slaughter developed a laser-induced graphene electrochemical immunosensor modified with AuNP-decorated MXene for C-reactive protein detection, demonstrating improved analytical sensitivity in spiked serum [75]. Daneshgar et al. reported an optically active nanocomposite-coated face mask for real-time detection of the SARS-CoV-2 spike protein S1, highlighting the potential of non-invasive sensing formats in clinical monitoring [98].

In addition to conventional protein biomarker detection, recent studies have also extended nanomaterial-based biosensing to cell-associated oxidative markers relevant to cancer progression. Zhang et al. developed a visual and fluorescence dual-mode platform for exosome detection in breast cancer screening, while Wu et al. reported a ratiometric electrochemical immunosensor for CA125 detection using a 3D carbon nanomaterial/MOF platform [73,103]. Ghosal et al. developed an Ag@Au nanocatalyst-based sensing platform

for the in situ detection of H_2O_2 in HepG2 human liver cancer cells, demonstrating the analytical potential of nanoplasmonic systems for oxidative stress-related cancer biomarkers [74]. Figure 9 illustrates the Ag@Au nanocatalyst-based sensing platform used for H_2O_2 detection in HepG2 cells, highlighting the H_2O_2 -responsive mechanism and the associated electrochemical and SERS-based analytical response [74].

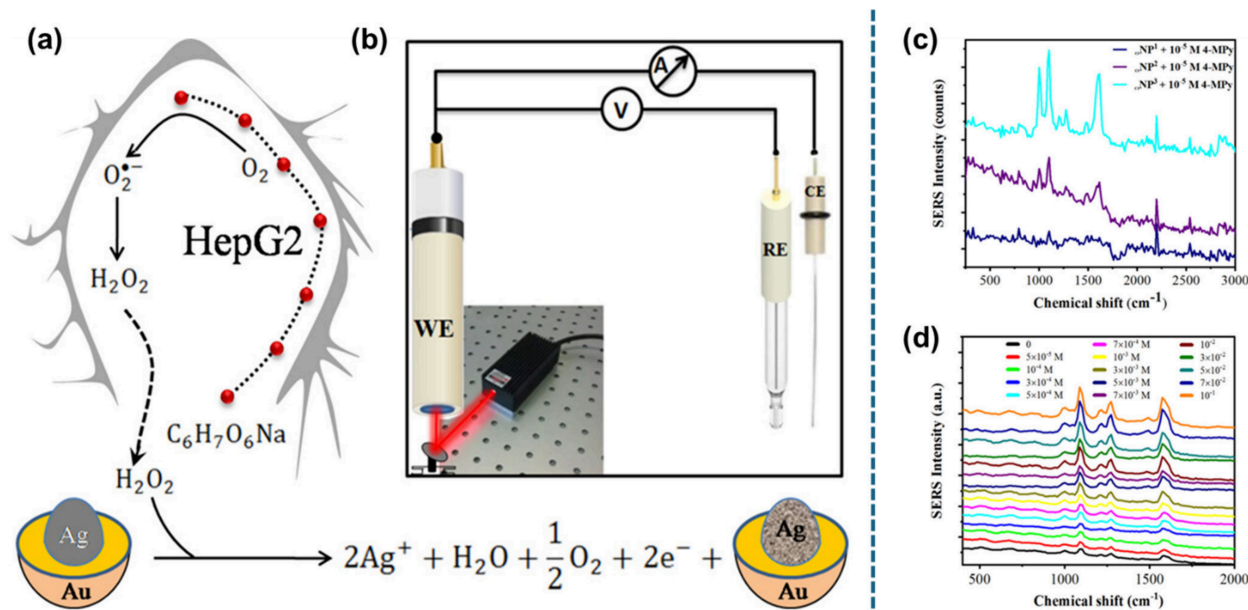


Figure 9. (a) Schematic illustration of ascorbic acid-induced H_2O_2 production in HepG2 human liver cancer cells. The generated H_2O_2 oxidizes the silver shell of Ag@Au nanoparticles, leading to the formation of Ag^+ species. (b) Schematic diagram of the electrochemical measurement setup used for electrode irradiation and signal acquisition. (c) Surface-enhanced Raman scattering (SERS) spectra of 4-mercaptopyridine (4-MPy) adsorbed on different Ag@Au nanoparticles. (d) SERS spectra showing signal enhancement as a function of H_2O_2 concentration, demonstrating the analytical response of the biosensing system. Reproduced with permission from Ref. [74]. Copyright 2025 American Chemical Society.

Collectively, these studies show that recent clinical biosensors increasingly combine nanomaterial-enabled signal enhancement with application-specific interface design to improve the detection of inflammatory, viral, and cancer-associated biomarkers.

4.2. Pathogen Detection and Nucleic Acid Detection

Biosensors designed for pathogen detection target bacteria, viruses, and genetic material associated with infectious diseases [20,120]. These applications require rapid response, high specificity, and reliable detection in complex sample matrices. Selectivity in pathogen detection is primarily determined by the choice of biorecognition elements, such as antibodies, aptamers, or nucleic acid probes, while nanomaterials contribute by providing stable interfaces for immobilization and signal amplification [80,121].

Recent work in pathogen and nucleic acid detection has emphasized rapid response, sequence specificity, and applicability in clinically relevant and complex samples. Lin et al. (2025) developed a near-infrared DNA biosensor for microRNA-155 detection using polysulfonate-coated UCNP [96]. The system employed a FRET mechanism, where target-induced conformational changes restored fluorescence. Catalytic hairpin assembly further amplified the signal, enabling sensitive detection with a low picomolar limit and reliable performance in serum samples [96]. Tanaka et al. (2025) further showed that cross-linking aggregation of DNA-modified AuNPs can be used for sensitive ssDNA detection, with probe density strongly influencing hybridization efficiency and optical response [100].

López-Palacios et al. (2025) reported an oligonucleotide-capped nanoporous anodic alumina platform for SARS-CoV-2 RNA detection, showing that gate-opening fluorescence strategies can support rapid viral diagnostics [47]. Zhang et al. (2025) further introduced a dual protein corona-mediated recognition system for the visual detection and single-molecule counting of nucleic acids, demonstrating ultrasensitive plasmonic recognition through CRISPR/dCas9-guided artificial protein corona formation [97]. Figure 10 illustrates the formation of the artificial protein corona and the workflow of the dual protein corona-mediated colorimetric assay used for ultrasensitive nucleic acid detection.

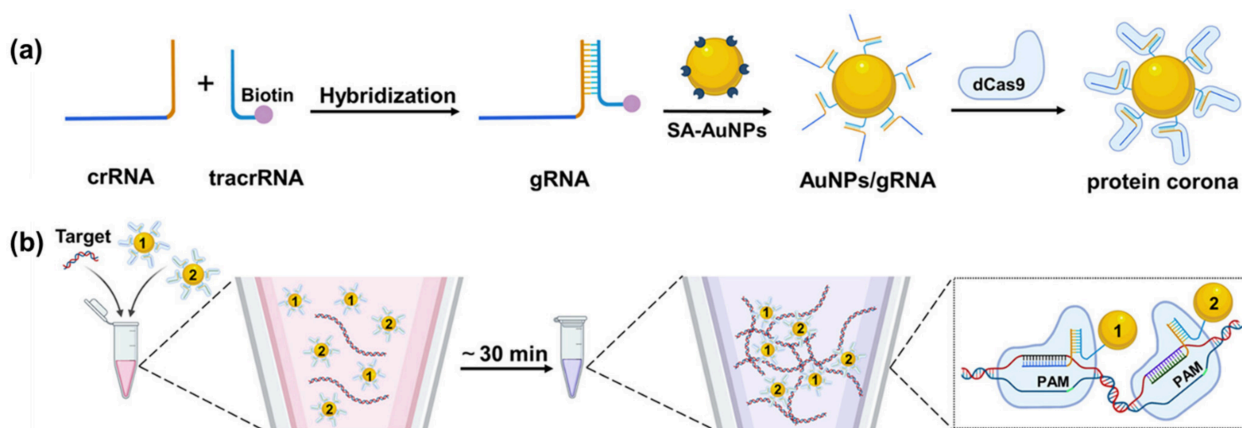


Figure 10. (a) Schematic of the formation of the artificial protein corona on nanoparticle surfaces mediated by CRISPR/dCas9-guided recognition. (b) Workflow of the dual protein corona-mediated colorimetric assay for nucleic acid detection. Labels 1 and 2 represent Protein corona-1 and Protein corona-2, respectively, consisting of distinct AuNP/gRNA/dCas9 complexes that recognize adjacent target sequences and induce nanoparticle aggregation. The system utilizes sequence-specific binding to induce controlled protein corona formation, which modulates nanoparticle aggregation and generates a measurable colorimetric response. This mechanism highlights how nanomaterial surface interactions and biomolecular recognition processes enable ultrasensitive detection, improving specificity, signal amplification, and analytical performance in nucleic acid biosensing. Reproduced with permission from Ref. [97]. Copyright 2025 American Chemical Society.

Beyond nucleic-acid recognition, recent studies have also developed nanomaterial-based immunosensors for direct detection of pathogen-associated antigens. Singh et al. developed an electrochemical immunosensor for the *Bacillus anthracis* protective antigen toxin, while Wu et al. reported a fluorescent-SERS dual-mode MXene–Au nanosheet biosensor integrated with CRISPR/Cas12a for endotoxin detection [72,122]. Hu et al. (2025) also presented a CRISPR/Cas12a-powered dual-signal platform for sensitive detection of pathogenic microorganisms in foods, while Mendoza et al. (2024) demonstrated Fe₃O₄-mediated extraction and electrochemical detection of *Escherichia coli* O157 genomic DNA [70,115]. In addition, Aye et al. (2024) developed a graphene oxide–antibody conjugate-based electrochemical immunosensor for the detection of *Opisthorchis viverrini* antigen in urine, showing that antibody-functionalized graphene interfaces can support sensitive parasitic antigen detection [79]. Figure 11 illustrates the construction of the electrochemical immunosensor used for *Opisthorchis viverrini* antigen detection, highlighting the graphene oxide–antibody conjugation strategy and the corresponding sensing configuration.

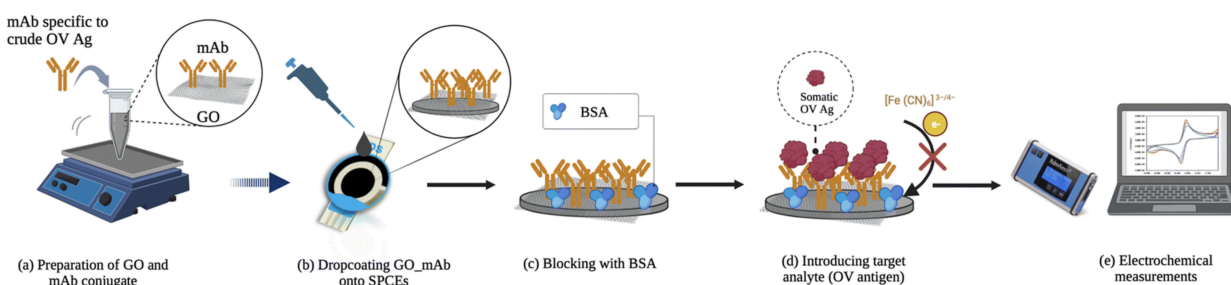


Figure 11. Schematic illustration of a graphene oxide (GO)-based electrochemical immunosensor for ovarian cancer antigen detection. (a) Preparation of the GO–monoclonal antibody (mAb) conjugate using antibodies specific to crude ovarian cancer antigen (OV Ag). (b) Drop-casting of the GO–mAb conjugate onto the screen-printed carbon electrode (SPCE) surface. (c) Blocking of nonspecific binding sites with bovine serum albumin (BSA). (d) Introduction and specific capture of the target ovarian cancer antigen on the modified electrode surface, resulting in inhibition of the ferri/ferrocyanide redox probe electron transfer. (e) Electrochemical measurement and signal acquisition for antigen detection. Reproduced with permission from Ref. [79]. Copyright 2024 RCS Publications.

Related strategies have been extended to viral serological analysis, where nanomaterial-engineered electrochemical interfaces support sensitive antibody detection. In a recent study, Freire et al. (2025) further developed a carboxylated graphene-based electrochemical biosensor for IgA–SARS-CoV-2 detection, demonstrating that interfacial graphene engineering can support sensitive serological analysis [84]. Figure 12 presents the electrochemical biosensor platform for IgA–SARS-CoV-2 detection, including the fabrication strategy and electrochemical validation of the sensing interface.

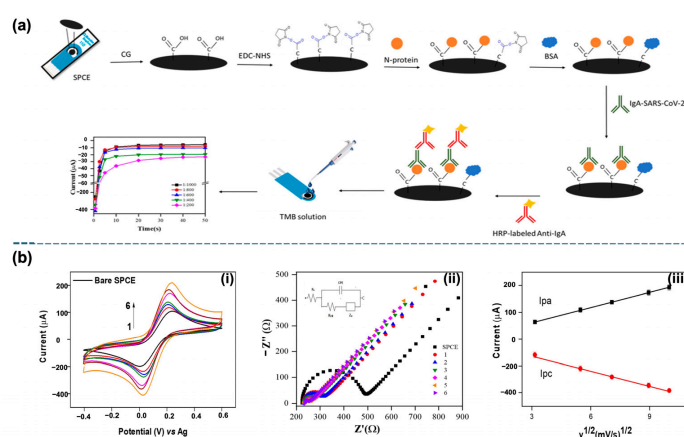


Figure 12. (a) Schematic illustration of the fabrication and sensing mechanism of a carboxylated graphene-based electrochemical biosensor for IgA–SARS-CoV-2 detection. The figure shows the modification of the electrode surface with carboxylated graphene, followed by immobilization of biorecognition elements and selective binding of target antibodies, which induces changes in interfacial electron transfer. (b) (i,ii) Cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) measurements recorded during electrode modification and sensing, and (iii) the linear relationship between peak current and the square root of scan rate, confirming diffusion-controlled electrochemical behavior. The carboxylated graphene interface provides high surface area, abundant functional groups for biomolecule immobilization, and enhanced conductivity, enabling improved signal transduction, sensitivity, and analytical performance in serological detection. Reproduced with permission from Ref. [84]. Copyright 2025 MDPI.

Collectively, these studies indicate that recent advances in pathogen and nucleic acid detection are driven by the integration of nanomaterials with highly selective molecular recognition strategies and application-specific signal transduction platforms.

4.3. Environmental and Food Safety Monitoring

Environmental and food safety applications involve the detection of pollutants, toxins, heavy metals, pesticides, and microbial contaminants [26]. These systems require robustness, portability, and cost-effective operation, often under non-laboratory conditions. In these applications, sensor design must account for variable environmental conditions, including pH, temperature, and potential interfering substances [123]. Nanomaterials with high stability and resistance to fouling are therefore particularly important [26].

Recent studies have focused on improving robustness, portability, and interference resistance. Shenoy et al. (2025) developed a U-bent optical fiber LSPR biosensor for amatoxin detection in water and mushroom-derived products, demonstrating the applicability of plasmonic sensing in toxin analysis [12]. Figure 13 illustrates the U-bent optical fiber immunosensor used for amatoxin detection, highlighting the antibody immobilization strategy on the plasmonic sensing surface.

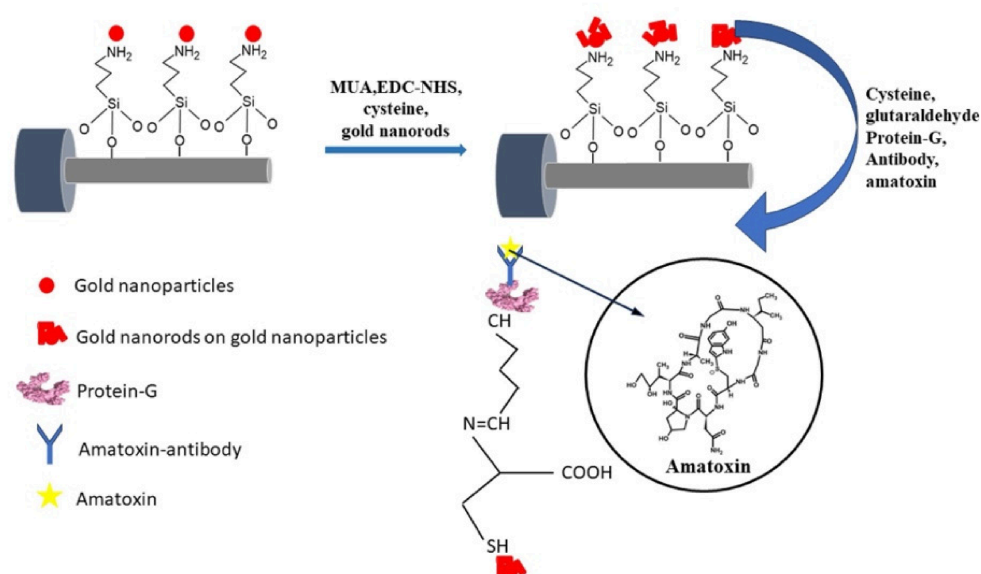


Figure 13. Schematic illustration of a U-bent optical fiber-based plasmonic immunosensor functionalized with surface-anchored gold nanoparticles (AuNPs) for amatoxin detection. The figure depicts antibody immobilization on the AuNP-modified sensing region, where specific antigen binding induces local refractive index changes that modulate localized surface plasmon resonance (LSPR) signals. The plasmonic interface enhances sensitivity through strong light–matter interactions and increased surface area for bioreceptor immobilization, enabling selective and sensitive toxin detection in environmental and food samples. Reproduced with permission from Ref. [12]. Copyright 2025 Elsevier.

In addition to optical fiber-based toxin sensing, recent studies have also developed flexible plasmonic substrates for pesticide detection in agrifood systems. Lospinoso et al. (2025) developed a flexible and sustainable SERS transducer composed of gold nanoparticles embedded in bacterial cellulose for thiram detection, demonstrating that biodegradable plasmonic substrates can support sensitive pesticide analysis [63]. Figure 14 shows the AuNPs@bacterial cellulose SERS platform reported for thiram detection, highlighting the substrate architecture and the Raman response obtained at different analyte concentrations. This platform demonstrates how sustainable nanostructured substrates can support sensitive SERS-based detection of pesticide residues [63]. Beheshti-Marnani et al. (2025) reported a Bi₂S₃@CuS/graphene oxide electrochemical sensor for ultra-trace acetamiprid detection in real samples, while Shobana et al. (2025) developed a Cu₂O@TiO₂/MXene photoelectrochemical sensor for selective detection of *Staphylococcus aureus* in polymicrobial environments [25,71]. These studies collectively show that recent environmental

and food safety applications are increasingly defined by the need for stable, field-relevant nanomaterial platforms capable of operating under complex matrix conditions.

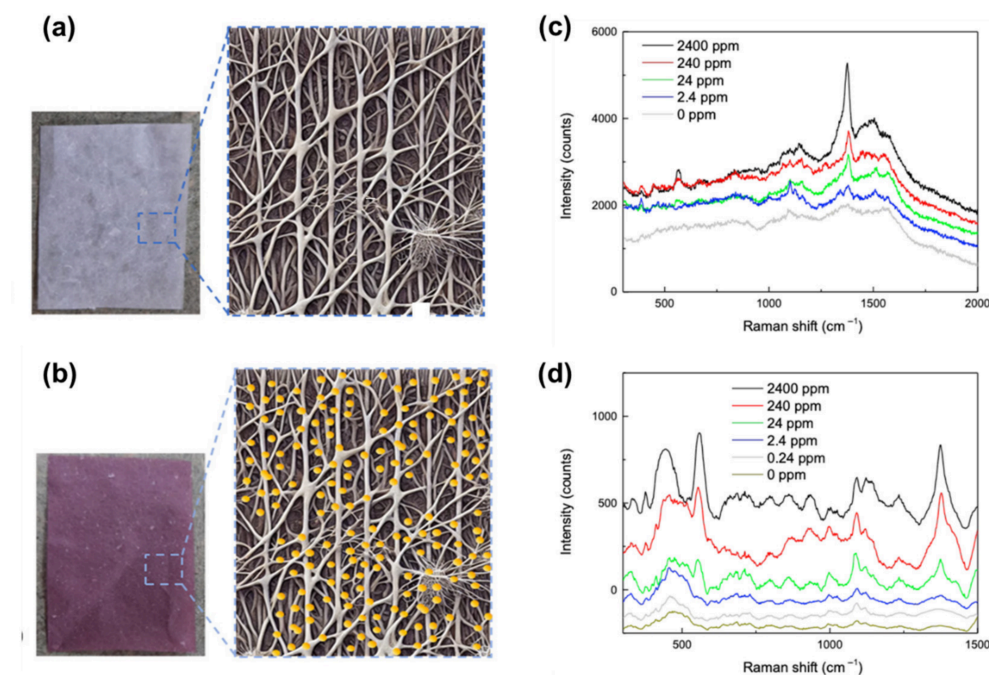


Figure 14. (a,b) Photographs of bacterial cellulose (BC) substrates without and with embedded gold nanoparticles (AuNPs), respectively, along with schematic representations of the nanofibrillar BC network and the distribution of AuNPs within the matrix. (c,d) Surface-enhanced Raman scattering (SERS) spectra of thiram at increasing concentrations obtained from AuNPs@BC substrates under 633 and 785 nm excitation. The incorporation of AuNPs into the porous BC scaffold generates plasmonic “hot spots” that enhance the local electromagnetic field, enabling signal amplification and sensitive Raman detection. The flexible and biodegradable BC matrix provides high surface area and uniform nanoparticle dispersion, demonstrating how nanostructured hybrid substrates support sensitive, portable, and environmentally relevant pesticide detection. Reproduced with permission from Ref. [63]. Copyright 2025 MDPI.

Overall, recent advances across these application domains demonstrate that practical biosensor performance depends on the successful integration of nanomaterial properties, transduction mechanisms, and sample-specific analytical requirements. This application-oriented perspective clarifies how nanomaterial-based biosensors are being adapted for increasingly specialized and real-world sensing tasks.

5. Challenges and Future Perspectives

Despite significant advances in nanomaterial-based biosensors, several challenges remain that limit their translation from laboratory-scale studies to practical applications. These challenges are primarily associated with material reproducibility, interfacial control, device integration, and long-term operational stability. Addressing these limitations requires a systematic approach that links nanomaterial design with transduction mechanisms and application-specific requirements.

5.1. Material Reproducibility

Material design remains a critical factor in the advancement of nanomaterial-based biosensors, particularly with respect to scalability, reproducibility, and cost-effectiveness. Although significant progress has been achieved, many systems are not readily transferable to large-scale production due to limitations in synthesis control and batch-to-batch

variability [103,124]. Furthermore, most biosensing platforms are optimized for single-analyte detection, which restricts their applicability in complex samples. The development of multi-analyte systems, including molecularly imprinted polymers (MIPs) and multi-aptamer platforms, offers a promising strategy; however, their design remains challenging, particularly for larger biomolecules [6,66].

5.2. Interface Engineering

The sensing interface governs biomolecule immobilization and signal transduction, and its stability is essential for reliable performance. Environmental factors such as temperature, pH, humidity, and ionic strength can significantly affect sensor response, particularly in antibody-based and colorimetric systems [6,125]. Robust surface modification and bio-functionalization strategies are therefore required to ensure stable immobilization and reproducible performance [6]. In addition, optimization of structural parameters, such as dielectric spacer layers in optical systems, plays a key role in maintaining sensitivity while minimizing signal loss [56].

5.3. Device Integration

Nucleic acid-based biosensors often exhibit reduced performance in complex biological matrices due to target isolation requirements, Debye length limitations, and nonspecific interactions [47,126]. These challenges can result in decreased sensitivity and increased false-positive responses. Emerging approaches, including CRISPR–Cas systems and nucleic acid-based amplification strategies, show potential for improving analytical reliability [126,127]. In parallel, material-related challenges associated with MOFs, quantum dots, and MXenes, including toxicity, limited conductivity, and stability, continue to limit practical applications [128]. Additionally, certain nanomaterials, such as magnetic nanoparticles, remain underexplored in environmental and food analysis [129,130].

5.4. Future Directions

Future work should focus on the rational design of nanomaterial-based biosensors through the integration of advances in material synthesis, interface engineering, and device architecture [131]. The development of multifunctional nanomaterials with high sensing performance, structural stability, and tolerance to environmental variability will be critical for improving reliability under practical conditions [132]. Progress in biofunctionalization strategies is equally important, as well-defined and reproducible surface chemistries for bioreceptor immobilization can enhance sensitivity and selectivity while ensuring consistent performance across platforms. At the same time, improving the stability of sensing interfaces in complex biological and environmental conditions remains a key challenge [133].

There is an increasing demand for sensing platforms capable of simultaneous multi-analyte detection. The development of multiplexed and multi-modal systems offers a promising pathway; however, careful control of signal transduction mechanisms is required to minimize cross-interference and maintain analytical accuracy. Continued investigation of emerging nanomaterials, including hybrid systems and two-dimensional materials, may help overcome current limitations related to conductivity, optical response, and biocompatibility. In parallel, the adoption of environmentally sustainable synthesis approaches will support the long-term viability of these technologies. Despite these advancements, nanomaterial-based biosensors still face challenges such as variability in material synthesis, interfacial instability, complex fabrication processes, and limited standardization, which continue to hinder large-scale implementation.

Simultaneously, attention must be directed toward sustainability, standardization, and responsible implementation. The adoption of green synthesis methods, improvement of

material biocompatibility, and establishment of standardized fabrication and evaluation protocols are essential for reducing environmental impact and ensuring reliable performance. Collaborative efforts between academia, industry, and regulatory bodies will be necessary to support reproducibility, data integrity, and large-scale deployment. Ultimately, the integration of nanomaterial-based biosensors into portable, user-compatible platforms, combined with advanced data analysis approaches such as machine learning, is expected to enable real-time monitoring and improved analytical robustness. Through the convergence of nanomaterials, device engineering, and computational methods, these systems are anticipated to evolve into intelligent and adaptive platforms with broad applications in healthcare, environmental monitoring, and food safety.

6. Conclusions

Nanomaterial-based biosensors have significantly advanced modern analytical science by improving sensitivity, selectivity, and functional versatility across a broad range of sensing platforms. In this review, these systems were examined through a structure–property–function framework that links nanomaterial characteristics to transduction mechanisms, performance determinants, and application-specific requirements. This perspective clarifies how plasmonic, electroactive, fluorescent, porous, and hybrid nanomaterials contribute differently to biosensor design and operation.

The studies discussed throughout this review demonstrate that biosensor performance depends not only on the choice of nanomaterial, but also on how effectively material properties are coupled to signal generation, biorecognition, and sensing conditions. Recent progress in electrochemical, optical, and hybrid transduction has enabled increasingly capable platforms for clinical biomarker detection, pathogen and nucleic acid analysis, and environmental and food safety monitoring. At the same time, major challenges remain in reproducibility, interface engineering, long-term stability, and scalable device integration.

Overall, future progress in nanomaterial-based biosensing will depend on the rational design of multifunctional sensing interfaces, improved standardization of material synthesis, and closer alignment between nanomaterial properties and real-world analytical demands. Addressing these challenges will be essential for translating promising laboratory-scale biosensors into robust and widely deployable technologies.

Author Contributions: Conceptualization, S.M. and T.R.L.; Methodology, S.M.; Resource, T.R.L.; Data Curation, S.M., R.A. (Ruwanthi Amarasekara) and M.A.G.; Writing—Original Draft Preparation, S.M.; Writing—Review and Editing, S.M., R.A. (Ruwanthi Amarasekara), P.C. and T.R.L.; Visualization, S.M., R.I. and R.A. (Refia Atik); Supervision, T.R.L.; Project Administration, P.C. and T.R.L.; Funding Acquisition, T.R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Air Force Office of Scientific Research (AFOSR FA9550-23-1-0581; 23RT0567).

Data Availability Statement: No new data were created or analyzed in this study.

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

References

1. Hua, Z.; Yu, T.; Liu, D.; Xianyu, Y. Recent Advances in Gold Nanoparticles-Based Biosensors for Food Safety Detection. *Biosens. Bioelectron.* **2021**, *179*, 113076. [[CrossRef](#)]
2. Yu, H.; Yu, J.; Li, L.; Zhang, Y.; Xin, S.; Ni, X.; Sun, Y.; Song, K. Recent Progress of the Practical Applications of the Platinum Nanoparticle-Based Electrochemistry Biosensors. *Front. Chem.* **2021**, *9*, 677876. [[CrossRef](#)]
3. Feng, Y.; Su, C.; Mao, G.; Sun, B.; Cai, Y.; Dai, J.; Ma, Y. When Synthetic Biology Meets Medicine. *Life Med.* **2024**, *3*, Inae010. [[CrossRef](#)]

4. Naresh, V.; Lee, N. A Review on Biosensors and Recent Development of Nanostructured Materials-Enabled Biosensors. *Sensors* **2021**, *21*, 1109. [[CrossRef](#)]
5. Yáñez-Sedeño, P.; Pingarrón, J.M. Gold Nanoparticle-Based Electrochemical Biosensors. *Anal. Bioanal. Chem.* **2005**, *382*, 884–886. [[CrossRef](#)]
6. Bhardwaj, H.; Archana; Noumani, A.; Himanshu, J.K.; Chakravorty, S.; Solanki, P.R. Recent Advancement in the Detection of Potential Cancer Biomarkers Using the Nanomaterial Integrated Electrochemical Sensing Technique: A Detailed Review. *Mater. Adv.* **2024**, *5*, 475–503. [[CrossRef](#)]
7. Quesada-González, D.; Merkoçi, A. Quantum Dots for Biosensing: Classification and Applications. *Biosens. Bioelectron.* **2025**, *273*, 117180. [[CrossRef](#)]
8. Fong, K.E.; Yung, L.-Y.L. Localized Surface Plasmon Resonance: A Unique Property of Plasmonic Nanoparticles for Nucleic Acid Detection. *Nanoscale* **2013**, *5*, 12043. [[CrossRef](#)]
9. Islam, R.; Maparathne, S.; Chinwangso, P.; Lee, T.R. Review of Shape-Memory Polymer Nanocomposites and Their Applications. *Appl. Sci.* **2025**, *15*, 2419. [[CrossRef](#)]
10. Paramasivam, G.; Sanmugam, A.; Palem, V.V.; Sevanan, M.; Sairam, A.B.; Nachiappan, N.; Youn, B.; Lee, J.S.; Nallal, M.; Park, K.H. Nanomaterials for Detection of Biomolecules and Delivering Therapeutic Agents in Theragnosis: A Review. *Int. J. Biol. Macromol.* **2024**, *254*, 127904. [[CrossRef](#)]
11. Karki, B.; Trabelsi, Y.; Pal, A.; Taya, S.A.; Yadav, R.B. Direct Detection of Dopamine Using Zinc Oxide Nanowire-Based Surface Plasmon Resonance Sensor. *Opt. Mater.* **2024**, *147*, 114555. [[CrossRef](#)]
12. Shenoy, A.G.; Sadani, K.; Nag, P. Optic Fiber Sensors with Tunable Sensitivities for Rapid Detection of Amatoxins in Water and Mushroom Derived Agro-Products. *Food Res. Int.* **2025**, *203*, 115885. [[CrossRef](#)]
13. Yu, L.; Li, N. Noble Metal Nanoparticles-Based Colorimetric Biosensor for Visual Quantification: A Mini Review. *Chemosensors* **2019**, *7*, 53. [[CrossRef](#)]
14. Subhan, M.A.; Neogi, N.; Choudhury, K.P.; Rahman, M.M. Advances in Biosensor Applications of Metal/Metal-Oxide Nanoscale Materials. *Chemosensors* **2025**, *13*, 49. [[CrossRef](#)]
15. Zhang, P.; Hou, H.; Xu, S.; Wen, Y.; Zhang, Y.; Xing, F. Localized Surface Plasmon Resonance Sensing Based on Monometallic Gold Nanoparticles: From Material Preparation to Detection of Bioanalytes. *Anal. Methods* **2025**, *17*, 892–915. [[CrossRef](#)]
16. Jiang, J.; Charconnet, M.; Vergara, A.G.; Zhang, S.; Zhang, Y.; Liang, Y.; Zubiria, J.; Sorarrain, A.; Marimon, J.M.; Peng, Y.; et al. Rapid, Economical Detection of *Helicobacter Pylori* Using Gold Colloidal Nanoparticle Biosensors. *ACS Omega* **2025**, *10*, 6559–6566. [[CrossRef](#)]
17. Borjikhani, P.; Granpayeh, N.; Zibaii, M.I. High Sensitivity Tapered Fiber Refractive Index Biosensor Using Hollow Gold Nanoparticles. *Sci. Rep.* **2025**, *15*, 1458. [[CrossRef](#)]
18. Demishkevich, E.; Zyubin, A.; Seteikin, A.; Samusev, I.; Park, I.; Hwangbo, C.K.; Choi, E.H.; Lee, G.J. Synthesis Methods and Optical Sensing Applications of Plasmonic Metal Nanoparticles Made from Rhodium, Platinum, Gold, or Silver. *Materials* **2023**, *16*, 3342. [[CrossRef](#)]
19. Zhao, Y.; Guan, M.; Mi, F.; Zhang, Y.; Geng, P.; Zhang, S.; Song, H.; Chen, G. A SERS/Colorimetric Biosensor Based on AuNSs@Ag Core–Shell Prussian Blue Nanozyme for Non-Interference and Rapid Detection of Staphylococcus Aureus in Milk. *Microchim. Acta* **2025**, *192*, 83. [[CrossRef](#)]
20. Zheng, Z.; Li, H.; Li, H.; Xia, F. Electrochemical Biosensors for Virus Detection. In *Electrochemical Biosensors for Whole Blood Analysis*; Xia, F., Li, H., Li, S., Lou, X., Eds.; Springer Nature Singapore: Singapore, 2023; pp. 217–233. ISBN 978-981-99-5643-2.
21. Maciulis, V.; Ramanaviciene, A.; Plikusiene, I. Recent Advances in Synthesis and Application of Metal Oxide Nanostructures in Chemical Sensors and Biosensors. *Nanomaterials* **2022**, *12*, 4413. [[CrossRef](#)]
22. Nguyen, M.D.; Hoijang, S.; Yarinia, R.; Ariza Gonzalez, M.; Mandal, S.; Tran, Q.M.; Chinwangso, P.; Lee, T.R. Magnetic Iron Oxide Nanoparticles: Advances in Synthesis, Mechanistic Understanding, and Magnetic Property Optimization for Improved Biomedical Performance. *Nanomaterials* **2025**, *15*, 1500. [[CrossRef](#)]
23. Ariza Gonzalez, M.; Hoijang, S.; Tran, D.B.; Tran, Q.M.; Atik, R.; Islam, R.; Maparathne, S.; Wongthep, S.; Yarinia, R.; Amarasekara, R.; et al. Surface-Modified Magnetic Nanoparticles for Photocatalytic Degradation of Antibiotics in Wastewater: A Review. *Appl. Sci.* **2026**, *16*, 844. [[CrossRef](#)]
24. Tripathy, N.; Kim, D.-H. Metal Oxide Modified ZnO Nanomaterials for Biosensor Applications. *Nano Conver.* **2018**, *5*, 27. [[CrossRef](#)]
25. Shobana, B.; Renugadevi, K.; Prakash, P. A High Sensitive Microbial Photoelectrochemical Sensor Based on Cuprous Oxide @ Titanium Dioxide/MXene for the Selective Detection of Staphylococcus Aureus in Polymicrobial Environment. *J. Electroanal. Chem.* **2025**, *977*, 118857. [[CrossRef](#)]
26. Zhou, J.; Gui, Y.; Lv, X.; He, J.; Xie, F.; Li, J.; Cai, J. Nanomaterial-Based Fluorescent Biosensor for Food Safety Analysis. *Biosensors* **2022**, *12*, 1072. [[CrossRef](#)] [[PubMed](#)]
27. Wang, Z.; Dai, Z. Carbon Nanomaterial-Based Electrochemical Biosensors: An Overview. *Nanoscale* **2015**, *7*, 6420–6431. [[CrossRef](#)]

28. Zhu, Z.; Garcia-Gancedo, L.; Flewitt, A.J.; Xie, H.; Moussy, F.; Milne, W.I. A Critical Review of Glucose Biosensors Based on Carbon Nanomaterials: Carbon Nanotubes and Graphene. *Sensors* **2012**, *12*, 5996–6022. [[CrossRef](#)] [[PubMed](#)]
29. Sireesha, M.; Jagadeesh Babu, V.; Kranthi Kiran, A.S.; Ramakrishna, S. A Review on Carbon Nanotubes in Biosensor Devices and Their Applications in Medicine. *Nanocomposites* **2018**, *4*, 36–57. [[CrossRef](#)]
30. Mousavi, S.M.; Nezhad, F.F.; Ghahramani, Y.; Binazadeh, M.; Javidi, Z.; Azhdari, R.; Gholami, A.; Omidifar, N.; Rahman, M.M.; Chiang, W. Recent Advances in Bioactive Carbon Nanotubes Based on Polymer Composites for Biosensor Applications. *Chem. Biodivers.* **2024**, *21*, e202301288. [[CrossRef](#)]
31. Castro, K.P.R.; Colombo, R.N.P.; Iost, R.M.; Da Silva, B.G.R.; Crespilho, F.N. Low-Dimensionality Carbon-Based Biosensors: The New Era of Emerging Technologies in Bioanalytical Chemistry. *Anal. Bioanal. Chem.* **2023**, *415*, 3879–3895. [[CrossRef](#)]
32. Zermane, M.; Teniou, A.; Berkani, M.; Sobti, N.; Catanante, G.; Gnanasekaran, L.; Vasseghian, Y.; Rhouati, A. MXene (Ti₃C₂T_x)-Fe₂O₃ Hybrid Nanomaterials for Electrochemical Ultra-Sensitive Testosterone Detection. *ACS Appl. Nano Mater.* **2025**, *8*, 5611–5622. [[CrossRef](#)]
33. Yoon, J.; Shin, M.; Lim, J.; Lee, J.-Y.; Choi, J.-W. Recent Advances in MXene Nanocomposite-Based Biosensors. *Biosensors* **2020**, *10*, 185. [[CrossRef](#)]
34. Yang, G.; Liu, F.; Zhao, J.; Fu, L.; Gu, Y.; Qu, L.; Zhu, C.; Zhu, J.-J.; Lin, Y. MXenes-Based Nanomaterials for Biosensing and Biomedicine. *Coord. Chem. Rev.* **2023**, *479*, 215002. [[CrossRef](#)]
35. Sinha, A.; Dhanjai; Zhao, H.; Huang, Y.; Lu, X.; Chen, J.; Jain, R. MXene: An Emerging Material for Sensing and Biosensing. *TrAC Trends Anal. Chem.* **2018**, *105*, 424–435. [[CrossRef](#)]
36. Elshafie, H.; Changalasetty, S.B.; Alavudeen Basha, A.; Mubarakali, A.; Venkatesh, M.; Parthasarathy, P. Pt-Doped Reduced Graphene Oxide-Porphyrin-CNT Composite-Based Electrochemical Sensor for Simultaneous Detection of Dopamine, Serotonin and Norepinephrine. *J. Electrochem. Soc.* **2025**, *172*, 027507. [[CrossRef](#)]
37. Saadh, M.J.; Ali, A.B.M.; Hanoon, Z.; Jain, V.; Pathak, P.K.; Kumar, A.; Almehizia, A.A.; Rao, D.P. The Ability of ZnO and MgO Nanocages for Adsorption and Sensing Performance of Anticancer Drug Detection. *J. Mol. Graph. Model.* **2025**, *137*, 109003. [[CrossRef](#)] [[PubMed](#)]
38. Pilvenyte, G.; Ratautaite, V.; Boguzaitė, R.; Ramanavicius, S.; Chen, C.-F.; Viter, R.; Ramanavicius, A. Molecularly Imprinted Polymer-Based Electrochemical Sensors for the Diagnosis of Infectious Diseases. *Biosensors* **2023**, *13*, 620. [[CrossRef](#)]
39. Singh, H.; Thakur, B.; Bhardwaj, S.K.; Khatri, M.; Kim, K.-H.; Bhardwaj, N. Nanomaterial-Based Fluorescent Biosensors for the Detection of Antibiotics in Foodstuffs: A Review. *Food Chem.* **2023**, *426*, 136657. [[CrossRef](#)]
40. Zhang, H.; Liu, P.; Wang, H.; Ji, X.; Zhao, M.; Song, Z. Label-Free Fluorescent Sensor for One-Step Lysozyme Detection via Positively Charged Gold Nanorods. *Anal. Bioanal. Chem.* **2021**, *413*, 1541–1547. [[CrossRef](#)]
41. Dongare, P.R.; Gore, A.H. Recent Advances in Colorimetric and Fluorescent Chemosensors for Ionic Species: Design, Principle and Optical Signalling Mechanism. *ChemistrySelect* **2021**, *6*, 5657–5669. [[CrossRef](#)]
42. Majumder, S.; Deb, S.; Hussain, S.; Dey, D.; Bhattacharjee, D.; Alodhayb, A.N.; Hussain, S.; Hussain, S.A. Spectroscopic Investigation of Two Xanthene Dyes and Design of a FRET Based Pesticide Sensor. *Sci. Rep.* **2025**, *15*, 2824. [[CrossRef](#)]
43. Yoo, K.; Cho, H.-S.; Kim, J.; Shin, M.; Chu, J.-S.; Jang, S.; Bae, H.-J.; Jung, H.S.; Kang, H.; Jun, B.-H. Aptamer-Conjugated Multi-Quantum Dot-Embedded Silica Nanoparticles for Lateral Flow Immunoassay. *Biosensors* **2025**, *15*, 54. [[CrossRef](#)]
44. Chiu, Y.-H.; Rinawati, M.; Chang, L.-Y.; Guo, Y.-T.; Chen, K.-J.; Chiu, H.-C.; Lin, Z.-H.; Huang, W.-H.; Haw, S.-C.; Yeh, M.-H. Carbon Nitride Quantum Dots/Polyaniline Nanocomposites for Non-Invasive Glucose Monitoring Using Wearable Sweat Biosensor. *ACS Appl. Nano Mater.* **2025**, *8*, 2340–2351. [[CrossRef](#)]
45. Ullah, N.; Bruce-Tagoe, T.A.; Asamoah, G.A.; Soleimani, S.; Danquah, M.K. Enhanced Optical Aptasensing Platform Utilizing Mesoporous Silica Nanoparticles for the Detection of Iron-Regulated Surface Determinant Protein A. *Microchem. J.* **2025**, *209*, 112784. [[CrossRef](#)]
46. Udourioh, G.A.; Solomon, M.M.; Epelle, E.I. Metal Organic Frameworks as Biosensing Materials for COVID-19. *Cel. Mol. Bioeng.* **2021**, *14*, 535–553. [[CrossRef](#)] [[PubMed](#)]
47. López-Palacios, A.; Aranda, M.N.; Caballos, I.; Hernández-Montoto, A.; Calabuig, E.; Gómez-Ruiz, M.D.; Tormo-Mas, M.Á.; Pemán, J.; Sancenón, F.; Martínez-Máñez, R.; et al. SARS-COV-2 Viral RNA Detection through Oligonucleotide-Capped Nanoporous Anodic Alumina Supports. *Sens. Actuators Rep.* **2025**, *9*, 100298. [[CrossRef](#)]
48. Pal, N.; Chakraborty, D.; Cho, E.-B.; Seo, J.G. Recent Developments on the Catalytic and Biosensing Applications of Porous Nanomaterials. *Nanomaterials* **2023**, *13*, 2184. [[CrossRef](#)] [[PubMed](#)]
49. Carrasco, S. Metal-Organic Frameworks for the Development of Biosensors: A Current Overview. *Biosensors* **2018**, *8*, 92. [[CrossRef](#)]
50. Kong, Y.; Qian, X.; Mei, X.; Ma, J.; Wu, K.; Deng, A.; Li, J. Electrochemiluminescence Immunoassay System Based on PCN-224-Mn and Gold-Platinum Bimetallic Nanoflowers for Sensitive Detection of Ochratoxin A. *Talanta* **2025**, *281*, 126937. [[CrossRef](#)]
51. Liu, M.; Fu, S.; Xu, J.; Yuan, C.; Ma, J.; Gu, C.; Jiang, T.; Bian, X. Simultaneous Monitoring of Creatinine and Urea in Diversified Clinical Samples Based on SERS-Active PDMS-Flower-like ZIF-67@Ag Nanoparticles. *Anal. Chim. Acta* **2025**, *1349*, 343829. [[CrossRef](#)]

52. Yuan, J.; Wang, L.; Duan, H.; Ye, S.; Ding, Y.; Li, Y.; Lin, J. A Press-Actuated Slidable Microfluidic Colorimetric Biosensor for Salmonella Detection Utilizing Nickel Mesh Sheet and MIL-88@Pd/Pt Nanoparticles. *Food Chem.* **2025**, *467*, 142343. [[CrossRef](#)]
53. Soto, D.; Orozco, J. Hybrid Nanobioengineered Nanomaterial-Based Electrochemical Biosensors. *Molecules* **2022**, *27*, 3841. [[CrossRef](#)]
54. Lv, J.; Huang, R.; Zeng, K.; Zhang, Z. Magnetic Immunoassay Based on Au Pt Bimetallic Nanoparticles/Carbon Nanotube Hybrids for Sensitive Detection of Tetracycline Antibiotics. *Biosensors* **2024**, *14*, 342. [[CrossRef](#)] [[PubMed](#)]
55. Wekalao, J. Graphene-Enhanced Terahertz Metamaterial Biosensor for Tuberculosis Detection with XGBoost-Based Machine Learning Optimization. *Plasmonics* **2025**, *21*, 217–232. [[CrossRef](#)]
56. Lisboa, B.; Soler, M.; Singh, R.; Castro-Esteban, J.; Peña, D.; Mugarza, A.; Lechuga, L.M.; Moreno, C. Nanoporous Graphene Integrated onto Bimodal Waveguide Biosensors for Detection of C-Reactive Protein. *ACS Appl. Nano Mater.* **2025**, *8*, 1640–1648. [[CrossRef](#)] [[PubMed](#)]
57. Zhao, L.; Wu, D.; Xiao, S.; Yin, Y.; Li, L.; Wang, J.; Wu, Y.; Qiu, Y.; Dong, Y. Dual-Mode Aptasensors with Cross Validation Capacity for Reliability Enhancement and Analytical Assurance. *TrAC Trends Anal. Chem.* **2024**, *177*, 117755. [[CrossRef](#)]
58. Viswanathan, S.; Radecka, H.; Radecki, J. Electrochemical Biosensors for Food Analysis. *Monatsh. Chem.* **2009**, *140*, 891–899. [[CrossRef](#)]
59. Sangeetha, P.; Ayyanar, N.; Prabhakar, G.; Rajaram, S. Study Review of Optical Biosensors Based on 2D Materials. *Plasmonics* **2025**, *20*, 7155–7169. [[CrossRef](#)]
60. Yoon, J.; Kwon, N.; Lee, Y.; Kim, S.; Lee, T.; Choi, J.-W. Nanotechnology-Based Wearable Electrochemical Biosensor for Disease Diagnosis. *ACS Sens.* **2025**, *10*, 1675–1689. [[CrossRef](#)]
61. Adarakatti, P.S. Fundamentals of Electrochemistry. In *ACS Symposium Series*; Manjunatha, J.G., Ed.; American Chemical Society: Washington, DC, USA, 2025; Volume 1496, pp. 17–46. ISBN 978-0-8412-9651-0.
62. Saputra, H.A. Electrochemical Sensors: Basic Principles, Engineering, and State of the Art. *Monatsh. Chem.* **2023**, *154*, 1083–1100. [[CrossRef](#)]
63. Lospinoso, D.; Colombelli, A.; Pal, S.; Cretì, P.; Martucci, M.C.; Giancane, G.; Licciulli, A.; Rella, R.; Manera, M.G. Sustainable and Flexible Surface-Enhanced Raman Scattering Transducer: Gold Nanoparticle-Bacterial Cellulose Composite for Pesticide Monitoring in Agrifood Systems. *Biosensors* **2025**, *15*, 69. [[CrossRef](#)] [[PubMed](#)]
64. Huang, Q.; Cao, J.; Huang, X.; Liu, Z. A Robust Electrochemical Sensor for Gefitinib Detection Using Three-Dimensional Framework Molecularly Imprinted Polymer-Loaded Carbon Nanotubes. *Microchem. J.* **2025**, *208*, 112485. [[CrossRef](#)]
65. Patel, M.; Agrawal, M.; Srivastava, A. Signal Amplification Strategies in Electrochemical Biosensors via Antibody Immobilization and Nanomaterial-Based Transducers. *Mater. Adv.* **2022**, *3*, 8864–8885. [[CrossRef](#)]
66. Rabiee, N.; Ahmadi, S.; Rahimizadeh, K.; Chen, S.; Veedu, R.N. Metallic Nanostructure-Based Aptasensors for Robust Detection of Proteins. *Nanoscale Adv.* **2024**, *6*, 747–776. [[CrossRef](#)]
67. Men, Z.; Singh, R.; Zhang, B.; Kumar, S. Seven-Core Tapered Optical Fiber LSPR Biosensor With CMC Structure for Ultra-Sensitive Detection of Paraoxon in Environmental Monitoring. *IEEE Trans. Instrum. Meas.* **2025**, *74*, 1–10. [[CrossRef](#)]
68. Vasudevan, M.; Perumal, V.; Karuppanan, S.; Ovinis, M.; Bothi Raja, P.; Gopinath, S.C.B.; Immanuel Edison, T.N.J. A Comprehensive Review on Biopolymer Mediated Nanomaterial Composites and Their Applications in Electrochemical Sensors. *Crit. Rev. Anal. Chem.* **2024**, *54*, 1871–1894. [[CrossRef](#)]
69. Pal, S.; Kumar, D.; Pillay, S.; Shukla, S.K.; Hussain, C.M. Multiplex Biosensor Interface Utilizing PANI-AgNP Nanocomposite for Glucose and Urea Detection. *Top. Catal.* **2025**, *69*, 892–905. [[CrossRef](#)]
70. Mendoza, D.J.; Atienza-Parcon, M.T.J.A.; Alocilja, E.C.; Fernando, L.M. Magnetic Nanoparticle-Mediated Extraction and Electrochemical Detection of *E. Coli* O157:H7 Genomic DNA. *Anal. Lett.* **2024**, *58*, 2593–2608. [[CrossRef](#)]
71. Beheshti-Marnani, A.; Rohani, T.; Kermani, M.A.; Mohammadi, S.Z. A Sensitive Chalcogenide-Based Electrochemical Sensor for Ultra-Level Detection of Mospilan Residues in Real Samples. *Sci. Rep.* **2025**, *15*, 5966. [[CrossRef](#)]
72. Singh, D.; Raviraju, G.; Gupta, M.; Upadhyay, S.; Goel, A.K.; Sharma, M.K. Electrochemical Immunosensor for *Bacillus Anthracis* PA Toxin Using a Polypyrrole-Gold Nanoparticle/Multiwall Carbon Nanotube Sensing Platform and Cadmium Sulphide Nanocrystal Signal Tag. *Anal. Methods* **2025**, *17*, 1531–1538. [[CrossRef](#)] [[PubMed](#)]
73. Wu, F.; Gao, H.; Qiu, R.; Zhang, H.; Ren, X.; Qi, X.; Miao, M.; Rui, C.; Chang, D.; Pan, H. A Novel Ratiometric Electrochemical Immunosensor for the Detection of Cancer Antigen 125 Based on Three-Dimensional Carbon Nanomaterial and MOFs. *Microchem. J.* **2024**, *200*, 110372. [[CrossRef](#)]
74. Ghosal, M.; Mondal, S.; Ghosh, T.; Prusty, D.; Senapati, D. Core-to-Shell Thickness-Regulated Ag@Au Nanocatalyst for LSPR-Improved *In Situ* Detection of Extracellular Peroxide: Response in a Cancer Cell. *Anal. Chem.* **2025**, *97*, 7651–7661. [[CrossRef](#)]
75. Torati, S.R.; Slaughter, G. Advanced Laser-Induced Graphene-Based Electrochemical Immunosensor for the Detection of C-Reactive Protein. *Bioelectrochemistry* **2025**, *161*, 108842. [[CrossRef](#)]

76. Wu, J.; Xia, Y.; Wang, T.; Zhang, Y.; Li, G. Efficient Voltammetric Platform Combining a Molecularly Imprinted Polymer and Silver-Nanoparticle-Decorated Black Phosphorus Nanosheets for Selective Determination of Gatifloxacin. *Food Chem. X* **2025**, *25*, 102094. [\[CrossRef\]](#)
77. Hamdi, F.; Roushani, M.; Hoseini, S.J. Novel Biosensor for Sarcosine Detection in Prostate Cancer: Combining Molecular Imprinted Polymer and Aptamer Strategies. *Microchem. J.* **2025**, *208*, 112429. [\[CrossRef\]](#)
78. Yahyavi, I.; Edalat, F.; Pirbonyeh, N.; Letafati, A.; Sattarahmady, N.; Heli, H.; Moattari, A. Nucleic Acid-based Electrochemical Biosensor for Detection of Influenza B by Gold Nanoparticles. *J. Mol. Recognit.* **2024**, *37*, e3073. [\[CrossRef\]](#)
79. Aye, N.N.S.; Maraming, P.; Tippayawat, P.; Daduang, S.; Techasen, A.; Jamnongkan, W.; Sithithaworn, P.; Daduang, J. Functionalized Graphene Oxide–Antibody Conjugate-Based Electrochemical Immunosensors to Detect *Opisthorchis viverrini* Antigen in Urine. *Mater. Adv.* **2024**, *5*, 4491–4503. [\[CrossRef\]](#)
80. Shi, Y.; Hu, B.; Liu, B.; Li, X.; Jing, Y.; Li, Z.; Li, Z.; Sun, S. Aptamer-Antibody Sandwich Immunosensor for Electrochemical Detection of FT4. *Microchim. Acta* **2025**, *192*, 105. [\[CrossRef\]](#)
81. Gao, H.; Qin, H.; Fu, H.; Feng, J.; Chen, M. Tau Biosensor on Aptamer-Modified Interdigitated Electrode for Monitoring Neurological Effect Caused by Anesthesia. *Heliyon* **2024**, *10*, e37449. [\[CrossRef\]](#)
82. Li, W.; Song, Y.; Zhao, L.; Ling, Z.; Xu, H. MXene-CuBTC Nanozyme with Oxygen Vacancies and Charge Transfer for Biosensing of *Listeria Monocytogenes*. *Chem. Eng. J.* **2025**, *509*, 161261. [\[CrossRef\]](#)
83. Li, M.; Shen, G.; Ding, Y.; Gong, Z.; Zhou, Y.; Chen, Y. Fullerene-Based PEC Aptasensor with DNA Super Sandwich Structures and Pb²⁺-G Quadruplex Structures. *Microchem. J.* **2025**, *208*, 112563. [\[CrossRef\]](#)
84. De Souza Freire, L.; Gandarilla, A.M.D.; Barcelay, Y.R.; Ruza, C.M.; Salgado, B.B.; Tavares, A.P.M.; Nobre, F.X.; De Souza Neto, J.N.; Astolfi-Filho, S.; Tălu, Ș.; et al. Carboxylated Graphene: An Innovative Approach to Enhanced IgA-SARS-CoV-2 Electrochemical Biosensing. *Biosensors* **2025**, *15*, 34. [\[CrossRef\]](#)
85. Zhao, M.; Wang, L.; Xu, H. Immobilization of Gold Nanoparticles on Electrospun Polyacrylonitrile/Carbon Nanotube Nanofiber for Self-Powered Electrochemical Biosensing of Myoglobin. *Mater. Chem. Phys.* **2025**, *339*, 130722. [\[CrossRef\]](#)
86. Dhaffouli, A.; Ali, E.; Moussaoui, Y.; Holzinger, M.; Salazar-Carballo, P.A.; Carinelli, S.; Barhoumi, H. Electrochemical Detection of Paracetamol in Real Samples Using Sensor Based on a Glassy Carbon Electrode Modified with Chitosan@SiO₂-APTES Composite: Synthesis, Characterization and Analytical Applications. *J. Electrochem. Soc.* **2025**, *172*, 017521. [\[CrossRef\]](#)
87. Ling, W.; Shang, X.; Liu, J.; Tang, T. A Skin-Mountable Flexible Biosensor Based on Cu-MOF/PEDOT Composites for Sweat Ascorbic Acid Monitoring. *Biosens. Bioelectron.* **2025**, *267*, 116852. [\[CrossRef\]](#)
88. Wang, G.; Tang, T.; Liu, R.; Li, J.; Xu, Y.; Liao, S. Novel Electrochemical Sensor Based on Cu-MOF/MWCNT-COOH for the Simultaneous Detection of Ascorbic Acid and Dopamine. *Langmuir* **2025**, *41*, 4102–4112. [\[CrossRef\]](#)
89. Li, J.; Liu, J.; Wang, J.; Li, W.; Wang, F. A Flexible Biosensor for Efficiently Glucose Monitoring in Sweat Based on Copper Nanoparticles Modified PHEMA Hydrogel. *Eur. Polym. J.* **2025**, *222*, 113630. [\[CrossRef\]](#)
90. Phamonpon, W.; Promphet, N.; Saengkiattiyut, K.; Boonyongmaneerat, Y.; Rattanawaleedirojn, P.; Hinestroza, J.P.; Rodthongkum, N. Novel Bioelectrode for Sweat Lactate Sensor Based on Platinum Nanoparticles/Reduced Graphene Oxide Modified Carbonized Silk Cocoon. *Sens. Actuators B Chem.* **2025**, *423*, 136717. [\[CrossRef\]](#)
91. Shafaei, S.; Mohammad-Rezaei, R.; Khalilzadeh, B.; Isildak, I. Platinum Nanoparticles Decorated on Electrodeposited Ti₃C₂T_x MXene Nanosheets as an Ultrasensitive Biosensor for CA15–3 Detection. *Sens. Actuators Rep.* **2025**, *9*, 100278. [\[CrossRef\]](#)
92. Yang, X.; Wu, F.; Huang, H.; Zheng, G.; Zhang, H.; Cai, W.; Li, J.; Yin, Z.Z.; Kong, Y. Au Nanoparticles Anchored Carbonized ZIF-8 for Enabling Real-Time and Noninvasive Glucose Monitoring in Sweat. *Biosens. Bioelectron.* **2025**, *272*, 117138. [\[CrossRef\]](#)
93. Mustafa, M.; Rehman, S.U.; Wu, H.-F. Synthesis of Two-Dimensional SnO₂-WO₃ (2D-TTO) Heterojunction Nanosheet and Its Application as a Highly Sensitive and Selective Fluorescence Sensor for Nifedipine Detection in Biological and Environmental Samples. *FlatChem* **2025**, *50*, 100836. [\[CrossRef\]](#)
94. Zhou, J.; Wang, Y.; Zhang, L.; Li, X. Plasmonic Biosensing Based on Non-Noble-Metal Materials. *Chin. Chem. Lett.* **2018**, *29*, 54–60. [\[CrossRef\]](#)
95. Girigoswami, K.; Akhtar, N. Nanobiosensors and Fluorescence Based Biosensors: An Overview. *Int. J. Nano Dimens.* **2019**, *10*, 1–17.
96. Lin, X.; Yang, Y.; Zhu, W.; He, X.; Liu, Y. Near-Infrared DNA Biosensors Based on Polysulfonate Coatings for the Sensitive Detection of microRNAs. *Nanoscale Adv.* **2025**, *7*, 549–559. [\[CrossRef\]](#)
97. Zhang, B.; Zhang, P.; Wang, H.; Wang, X.; Hu, Z.; Wang, F.; Li, Z. Dual Protein Corona-Mediated Target Recognition System for Visual Detection and Single-Molecule Counting of Nucleic Acids. *ACS Nano* **2025**, *19*, 6929–6941. [\[CrossRef\]](#)
98. Daneshgar, H.; Fatahi, Y.; Salehi, G.; Bagherzadeh, M.; Rabiee, N. Highly Sensitive and Selective Detection of SARS-CoV-2 Spike Protein S1 Using Optically-Active Nanocomposite-Coated Melt-Blown Masks. *Anal. Chim. Acta* **2025**, *1336*, 343534. [\[CrossRef\]](#)
99. Guo, W.; Yan, S.; Xiao, C.; Shi, D.; Hua, Q.; Hao, X.; Zhang, W.; Zhuang, X. A Novel Molecularly Imprinted Electrochemiluminescence Sensor Based on Mxene Quantum Dots for Selective Detection of Oseltamivir in Biological Samples. *Molecules* **2025**, *30*, 152. [\[CrossRef\]](#)

100. Tanaka, Y.; Hirao, G.; Fukuzumi, N.; Asahi, T.; Maeda, M.; Ogawa, A.; Zako, T. Effect of DNA Density on Nucleic Acid Detection Using Cross-Linking Aggregation of DNA-Modified Gold Nanoparticles. *Langmuir* **2025**, *41*, 4560–4568. [\[CrossRef\]](#)
101. Alarcón-Iniesta, H.; De Arana, G.; López-Valls, M.; Pardo, D.; Escalona-Noguero, C.; Rodríguez, C.; Castellanos, M.; Cobelo, S.; Martínez-Ramírez, I.; Camarero, J.; et al. CRISPR-Associated Plasmonic Colorimeter Method (Ca-PCM): A Real-Time RGB Detection System for Gold Nanoparticles-Based Nucleic Acid Biosensors. *Anal. Chim. Acta* **2025**, *1338*, 343601. [\[CrossRef\]](#)
102. Yang, X.; Guo, J.; Yang, F.; Yang, G.; Wu, Y.; Li, Z.; Liu, Y.; Yang, X.; Yao, J. Tapered Optical Fiber LRSPR Biosensor Based on Gold Nanoparticle Amplification for Label-Free BSA Detection. *Sens. Actuators B Chem.* **2025**, *426*, 136986. [\[CrossRef\]](#)
103. Zhang, Q.; Liu, Q.; Long, K.; Zhou, K.; Yang, Z.; Ge, A.; Hu, J.; Peng, C.; Wang, W.; Wang, H.; et al. Visual and Fluorescence Dual Mode Platform for Sensitive and Accurate Screening of Breast Carcinoma. *Biosens. Bioelectron.* **2025**, *271*, 117047. [\[CrossRef\]](#)
104. Kilimci, U.; Öndeş, B.; Sunna, Ç.; Uygun, M.; Aktaş Uygun, D. Development of Label-Free Immunosensors Based on AuNPs-Fullerene Nanocomposites for the Determination of Cancer Antigen 125. *Bioelectrochemistry* **2025**, *163*, 108863. [\[CrossRef\]](#)
105. Cui, K.; Tang, Q.; Zhao, T.; Qiao, M.; Peng, H.; Ding, L.; Fang, Y. Bifunctional Mesoporous Silica Nanoparticles with Europium (III) and Pyrene for Visual Detection and Discriminative Identification of Six Fluoroquinolone Antibiotics. *Sens. Actuators B Chem.* **2025**, *427*, 137162. [\[CrossRef\]](#)
106. Haq, F.U.; Batool, A.; Ali, K.; Raza, A.; Jiang, H.; Huang, G.; Khan, I.M.; Wang, Z. Target-Triggered Aptasensor Using Dual-Colored Dye-Doped Silica Nanoparticles for Simultaneous Detection of Ampicillin and Oxytetracycline. *Talanta* **2025**, *291*, 127908. [\[CrossRef\]](#)
107. Gutema, K.F.; Mekonnen, M.L.; Yilma, B.T.; Asrat, T.E.; Dellith, J.; Diegel, M.; Csáki, A.; Fritzsche, W. Rapid Colorimetric Detection of Sulfite in Red Wine Using Alginate-Copper Laccase Nanozyme with Smartphone as an Optical Readout. *ACS Meas. Sci. Au* **2025**, *5*, 145–154. [\[CrossRef\]](#)
108. Meira, D.I.; Barbosa, A.I.; Borges, J.; Reis, R.L.; Correlo, V.M.; Vaz, F. Label-Free Localized Surface Plasmon Resonance (LSPR) Biosensor, Based on Au-Ag NPs Embedded in TiO₂ Matrix, for Detection of Ochratoxin-A (OTA) in Wine. *Talanta* **2025**, *284*, 127238. [\[CrossRef\]](#)
109. Wu, Y.; Wu, Z.; Xu, W.; Zeng, R.; Weng, J.; Sun, L. A Label-Free Colorimetric Biosensor Utilizing Natural Material for Highly Sensitive Exosome Detection. *Talanta* **2024**, *275*, 126182. [\[CrossRef\]](#)
110. Thajudeen, K.Y.; Ahmed, M.M.; Alshehri, S.A.; Salam, S.; Rahamathulla, M. Detection of COVID-19 with the Naked Eye Using C₆₀-Based Sensors for Isobutyric Acid in Exhaled Air: A DFT/TDDFT Study. *Diam. Relat. Mater.* **2025**, *153*, 112013. [\[CrossRef\]](#)
111. Koyambo-Konzapa, S.-J.; Oubella, A.; Altharawi, A.; Aldakhil, T. COVID-19 Detection via Isobutyric Acid Biomarker: A DFT Computational Study on Beryllium-Doped C₆₀ Fullerene. *J. Mol. Graph. Model.* **2025**, *137*, 108987. [\[CrossRef\]](#)
112. Li, Q.; Li, J.; Yang, D.; Xiang, C.; Yang, Y. Dual-Mode Colorimetric-Fluorescence Biosensor for Endotoxin Detection Based on CS@Fe₃Cu/CDs-MnO₂ Nanomaterials. *Talanta* **2025**, *285*, 127330. [\[CrossRef\]](#)
113. Aidli, W.; Fumagalli, D.; Pifferi, V.; Falciola, L. From Dual-Mode to Multi-Modal Electrochemical Based Sensors: A Path toward Accurate Sensing. *Curr. Opin. Electrochem.* **2025**, *50*, 101655. [\[CrossRef\]](#)
114. Wei, Q.; Zhu, X.; Zhang, D.; Liu, H.; Sun, B. Innovative Nanomaterials Drive Dual and Multi-Mode Sensing Strategies in Food Safety. *Trends Food Sci. Technol.* **2024**, *151*, 104636. [\[CrossRef\]](#)
115. Hu, S.; Wu, M.; Zhang, C.; Yao, X.; Wang, L.; Luo, J.; Duan, Y.; Li, Y. CRISPR/Cas12a-Powered Universal Platform with Dual-Signal Readout for Isothermal and Sensitive Detection of Pathogenic Microorganisms in Foods. *LWT* **2025**, *215*, 117230. [\[CrossRef\]](#)
116. Liu, M.; Liu, Y.; Xiao, J.; Ren, Y.; Gao, X. Colorimetric-Ratiometric Fluorescence Sensors Dual-Mode Detection of Ofloxacin Based on Fe-Ni Bimetallic Metal-Organic Frameworks and Carbon Dots. *Food Control* **2025**, *169*, 110989. [\[CrossRef\]](#)
117. Sun, B.; Panferov, V.; Guo, X.; Xiong, J.; Zhang, S.; Qin, L.; Yin, C.; Wang, X.; Liu, C.; Han, K.; et al. A Novel Triple-Signal Biosensor Based on ZrFe-MOF@PtNPs for Ultrasensitive Aflatoxins Detection. *Biosens. Bioelectron.* **2025**, *267*, 116797. [\[CrossRef\]](#)
118. Malik, S.; Singh, J.; Goyat, R.; Saharan, Y.; Chaudhry, V.; Umar, A.; Ibrahim, A.A.; Akbar, S.; Ameen, S.; Baskoutas, S. Nanomaterials-Based Biosensor and Their Applications: A Review. *Heliyon* **2023**, *9*, e19929. [\[CrossRef\]](#) [\[PubMed\]](#)
119. Tonelli, D.; Scavetta, E.; Gualandi, I. Electrochemical Deposition of Nanomaterials for Electrochemical Sensing. *Sensors* **2019**, *19*, 1186. [\[CrossRef\]](#)
120. Zang, Y.; Xu, Y.; Zhao, L.; Wang, Z.; Liu, G.; Wang, T.; He, P.; Zhou, H.; Wang, Q. Improved Surface-Enhanced Raman Scattering Detection of miRNA Employing Polyhedral Gold Plasmonic Nanoparticles in Conjunction with DNA Cascade Amplification Strategy. *Sens. Actuators B Chem.* **2025**, *429*, 137320. [\[CrossRef\]](#)
121. Tetsuo, K.; Hajime, F.; Kiyoshi, K.; Yoshitane, D.; Atsushi, H.; Yutaka, T.; Goro, K.; Tsunehisa, A. A Monoclonal Antibody Specific for a Distinct Region of Hen Egg-White Lysozyme. *Mol. Immunol.* **1982**, *19*, 619–630. [\[CrossRef\]](#)
122. Wu, H.; Zhang, R.; Lai, H.; Lai, L.; Liu, Y.; Fan, Y.; Zhang, Y.; Shi, J.; Yang, M. A MXene-Au Nanosheets-Based Fluorescent-SERS Dual-Mode Biosensor Integrated with CRISPR/Cas12a System for Endotoxin Detection. *Sens. Actuators B Chem.* **2025**, *427*, 137120. [\[CrossRef\]](#)

123. Ghaani, M.; Azimzadeh, M.; Büyüktaş, D.; Carullo, D.; Farris, S. Electrochemical Sensors in the Food Sector: A Review. *J. Agric. Food Chem.* **2024**, *72*, 24170–24190. [[CrossRef](#)] [[PubMed](#)]
124. Piskin, E.; Alakus, Z.; Budak, F.; Cetinkaya, A.; Ozkan, S.A. Nanoparticle-Supported Electrochemical Sensors for Pesticide Analysis in Fruit Juices. *J. Pharm. Biomed. Anal. Open* **2025**, *5*, 100056. [[CrossRef](#)]
125. Piriya V.S, A.; Joseph, P.; Daniel S.C.G., K.; Lakshmanan, S.; Kinoshita, T.; Muthusamy, S. Colorimetric Sensors for Rapid Detection of Various Analytes. *Mater. Sci. Eng. C* **2017**, *78*, 1231–1245. [[CrossRef](#)]
126. Zhang, Z.; Sen, P.; Adhikari, B.R.; Li, Y.; Soleymani, L. Development of Nucleic-Acid-Based Electrochemical Biosensors for Clinical Applications. *Angew. Chem.* **2022**, *134*, e202212496. [[CrossRef](#)]
127. Gunasekaran, B.M.; Srinivasan, S.; Ezhilan, M.; Nesakumar, N. Nucleic Acid-Based Electrochemical Biosensors. *Clin. Chim. Acta* **2024**, *559*, 119715. [[CrossRef](#)] [[PubMed](#)]
128. Du, L.; Chen, W.; Zhu, P.; Tian, Y.; Chen, Y.; Wu, C. Applications of Functional Metal-Organic Frameworks in Biosensors. *Biotechnol. J.* **2021**, *16*, 1900424. [[CrossRef](#)]
129. Behyar, M.B.; Nilghaz, A.; Ebrahimi, R.; Hasanzadeh, M.; Shadjou, N. Advancements in Magnetic Aptasensors: Recent Progress and Future Trends in Biosensor Technology. *TrAC Trends Anal. Chem.* **2024**, *172*, 117549. [[CrossRef](#)]
130. Nabil, M.; Megahed, F. Quantum Dot Nanomaterials: Preparation, Characterization, Advanced Bio-Imaging and Therapeutic Applications. *J. Fluoresc.* **2024**, *34*, 2467–2484. [[CrossRef](#)]
131. Arumugam, S.; Colburn, D.A.M.; Sia, S.K. Biosensors for Personal Mobile Health: A System Architecture Perspective. *Adv. Mater. Technol.* **2020**, *5*, 1900720. [[CrossRef](#)]
132. Chen, L.-C.; Wang, E.; Tai, C.-S.; Chiu, Y.-C.; Li, C.-W.; Lin, Y.-R.; Lee, T.-H.; Huang, C.-W.; Chen, J.-C.; Chen, W.L. Improving the Reproducibility, Accuracy, and Stability of an Electrochemical Biosensor Platform for Point-of-Care Use. *Biosens. Bioelectron.* **2020**, *155*, 112111. [[CrossRef](#)]
133. Demir, E.; Kırboğa, K.K.; Işık, M. An Overview of Stability and Lifetime of Electrochemical Biosensors. In *Novel Nanostructured Materials for Electrochemical Bio-Sensing Applications*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 129–158. [[CrossRef](#)]

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.