Industrial Crops & Products 233 (2025) 121337

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Short communication

Sustainable and smart nano-biosensors: Integrated solutions for healthcare, environmental monitoring, agriculture, and food safety

Muthu Thiruvengadam [a], Hee-Youn Chi [a], Hee-Jin Choi [a], Bum-Su Jung [a], Seung-Bin Lee [a], Yunwoo Park [a], Dagyeom Jeon [a], Fatih Ciftci [b], Mohammad Ali Shariati [c], Seung-Hyun Kim [a,*]

[a] *Department of Crop Science, College of Sanghuh Life Science, Konkuk University, Seoul 05029, Republic of Korea*
[b] *Department of Biomedical Engineering, Faculty of Engineering, Fatih Sultan Mehmet Vakıf University, Istanbul 34015, Turkey*
[c] *Kazakh Research Institute of Processing and Food Industry, Semey Branch of the Institute, 238«G» Gagarin Ave, Almaty 050060, Kazakhstan*

ARTICLE INFO

Keywords:
Biosensors
Nanotechnology
Phytochemicals
Diagnostics
Environmental monitoring
Food safety

ABSTRACT

The demand for highly sensitive and specific biosensors is growing rapidly across multiple sectors, including medical diagnostics, environmental monitoring, pathogen detection, and food safety. This review critically explores the advancements in nano-enabled biosensor technologies, focusing on bio-based nanosensors synthesized using plant-derived phytochemicals, cellulose, and lignin. These naturally derived materials serve as eco-friendly stabilizing and reducing agents for the formation of functional nanoparticles (NPs). This review (i) discusses the synthesis and characterization techniques of bio-nanosensors; (ii) examines their physical, chemical, and biological interactions; and (iii) evaluates their applications in early disease screening, diagnostics (e.g., cancer and diabetes), and the detection of pathogens, pollutants, and toxins. In addition, we address key challenges associated with bio-based nanomaterials, including NP toxicity, biocompatibility, and the need for appropriate regulatory frameworks. Furthermore, we highlight the growing role of artificial intelligence, machine learning, and the Internet of Things in enhancing biosensor performance and commercialization. This review concludes by emphasizing the potential of bio-based nanosensors for clinical, environmental, and food safety applications, while advocating the development of micro- and disposable sensor formats. By highlighting the potential and limitations of bionanosensors, this review provides a foundation for future research and the development of clinical and commercial applications.

1. Introduction

Biosensors, integrated devices that utilize biological sensing elements (bioreceptors) and physical elements such as transducers, are used in various applications, including industrial process control, food quality control, environmental monitoring, healthcare, and microbiology (Ramesh et al., 2023). A bioreceptor is a biomolecule that recognizes an analyte and is connected to a transducer that converts the physical or chemical changes into measurable signals. The intensity of the produced signal is related to the analyte concentration, and the performance of biosensors depends on the materials used for their fabrication (Malik et al., 2020). Biosensors are classified based on their bioreceptors (enzymatic, immune, aptamer, nucleic acid, microbial, or whole cell), transducers (electrochemical, electronic, thermal, optical, and gravimetric), and bioreceptor-analyte interactions (photonic, electrical, electronic, thermodynamic, kinetic, and magnetized) (Naresh and Lee, 2021) (Fig. 1).

The advantages of biosensors include robustness, portability, low cost, miniaturization, rapid response times, high sensitivity, and small volumes of analytes (Zhang et al., 2017). The main limitations of biosensors are (i) capturing biorecognition signals and the transformation of signals, (ii) improving the performance of transducers, and (iii) developing efficient fabrication technology. Thus, the development of an efficient biosensor with the required sensitivity and reproducibility remains challenging. These challenges can be overcome by integrating sensing technologies with nanomaterials with a high surface-to-volume ratio, good conductivity, and tunability (Naresh and Lee, 2021; Chen et al., 2018). Various bio-based nanosensors that are environmentally friendly, economical, quick, and nontoxic have been developed. Nanostructures have been used to develop biosensors for several applications. The main use of nanomaterials in biosensors is to enhance the stability of biomaterials and their sensitivity, catalytic processes, ability to react at

* Corresponding author.
E-mail address: kshkim@konkuk.ac.kr (S.-H. Kim).

https://doi.org/10.1016/j.indcrop.2025.121337
Received 15 April 2025; Received in revised form 20 May 2025; Accepted 7 June 2025
Available online 13 June 2025
0926-6690/

low potentials, and efficient and rapid transfer of electrons from the active reaction center to the electrode surface (Sun et al., 2019). Thus, nanosensing is a dynamic field that senses signals, such as forces and electrochemical or biological substances. Generally, nanosensors operate at nanoscale sizes and their specificity can be imparted by targeting ligands. The functionality of the ligand determines its ability to attract specific analyte markers, whereas nanoparticles (NPs) enhance sensitivity by converting signals between different forms or detecting the generated signals (Liao et al., 2014). Owing to their large surface area and high surface free energy, NPs are key in the adsorption of biomolecules onto their surfaces (Figueroa et al., 2024). Moreover, the application of nanomaterials in biosensors leads to the structural minimization of devices and can be used for various applications in clinical, industrial, environmental, and agricultural fields (Guo et al., 2014). This review examines and emphasizes the significance of bio-based nanomaterials for smart biosensing in various applications such as the diagnosis and detection of plant pathogens. We have also discussed the limitations, challenges, and prospects of using nano-biosensors in various industries.

2. Types of bio-based nanomaterials used in biosensing

2.1. Plant-derived nanomaterials

Phytochemicals and plant products have been used in various biosensing applications to detect various targets, including pathogens, toxic compounds, biomarkers, pharmaceutical compounds, hormones, DNA, and RNA, and to analyze environmental, biological, and clinical samples (Naghdi et al., 2020). Phytochemicals, such as polyphenols, carotenoids, alkaloids, nitrogen-containing compounds, and organo-sulfur compounds, are non-nutritive molecular species found in fruits, vegetables, grains, legumes, and nuts (Liu, 2004). Phytochemicals and plant extracts are used to synthesize NPs, and can act as reducing agents and stabilizers during NP synthesis (Zuhrotun et al., 2023; Maqsood et al., 2023). Fig. 2 illustrates the biosynthesis of nanomaterials for biosensor development. Cellulose is a biopolymer comprising glucose-based polymer chains present in plant cell walls. Cellulose and its derivatives are known for their high sensitivity, high precision, and fast response times, which make them ideal for use in paper-based biosensors and nanosensors, particularly because of their large surface-area-to-volume ratios and porous structures (Kamel and Khattab, 2020). Conversely, lignin is a phenolic polymer that is abundantly available and plays a crucial role in strengthening and reinforcing plant cell walls. It facilitates water transport within plants and serves as a protective barrier against pathogens (Moreno and Sipponen, 2020). Recently, cellulose-based NPs have been extensively investigated for the development of chemical sensors, biosensors, and energy-conversion devices (Khattab et al., 2019). In the following section, we highlight the importance of cellulose, lignin, hemicellulose, phytochemicals, plant extracts, NPs, and nanomaterials. Table 1 lists bio-based nanomaterials used in biosensing.

2.1.1. Cellulose and cellulose nanofibers

Natural polymers are promising bioresources for replacing nondegradable polymers. Cellulose has received increased attention owing to its biodegradability, biocompatibility, and nontoxicity (Hu et al., 2021). Nawaz et al. (2020) fabricated a cellulose-based multiresponsive fluorescent sensor that exhibited visual and ultrasensitive detection of borate ($B4O7^{2-}$), phosphate ($PO4^{3-}$), and carbonate ($CO3^{2-}$) anions in a mixture of anions based on changes in fluorescence and/or visible colors. A groundbreaking, portable, probe-free liquid cellulose biosensor was developed to detect copper(II) (Cu^{2+}) ions in biological samples such as urine and serum within 10 s, offering improved accuracy and biocompatibility (Wang et al., 2019b). This cellulose paper-based biosensor is equipment-free, cost-effective, portable, and can detect transcription factors using dopamine. The detection process is based on exonuclease III-assisted cycling amplification, and can be observed with

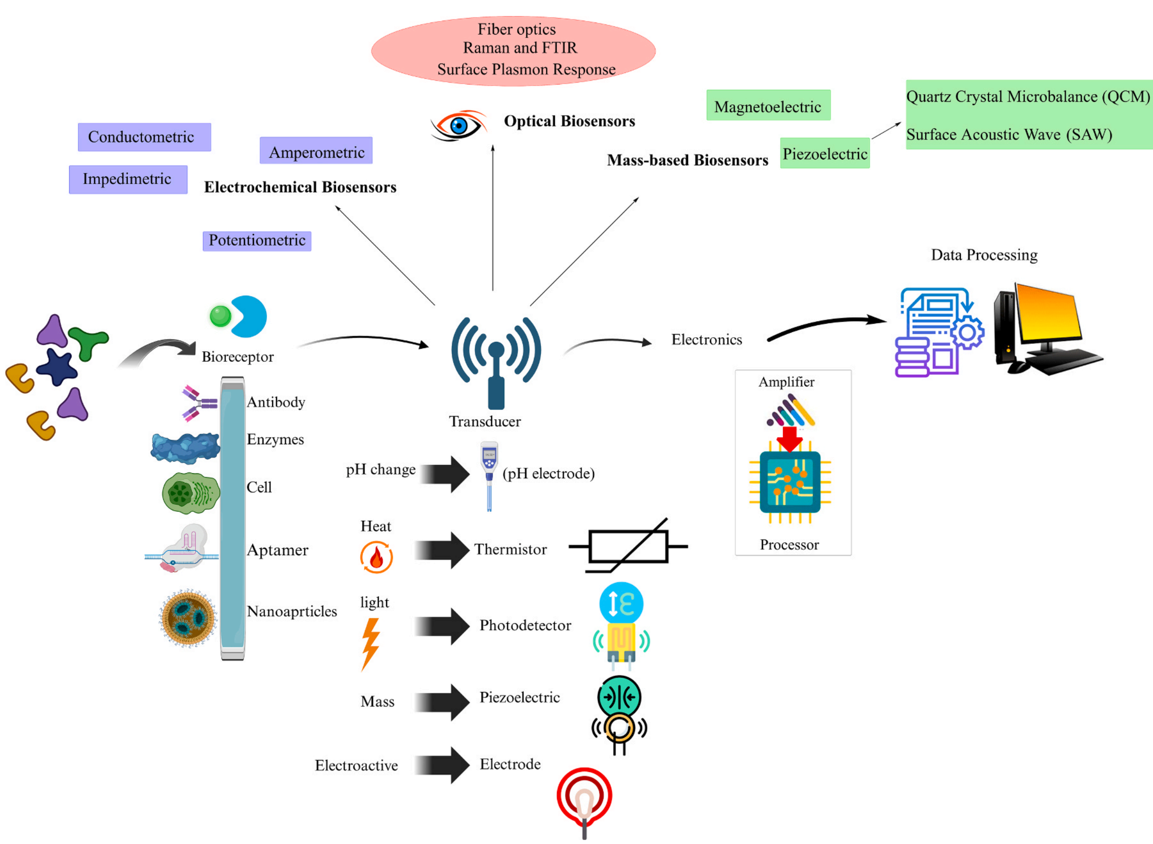

Fig. 1. Schematic illustration of biosensors and their key components. [Adapted from (Ramesh et al., 2023) and created using BioRender].

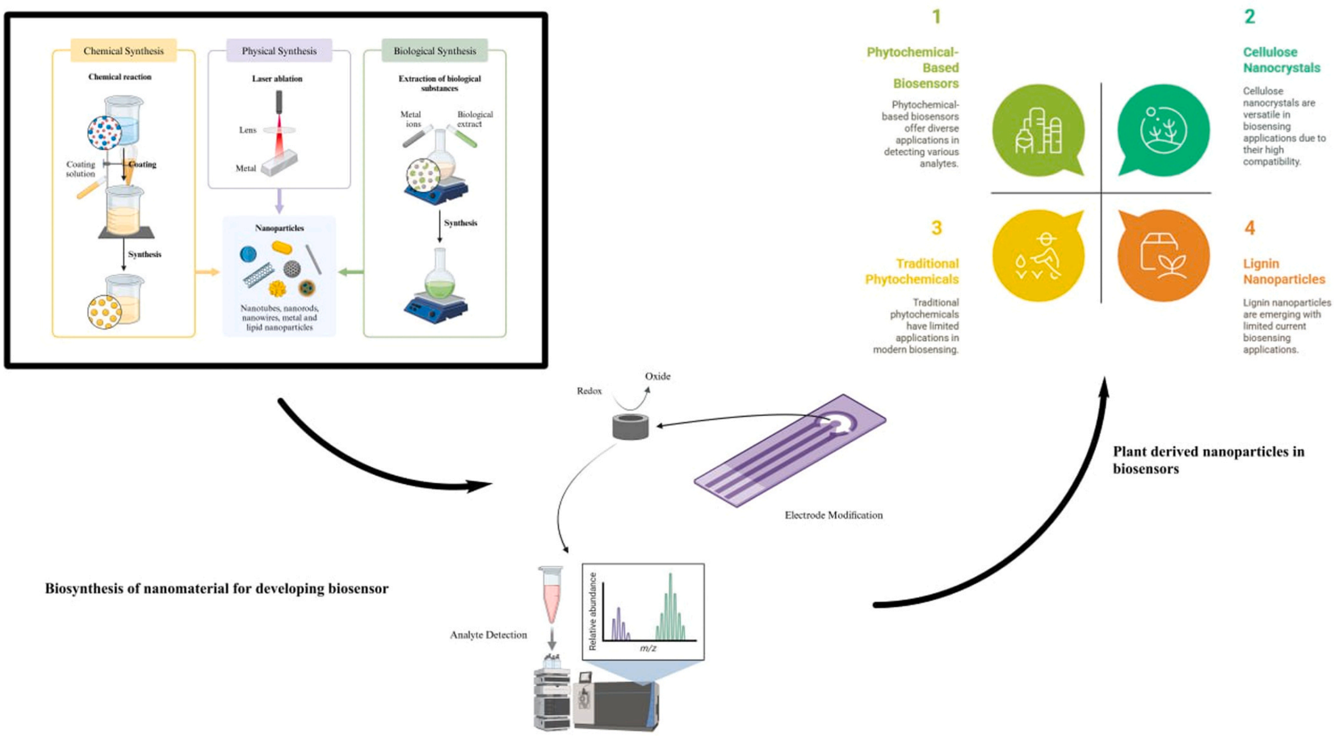

Fig. 2. Biosynthesis of nanomaterials for the development of biosensors. [Created using BioRender].

Table 1
Bio-based nanomaterials used in biosensing.

S. No	Biobased Nanomaterials	Biosensors	Detection/sensitivity	References
1.	Pure and copper-doped titanium dioxide (Cu-TiO_2) nanostructures	The Cu-doped TiO_2 nanomaterial-based Myoglobin biosensor	Higher sensitivity of 61.51 μAcm−2/nM; LOD: 14 pM Response time: less than 10 ms	(Umar et al., 2022)
2.	Single-walled carbon nanotube/reduced graphene oxide/ cobalt phthalocyanines nanohybrid modified glassy carbon electrode	Glucose sensor	LOD 0.12 μM: Detection sensitivity of 992.4 $\mu A{\cdot}mM^{-1}{\cdot}cm^{-2}$	(Adeniyi et al., 2021)
3.	Biofunctionalized tapered optical fiber with the integration of polyamidoamine dendrimer for the detection of dengue E protein	Dengue E protein sensor	LOD: 1 pM, Kd = 1.02×10^{-10} M	(Kamil et al., 2019)
4.	Au NPs@PDA@CuInZnS QDs nanocomposites	Electrochemiluminescence biosensor for detecting tumor suppressor p53 gene	Linear response in the range of 0.1 nmol/L to 15 nmol/L with a detection limit of 0.03 nmol/L	(Liu et al., 2018)
5.	MoS_2 and CdTe quantum dots	Dual-signal fluorescent sensor for detecting	Linear range 0.1–1 μM	(Liang et al., 2022)
6.	AuNPs/SWCNT	Nanogap device for DNA hybridization detection	Detection limit of 1 pM	(Yu et al., 2020)
7.	Carbon nanotube	CNT FET biosensors ultrasensitive detection of multiple biological molecules	LOD as low as 60 aM and 6 particles/mL	(Liang et al., 2020)
8.	Self-assembled monolayer/reduced graphene oxide-polyamidoamine dendrimer	SPR sensor towards DENV−2 E-proteins	Good linearity (R2 = 0.92) with the lowest detection of 0.08 pM	(Omar et al., 2020)

the naked eye (Lin et al., 2019). Additionally, an advanced antifouling electrochemical biosensor was developed using oxidized bacterial cellulose combined with a quaternized chitosan composite hydrogel. This biosensor can detect involucrin in wound exudate with a low limit of detection (LOD) of 0.45 pg/mL, and it offers a linear sensing range of 1.0 pg/mL to 1.0 μg/mL (Lv et al., 2024). A colorimetric biosensor was developed using a xanthine oxidase-immobilized cellulose membrane to detect xanthine with enhanced selectivity and sensitivity using a colorimetric method with a color change from yellow to purple (Sun et al., 2024). Despite these advantages, cellulose has some limitations, including high water absorption and poor adhesion. Therefore, cellulose has become less attractive for industrial applications. These issues can be resolved by fabricating nanocellulose materials for high-throughput applications (Sharma et al., 2019).

Nanocellulose materials can be categorized into nanofibrillated cellulose, cellulose nanocrystals, and bacterial nanocellulose. Recently, cellulosic nanomaterials, including cellulose nanocrystals and nanofibers, were found to be efficient green-filling nanomaterials owing to their low cost, large specific surface area, excellent hydrophilicity, and biological compatibility (Wei et al., 2019). Compared to other nanomaterials, including carbon and metals, cellulose possesses good compatibility and dispersibility (Jayaramudu et al., 2021). Zhu et al. (2022) developed a cellulose nanofiber/nanotube that exhibited a humidity sensor with high sensitivity (87.3 %) owing to its excellent porous nature, response limit of 100 %, and humidity range of 29–95 %. A chiral nematic composite film derived from biomass was created by combining cellulose nanocrystals with the water-soluble polymer β-cyclodextrin. This composite demonstrated high specificity and selectivity for the detection of methanol in mixed solvents commonly found in industrial products (Hu et al., 2022). In a previous study, cotton cellulose nanocrystals were developed and demonstrated to serve as effective and sensitive sensors for detecting human neutrophil elastase, making them a valuable tool for diagnosing and monitoring various inflammatory diseases (Ling et al., 2019). Bondancia et al. (2022) fabricated bacterial nanocellulose substrates to identify the oncogenic biomarker p53 antigen in MCF7 cell lysates using electrochemical impedance spectroscopy and detected concentrations ranges between 0.01 and 1000 Ucell/mL with a detection threshold of 0.16 Ucell/mL. Functional nanocellulose and activated carbon films were developed for their biosensing properties, and showed increased tensile strength and thermal stability (300–400 °C), and could be used for its smart packaging applications (Sobhan et al., 2019).

Cholesterol oxidase immobilized on a polyaniline/crystalline nanocellulose/ionic liquid-modified screen-printed electrode demonstrated a significantly improved sensitivity of 35.19 μA mM/cm^2. This sensor showed a dynamic linear detection range of 1 μM to 12 mM (R^2 = 0.99083) for cholesterol, with a lower LOD of 0.48 μM (Abdi et al., 2019). Nanocellulose/MXene/ZrO_2 was developed as an immunosensor to detect ovalbumin with LODs of 1.1 fg/mL, 0.01 pg/mL, and 0.1497 μA pg/mL cm^{-2}, showing high selectivity and reproducibility in food samples and could be used for food safety monitoring (Kareem et al., 2024). Nanocellulose paper-based analytical microfluidic devices have been fabricated to detect blood biomarkers of Alzheimer's disease, including glial fibrillary acidic proteins, with a detection threshold level of 150 fg/mL using a surface-enhanced Raman scattering (SERS) immunoassay (Yuan et al., 2024).

2.1.2. Lignin and hemicellulose NPs

Lignin is a byproduct of the pulping and papermaking industries, with an annual global production of approximately 30 million tons. Lignin has been assessed for its dynamic applications in many fields, such as electrochemistry, pharmacy, biomedicine, and sensing. Yuan et al. (2019) synthesized $Fe_3C@C$ by carbonizing Fe_3O_4-lignin clusters, which exhibited a good linear relationship with detection sensitivity for prion protein (0.1–200 ng/mL), over 10-fold compared to surface plasmon resonance (SPR) detection, and ultimately serves as an efficient sensor that could be used to diagnose prion diseases. A sustainable graphene nanofiber laser biosensor enhanced with oil-palm lignin-based synthetic silver NPs (AgNPs) was designed and evaluated for the detection of *Mycobacterium tuberculosis*. The study revealed that it could afford more stability with a high-precision detection of up to 1 fM and a detection range of 10–15 M calculated by assessing the signal-to-noise ratio (S/N = 3:1) as 3σ (Tai et al., 2021). A straightforward and efficient approach was devised to transform biomass-derived lignin into fluorescent carbon dots, which exhibited stable fluorescence, remarkable water solubility, and potential applicability as a distinctive model for ionic biosensors through metal-induced quenching mechanisms (Li et al., 2018). In another study, disposable electrodes fabricated from lignin demonstrated excellent analytical performance for lactate detection, offering a broad linear detection range of up to 16 mM and enhanced sensitivity, reaching 1.21 μA mM^{-1} (Meng et al., 2022). The CPE/Fe_3O_4/Lig/PDA/GOx/Fc biosensor was fabricated using lignin, which exhibited excellent potential for detecting glucose and was tested in commercially available glucose samples (Jędrzak et al., 2019). Lignin-based graphene quantum dots were developed with excellent fluorescence stability, quantum yield, and biocompatibility for selectively detecting Fe^{3+} and ascorbic acid with LODs of 1.49 and 1.62 μmol/L, respectively (Zhu et al., 2022).

Capecchi et al. (2020) reported that lignin NPs are an efficient green platform for the immobilization of horseradish peroxidase and glucose oxidase mediated by concanavalin A and a novel system for the detection of glucose. In the same study, compared to other HRP–GOX immobilized systems, the lignin NP-based HRP–GOX system showed a better LOD value (0.85 μM). Tortolini et al. (2021) developed novel nanoarchitectures based on lignin NPs and found that three-layered kraft lignin NPs exhibited better analytical performance for glucose detection than different layers modified with gold electrodes and acted as efficient biosensors. Troponin I is released into the bloodstream and commonly used as a biomarker to diagnose myocardial injury. Vasudevan et al. (2023) developed lignin-based AgNPs (three-dimensional LSG/MoS_2/N-GQDs/L-AgNPs) to selectively capture and interact with Troponin I at a LOD of 100 aM, exhibiting efficient analytical performance with respect to linearity, selectivity, repeatability, and stability (Vasudevan et al., 2023).

Hemicellulose, a heteropolysaccharide found in plant cell walls and seeds along with cellulose and lignin, consists of pentose and alternating units of mannose, glucose, and galactose. It is classified based on its primary sugar backbone as xylans, mannans, and glucans. Despite their varied chemical compositions, hemicelluloses have been effectively employed in the development of sensory sensors for the detection of various analytes, both physical and chemical, with high selectivity and LODs reaching femtomolar levels (Gao et al., 2023a). A xyloglucan film extracted from *Hymenaea courbaril* L. was used to fabricate a biosensor capable of distinguishing lectins in their native and denatured states, and to evaluate the toxicity of ricin in castor seed meal (Furtado et al., 2012). Novel xyloglucan-block-poly(ϵ-caprolactone) NPs coated with chitosan effectively enhanced cytotoxic effects against B16F10 melanoma cells compared to L929 fibroblast cells, acting as an effective drug delivery system (Mazzarino et al., 2014). A fabricated wearable biosensor developed using phosphate lignin and biomass-based carbon nanofibers can accurately and selectively detect uric acid in artificial urine (Zheng et al., 2022). Multiwalled carbon nanotubes developed using fungal (1 → 3) (1 → 6)-β-D-glucan was developed to indirectly assess spironolactone using analytical dopamine signals, exhibiting a LOD of 0.94 μmol/L (Coelho et al., 2019).

2.1.3. Phytochemicals and plant extract-based nanomaterials

One study developed three bio-AgNP-based biosensors using green tea leaves, mangosteen peels, and grapefruit peels *via* electrochemical methods. Among them green tea-AgNP exhibited effective sensing against 4-nitrophenol in tomato samples with a concentration range of 0.5–50 μM, a high sensitivity of 1.25 μA μM/L cm^{-2}, and a low LOD of 0.43 μM (Trang et al., 2022). Table 2 lists the phytochemicals and plant extract-based nanomaterials. Interestingly, palladium NPs attached to biochar extracted from *Artocarpus heterophyllus* seeds have been developed as novel nanozymes to mimic the peroxidase activity for hydrogen peroxide detection, which aids in the analysis of glucose and glutathione. Additionally, one study revealed that nanoenzymes can be recycled three times without affecting enzyme activity (Banu et al., 2023). AgNPs and gold NPs (AuNPs) were synthesized using *Rumex roseus* L., plant extract, which served as a reducing agent and provided a cost-effective alternative biosensor for quantifying paracetamol within a linear range of 50–300 μM, achieving an LOD of 3 μM and a limit of quantification (LoQ) of 10 μM (Antunes et al., 2021). In addition, a biodegradable polysaccharide-based film has been developed using starch extracted from jackfruit seeds infused with anthocyanin, a natural pigment derived from black grapes. This film functioned as a sensor for monitoring the freshness of tilapia and shrimp by exhibiting color changes in response to pH variations caused by spoilage (Costa et al., 2020). Interestingly, silk fabric dyed with anthocyanins demonstrated visual sensitivity to pH fluctuations, offering enhanced reusability and stability. This property highlights their potential applications in environmental monitoring, medical diagnostics, and smart textiles (Tang et al., 2019). A robust and sustainable sensor was developed using anthocyanins isolated from black rice and immobilized on a film formed of carboxymethylcellulose and starch to detect Al(III) ions in water (Silva et al., 2020). AgNPs were synthesized from rutin in ascorbic acid and used as chromogenic probes for the selective detection of Fe^{3+} in

Table 2
Phytochemicals and plant-extract-based nanomaterials.

S. No	Phytochemicals/ Plant extracts	Biosensors	Detection	References
1.	Lobeira (*Solanum lycocarpum* St. Hill)	Plant-based polyphenol oxidases-based biosensor to analyse paracetamol tablet formulations	Linear range from 50 to 300 μM, LoD and LoQ of 3 μM and 10 μM	(Antunes et al., 2021)
2.	Basil, Geranium, Eucalyptus, Melia, and Ruta extract	Highly sensitive electrochemical sensor based on AgNP paracetamol detection	Low LOD of 0.42 μM with repeatable and reproducible with RSDs of 5.49 % and 3.18 %	(Jebril et al., 2021)
3.	Pepper seed extract	Green-synthesized Ag-NPs used as novel self-ratiometric fluorescent nanosensor for vanillin detection	LOD 9.0 ng/mL and a linear range of 0.05–8.0 μg/mL	(El Hamd et al., 2023)
4.	Ashwagandha (*Withania somnifera* L.) plant extract	Fluorescent copper nanoclusters for detection of pyrethroid pesticides in food samples	Linear concentration range of 0.01–100 μM and of 0.05–100 μM for cypermethrin and lambda-cyhalothrin	(Nayak et al., 2025)
5.	Green tea leaf, grapefruit peel, and mangosteen peel	Bio-AgNP electrochemical sensor for detection of 4-nitrophenol (4-NP) in tomato samples	Sensitivity of 1.25 μA μM^{-1} cm^{-2} and a detection limit of 0.43 μM in the detection range from 0.5–50 μM	(Trang et al., 2022)
6.	*Ganoderma lucidum* (Curtis) extract	Nanosensor detection of Fe^{3+}	Detection limit of 1.85 nM	(Nguyen et al., 2022)
7.	Miracle tree (*Moringa oleifera* Lam) plant extract	Green synthesized CuNPs with detection of daptomycin and meropenem	LOD of 0.01 g	(Ben Jaballah et al., 2022)
8.	Cubeb (*Piper cubeba* L.f.) seed extract	Fluorescent nanosensors for the spectrofluorimetric determination of ornidazole and miconazole nitrate	Concentration in the range of 5.0–80.0 μM and 20.0–100.0 μM with LOD of 0.35 μM and 1.43 μM for ONZ and MIZ	(Magdy et al., 2022)
9.	Waste tea extract	Fluorescent nanosensors for detecting mercury detection	LOD of $CrO4^{2-}$ and Fe^{3+} were about 0.81 and 0.15 μM, range of 1.9 – 115.4 μM with a correlation coefficient of 0.9975	(Chen et al., 2019a)

aqueous solutions. The LOD and LoQ were 17 and 56 nmol/L, respectively (Coutinho et al., 2019). A curcumin-loaded zein membrane was fabricated as an optical sensor using citric acid as a crosslinker to detect Fe^{3+} with a LOD of 0.4 mg/L (Saithongdee et al., 2014). $NiCo_2O_4$ nanostructures were fabricated using radish white peel extract to detect uric acid with a LOD of 0.005 mM and an LoQ of 0.008 mM (Solangi et al., 2023). To detect ovarian cancer, chitosan-conjugated butein was fabricated to specifically identify CD24 nucleic acids even at ultralow sample concentrations (Krishnan et al., 2021). Sol-gel encapsulated curcumin was fabricated to develop a biosensor to detect small molecules including hydrogen peroxide, the sodium salt of nitrite, hydroxide, bromide, and iodide that ultimately quenches fluorescence emitted by sol-gel encapsulated curcumin (Iwunze and McEwan, 2007). A glucose biosensor was developed using a CeO_2@CuO core shell nano structure and leaf extract of tulasi (*Ocimum tenuiflorum* L.). It showed a sensitivity of 3319.83 μAm M^{-1} cm^{-2} within a detection threshold of 0.019 μM (Dayakar et al., 2018). AuNP paper strips were fabricated using poly (γ-glutamic acid) as the linker for label-free rapid detection of brassinosteroids in plant tissues (Chen et al., 2017).

2.2. Carbon-based bio-nanomaterials

Carbon-based nanomaterials such as fullerenes, carbon nanotubes, graphene and its derivatives, graphene oxide, nanodiamonds, and carbon-based quantum dots have gained significant attention because of their properties (Díez-Pascual, 2021). Their nanoscale size; large surface area; and exceptional mechanical, electrical, thermal, optical, and chemical characteristics make them highly versatile. These attributes have enabled their application in various fields, particularly biomedicine, where they are used for cell and tissue imaging, targeted drug delivery for disease treatment, tissue repair, and diagnostic purposes (Díez-Pascual, 2021). In this section, we highlight the applications of graphene, carbon nanotubes, biochar, and carbon quantum dots in biosensing. Table 3 lists the details of the carbon materials used for biosensing.

2.2.1. Graphene and carbon nanotubes from biomass

A graphene oxide-modified sensor was developed to detect proteins and metal ions in living cells infected with porcine reproductive and

Table 3
Carbon dots in biosensing.

S. No	Carbon dots	Biosensors	Mechanism	References
1.	Carbon dot NPs	Fluorescent nanosensors	Detecting bacterial DNA for the antibiotic-resistance gene KPC−2 from *Klebsiella pneumoniae* even with minimal amount of DNA (≈100 pmol)	(Lee et al., 2017)
2.	Fluorescent carbon dots	Fluorescent nanosensors	Detecting cefixime with linear relationship from 0.2×10^{-6} M to 8×10^{-6} M, detection limit of 0.5×10^{-7}	(Akhgari et al., 2017)
3.	Nicotinamide-functionalizing of carbon quantum dots	Nanosensors	vitamin B12 detection with wide linear ranges from 0.1 to 60 μM with the detection limits of 31.7 nM	(Dadkhah et al., 2022)
4.	Nanocomposite of carbon dots and graphene oxide	Fluorescence-based nanosensors	Creatinine detection with linear detection range 10^{-5} to 0.1 mg/dL (R2 = 0.998), with a limit of detection of 4.3×10^{-2} mg/dL	(Bhatt et al., 2024)
5.	Graphene quantum dots	carbon-based nanosensors for Detection of ds-DNA	LOD in the picomolar range	(Santiago et al., 2022)
6.	CdSe quantum dots	Bioelectro-nanosensors for detection of arginine, alanine, methionine and cysteine	Concentrations in the ranges of 0.287–33670 μM and detection limits of 0.081, 0.158, 0.094 and 0.116 μM	(Hooshmand and Es'haghi, 2017a)
7.	Carbon quantum dots	Nanosensors for detection of gastric cancer-associated genes	LOD of 0.098 μM, within a concentration range 1.30–11.49 μM	(Öztürk and Durmuş 2025)
8.	Carbon quantum dots	Sensors for detection of aflatoxin M1	Fluorescent nanosensors with high sensitivity towards AFM1 in the range of 0.2–0.8 ng/mL with low limit of detection i.e., 0.07 ng/mL	(Singh et al., 2022)
9.	Carbon nano-dots	Novel sensitive electrochemical nanosensors uric acid and creatinine	Linear ranges between 0.297 and 2.970×10^3 and 0.442–8.840×10^3 μM, with the detection limits of 0.083 and 0.229 μM and relative standard deviations of 2.4 % and 1.8 %, for UA and Crn	(Hooshmand and Es'haghi, 2017b)

respiratory syndrome virus, showing linear detection in the range 0.2–1.7 ($R2 = 0.998$) (Liu et al., 2022). A mobile, versatile, point-of-care, rapid paper based biosensor using graphene conductive polymer was fabricated to detect dopamine, TNF-α, and interleukin 6 within ranges of 12.5–400 μM, 0.005–50 ng/mL, and 2 pg/mL–2 μg/mL using a sample volume of 2 μL with LODs of 3.4 μM, 5.97 pg/mL, and 9.55 pg/mL, respectively (Rahman et al., 2023). In a concentration range of 1 fg/mL–100 ng/mL, with a LOD 0.187 fg/mL (1.61 aM). To detect β-galactosidase, a functionalized biosensor was developed using graphene-based field effect transistors that could identify activity of β-gal produced by *Escherichia coli* and analyze water pollution (Wei et al., 2023b). Graphene and samarium oxide NPs were fabricated to develop nonenzymatic amperometric glucose sensors with a detection threshold of 107 nM and sensitivity of 20.8 μA/μM at a LOD of 70 nM (Sanad et al., 2021). A biomass-derived graphene was fabricated as a superhydrophobic coating in biosensors and disinfectants to combat COVID-19 (Arifin et al., 2021). Multifunctional graphene-based electronics from lignocellulose-based biopaper exhibited enhanced tensile strength and excellent waterproofing compared with pure cellulose (Zhao et al., 2023). The integrated three-dimensional macroporous carbon/nanocomposite electrode showed excellent electrocatalytic performances in reducing hydrogen peroxide; the oxidizing glucose and ultimately three-dimensional macroporous carbon exhibited the low-cost renewable, excellent supporting materials for an electrochemical sensor and biosensor (Wang et al., 2014a). A study reported the development of a hybrid electrode for glucose detection by anchoring copper oxide NPs onto porous nitrogen-doped reduced graphene oxide. This electrode demonstrated high sensitivity (2906.07 μA mM^{-1} cm^{-2}), a LOD of 0.13 μM, and a broad linear detection range of 3 μM to 6.772 mM (Wei et al., 2023a). Additionally, an amperometric biosensor was fabricated using nitrogen-doped graphene-like mesoporous nanosheets, which exhibited improved sensitivity (144.65 μA mM^{-1} cm^{-2}), a wide linear detection range (10–5640 μM), and a lower LOD of 0.51 μM for vitamin C detection (Sha et al., 2019).

An electrochemical lactate biosensor was developed using carbon nanorods embedded within a coral-like hierarchical meso-macroporous carbon structure derived from cucumber (*Cucumis sativus* L.). This biosensor exhibited an extended linear detection range, a lower LOD of 3.6 μM, and enhanced sensitivities of 57.18 and 30.99 μA mM^{-1} cm^{-2}, outperforming carbon nanotube-based biosensors in detecting lactate levels in real samples (Xu et al., 2022). A novel lipase-conjugated carbon nanotube-based SPR fiber-optic sensor was designed to detect tributyrin. This sensor demonstrated a linear detection range of 0.5–4 mM, a high-precision detection capability of 4.45 nm mM^{-1} , and a detection threshold of 0.34 mM, making it suitable for applications in food safety monitoring and human health assessments (Zhang et al., 2024). A chitosan/carboxymethylated multiwalled carbon nanotube composite sensor showed a variation in humidity from 11 % to 97 %, whereas the wet hysteresis showed 0.95 % relative humidity. It was able to monitor the human respiration rate and depth in real time, help differentiate various types of obstructive sleep apnea syndromes, and could be used for daily health monitoring (Gao et al., 2024). An electrochemical sensor was fabricated using carbon nanotubes with multiple walls and used for the rapid detection of laccase activity in *Penicillium simplicissimum* (Liu et al., 2008). Three-dimensional interconnected carbon nanofibers derived from bacterial cellulose biomass coupled with Au@PEI formed an immunosensor that exhibited a good linear response to aflatoxin B1 in wheat samples at concentrations ranging from 0.05 to 25 ng/mL, with an LOD of 0.027 ng/mL (Huang et al., 2020). Single-layer carbon nanotubes were used to develop an SPE-SWCNT-Ty biosensor to detect hydroxytyrosol in various extra virgin olive oils with an LOD of 3.49×10^{-8} M and a broad linearity range (0.49–15.602 μM) (Bounegru and Apetrei, 2022). Multiwalled carbon nanotube-based sensors showed increased signals for glucose (65–869 nA) and ethanol (65–869 nA), which were four- and 5-fold higher, respectively (Plekhanova et al., 2019). Multiwalled carbon nanotubes together with AuNPs and chitosan immobilized with choline oxidase using glutaraldehyde cross-linking exhibited a linear response in detecting choline in milk samples with a concentration range of 3–120 μM, sensitivity of 204 $\mu Acm^{-2}mM^{-1}$, and a LOD of 0.6 μM (Magar et al., 2017). A hybrid biosensor composed of carbon nanotubes and a ferrocene-based redox-active polymer was developed to detect the biochemical oxygen demand. This biosensor exhibited high sensitivity with a LOD as low as 0.1 mg/dm^3 in surface water samples, making it a promising tool for water quality monitoring (Arlyapov et al., 2021).

2.2.2. Biochar and carbon quantum dots from plant sources

A BCNP/Tyr/Nafion/GCE biosensor was developed to detect BPA in the environment using highly conductive biochar NPs derived from sugarcane. It was validated using HPLC and demonstrated excellent sensitivity with a linear range of 0.02–10 μM, a LOD of 3.18 nM, a low *K*m value, and high reproducibility (Liu et al., 2019). The hybrid biofilm@biochar material provides a rapid and cost-effective tool for the bioremediation of heavy metal ions, such as Pb^{2+}, Hg^{2+}, and Cu^{2+}. It significantly decreases exchangeable Pb^{2+} in the soil, and subsequently decreases Pb^{2+} accumulation in maize plants, which improves maize growth and biomass (Zhu et al., 2024b). An electrochemical biosensor was developed using a biochar-supported Cu^{2+}/Cu^{+} composite for the detection of ractopamine in pork sausages, which showed excellent electrochemical detection capability with a low LOD and high sensitivity (0.041 μM and 416 $\mu A \cdot mM^{-1} \cdot cm^{-2}$, respectively) in the concentration range of 0.1–1.75 μM (Cao et al., 2021a). Biochar was developed using corn stalk, and a biochar-based immunosensor was developed using gold electrodes functionalized with streptavidin and biotin-labeled anti-*E. coli* polyclonal antibodies, and detected *E. coli* O157:H7 cells with an LOD of 4 log CFU/mL without incubation (Sobhan et al., 2022). To detect glucose in real and spiked human saliva and blood serum samples, the EDC/Hydroxysuccinimide pair was employed for immobilization of the enzyme on biochar that ultimately showed a wide linear dynamic response range (0.05–5.0 mmol/L), LOD (0.94 μmol/L), and quantification (3.13 μmol/L) (Kalinke et al., 2024). In another study, biochar was produced from sugarcane bagasse pyrolysis, and the immobilized receptor-binding-domain *via* EDC/NHS crosslinking reaction was able to detect antibodies against SARS-CoV-2 (Valenga et al., 2022).

Green-emitting carbon dots, negatively charged and doped with calcium, nitrogen, and sulfur, were synthesized from plants and m-phenylenediamine through a one-step hydrothermal carbonization process for the sensing and imaging of Congo red in living cells and zebrafish. Additionally, it has been used to quantitatively detect Congo red and other toxic dyes in live samples such as fish tissues and industrial wastewater (Durrani et al., 2022). *Porphyromonas gingivalis*, derived from carbon dots, acts as an excellent biosensor with strong fluorescence and stability potential, an Fe^{3+} sensor, and an intracellular imaging agent with high biocompatibility (Liu et al., 2021). Carbon quantum dots were fabricated as fluorescent biosensors using carrot juice as a carbon source *via* a superhydrothermal method to detect *E. coli* in food based on single-stranded DNA (ssDNA) with a dynamic range of 1×10^{2}–1 to $\times 10^{8}$ CFU/mL, a determination coefficient ($R2$) of 0.9870, and a LOD of 60 CFU/mL (Bai et al., 2023). To detect acrylamide, a simple fluorescent biosensor was fabricated using carbon quantum dots based on ssDNA in food products, which showed a LOD of 2.41×10^{-8} M, a linear relationship range of 5×10^{-3}–1×10^{-7} M, and a determination coefficient of 0.9895 (Wei et al., 2021). Carbon dots were used as photosensitizers in a biosensor fabricated from gold nanorods using titanium dioxide, assembled with microRNA-21, and fixed with hairpin probes. In the presence of a target, miRNA hybridizes with the hairpin probe and stimulates nuclease, which is involved in miRNA release, resulting in photocurrent enhancement. The photocurrent intensity exhibited a direct relationship with miRNA concentration, ranging from 0.1 fM to 100 pM, along with a low LOD (Yang et al., 2022a). Similarly, carbon quantum dot-polyethylene imine-graphene oxide nanocomposites were constructed, and ECL achieved a sensitivity of miRNA-222 with a LOD as low as 1.95 fM in the prediction of tumorigenesis (Zhong et al., 2023).

2.3. Comparative evaluation of bio-based nanosensors and synthetic nanomaterial-based/conventional biosensors

Bio-based nanosensors made from natural biopolymers (e.g., cellulose, chitosan, and alginate) or biological recognition components (e.g., enzymes, antibodies, and aptamers) have received considerable attention owing to their sustainability, biocompatibility, and environmental friendliness (Praharaj et al., 2025). In contrast, synthetic nanomaterial-based and conventional biosensors frequently rely on artificial nanomaterials such as carbon nanotubes, quantum dots, or metal oxides, which provide great sensitivity and stability at the expense of biotoxicity, environmental persistence, and higher production costs (Praharaj et al., 2025). Synthetic nanomaterials typically outperform bio-based systems in terms of sensitivity and selectivity, owing to their customizable surface chemistry and improved electron transfer characteristics. When combined with high-affinity biological recognition elements, bio-based sensors provide equivalent selectivity, allowing for specificity in complicated biological or food matrices (Hemdan et al., 2025). Bio-based nanosensors offer distinct advantages in terms of their biocompatibility and environmental impact. Their biodegradability minimizes environmental accumulation and toxicity, making them ideal for applications in food safety, environmental monitoring, and *in vivo* diagnostics (Jafarzadeh et al., 2025). Although robust, their synthetic counterparts pose concerns regarding long-term ecological risks and disposal issues. Synthetic sensors have a higher stability and shelf life because they are resistant to deterioration and environmental variations (Ghosh et al., 2022). However, bio-based nanosensors may have a shorter shelf life and are sensitive to humidity and temperature, thus demanding advances in formulation and encapsulation methods. Bio-based systems are generally cost-effective and scalable, particularly when derived from agricultural or food waste (Praharaj et al., 2025). Their low-cost raw ingredients and green synthetic pathways render them attractive for large-scale use in resource-constrained environments. Although synthetic nanomaterials outperform bio-based nanosensors in some respects, they are more sustainable and biocompatible options with promising possibilities. A trade-off exists between sensitivity and eco-friendliness, and future research should seek to bridge this gap by combining natural and synthetic materials to improve performance and sustainability.

3. Synthesis and fabrication of bio-based nanomaterials for biosensing applications

Bio-based nanomaterials can be synthesized using various physical, chemical, and biological methods. In this section, we highlight green synthesis, enzyme-assisted synthesis, microwave- and ultrasound-assisted techniques, and sol-gel and hydrothermal methods.

3.1. Green synthesis methods

In recent years, green synthesis methods have been extensively used and have been reported to be more advantageous than conventional physical and chemical methods. Green synthesis methods are simpler, less toxic, cost-effective, and more eco-friendly than physical and chemical methods (Soni et al., 2018; Bora et al., 2022). The limitations of the physical and chemical methods include the use of expensive equipment, increased thermal production, enhanced energy utilization, and decreased production. NP synthesis methods can be categorized into top-down and bottom-up. In top-down approaches, bulk and complex materials are broken down into nanosized materials based on size reduction *via* physical and chemical techniques. This may result in NPs with imperfect surface structures, which are unsuitable for large-scale production. The synthesis of NPs using bottom-up approaches *via* chemical and biological methods involves the self-assembly of structures at the atomic and molecular levels to synthesize NPs with exact sizes, shapes, and molecular compositions (Bahrulolum et al., 2021). The current focus is on the sustainable synthesis of NPs from biological sources, such as microorganisms, microbial enzymes, plants, polysaccharides, and degradable polymers (Khan et al., 2018). The ability to modify these conditions allows for the precise control of the size, shape, and surface qualities, which are critical for biosensor applications that require high surface reactivity and sensitivity.

Characterization of green-synthesized nanomaterials is required to determine their suitability for biosensor development (Noah and Ndangili, 2022). Transmission electron microscopy (TEM) produces high-resolution images that confirm the particle size, shape, and dispersion. Fourier-transform infrared spectroscopy (FTIR) detects functional groups on NP surfaces, indicating the interactions between phytochemicals and metallic ions. Dynamic light scattering was used to measure the size distribution and zeta potential, indicating colloidal stability, which is essential for sensor reproducibility. UV-Vis spectroscopy is commonly used to measure the SPR and confirm NP production. Collectively, these strategies ensure that the synthesized nanomaterials meet the structural and functional requirements of biosensor platforms, including improved signal transduction, stability, and selective target identification (Fu et al., 2024). Thus, the combination of green synthesis and sophisticated characterization lays the groundwork for the development of sensitive, stable, and environment-friendly biosensors for biomedical and environmental monitoring.

A nanobiosensor was constructed by synthesizing nickel oxide NPs using the extract of the herb coriander (*Coriandrum sativum* L.) and interacting with calf thymus DNA as a conjugate material for nucleic acid biosensors, which could be used for various pharmacological, epidemiological, and medical applications (Sarkar et al., 2020). Polyhedral AuNPs with a size of 20 $\pm$ 10 nm were synthesized by culturing *Acinetobacter* sp. for 24 h at an SW cell density of 2.4 $\times$ 10(9) cfu/mL at 50 °C and pH 9 in 0.5 mM $HAuCl_4$ salt solution. At pH 9 and 50 °C, AuNPs were released into solution from the bacterial cell surface and proven to be a cost effective and eco-friendly biosensors (Wadhwani et al., 2014). A green and eco-friendly method was used to develop chitosan-AgNP nanocomposites. Moreover, AgNPs act as linking agents between luminol (ECL agent) and chitosan, and ultimately, the nanosensor acts as a highly ultrasensitive and specific recognition agent for prostate-specific antigens (Nasrollahpour et al., 2023). An enzyme-free electrochemical biosensor was developed using WO3/poly glutamic acid nano-biocomposites that effectively detected HER-2, even at a low concentration of 1 fg/mL, with a broad linear response range between 1 ng/mL and 1 fg/mL in untreated serum samples of patients with breast cancer (Nasrollahpour et al., 2021). In another study, AuNPs were green synthesized using different isolates of *Pseudomonas* sp., *Acinetobactor baumani*, and *Cupriavidus* sp. The NP size was in the range of 4–60 nm because of different species of bacteria, pH and temperature of the media, and incubation time. It was further developed as lyso@Au-GSH, which was immobilized with Nafion on a carbon electrode to create a label-free impedance biosensor for the selective detection of gram-positive bacteria within the linear range of 3.0×10^1–3×10^{10} cfu/mL with excellent correlation (R2 = 0.999), and would be suitable for monitoring contamination in biofluids, food, and environmental samples (Sen and Sarkar, 2024). Gold nanoclusters green-synthesized with pregabalin were investigated as a responsive and specific fluorescent nanosensor for Cu^{2+} detection within a limit of 1.11×10^{-7} M and were suitable for drug delivery systems and medical applications (Ali et al., 2022).

3.1.1. Enzyme-assisted synthesis

A protease-activatable nanosensor was engineered using peptide nucleic acid-peptide-DNA copolymers for the detection of miRNA-21, enabling the optical imaging of live tumor cells (Xi et al., 2023).

Glucose oxidase was immobilized on carbon-based nanoelectrodes using a sequential dip-coating technique to develop a nanosensor. When inserted into growing single NG108–15 cells, this nanosensor generates a positive current response corresponding to intracellular glucose levels (Marquitan et al., 2020). Furthermore, a novel Janus NP was designed as an enzyme-powered nanomachine utilizing glucose oxidase for self-propulsion and targeted drug delivery. Upon exposure of HeLa cancer cells to glucose, enzymatic reactions produce hydrogen peroxide and gluconic acid, propelling the nanomachine while lowering the pH, which the controlled release of doxorubicin and enhances its therapeutic effect against cancer cells (Mayol et al., 2024). Glucose oxidase-wrapped single-walled carbon nanotubes exhibited a strong response toward glucose within the range of 3×10^{-3} to 30×10^{-3} m and with KM (app) $\approx 13.9 \times 10^{-3}$ m and could serve as a prerequisite for continuous glucose monitoring (Zubkovs et al., 2017). Nanodevices (Au-mesoporous silica Janus NPs capped with benzimidazole/β-cyclodextrin) were integrated with a bi-enzymatic cascade (glucose oxidase and invertase) that mediates the hydrolysis of sucrose-producing glucose, which is further converted by glucose oxidase into gluconic acid, which automatically affects pH-sensitive supramolecular gates at the Janus NPs to automatically release doxorubicin in HeLa cancer cells (Jimenez-Falcao et al., 2019). A nanosensor was developed using DNAzyme to detect and image Pb^{2+} and understand the metabolic pathways of Pb^{2+} and lead poisoning in biological systems (Huang et al., 2021a). A core satellite nanoprobe was developed using alkaline phosphatase (ALP) to detect prostate cancer-specific antigens. For colorimetric detection, the nanosensor exhibited a linear PSA range of 0.05–100 ng/mL, with a detection threshold of 6.71 pg/mL for photothermal analysis, which showed a linear range of 0.5–90 ng/mL with a detection threshold of 0.13 ng/mL (Gao et al., 2023b).

3.1.2. Microwave- and ultrasonication-assisted techniques

Red fluorescent copper nanoclusters were synthesized using trypsin *via* a microwave-assisted method to detect Pb^{2+} and Hg^{2+} ions *via* fluorescence quenching. The nanosensor exhibited excellent linearity within the ranges of 0.1–25 μM for Pb^{2+} and 0.001–1 μM for Hg^{2+}, with low LODs of 14.63 nM and 56.81 nM, respectively (Joshi et al., 2022). Additionally, a label-free fluorescence 'turn-on' nanosensor was developed through microwave-assisted interactions with α-casein, β-casein, and ovalbumin, demonstrating LODs of approximately 118.5 nM, 28.9 nM, and 54.8 nM for their tryptic digests, respectively (Ke et al., 2016). Moreover, carbon nanodots synthesized *via* a microwave-assisted hydrothermal method exhibit strong blue fluorescence and demonstrate high precision in detecting mercury ions, achieving a low LOD of 15 nM through fluorescence quenching (Xiao et al., 2020). Furthermore, a ZnNi NPs@f-MWCNT-based sensor was fabricated using a microwave irradiation process to detect uric acid, dopamine, and ascorbic acid in real samples, showing broad linear responses of 0.2–1.1, 0.2–1.2, and 0.3–1.1 mM, respectively (Savk et al., 2019). A novel, rapid, and highly sensitive carbon dot was prepared from *Eruca sativa* juice using a microwave method. Carbon dots were employed to detect prucalopride, where increasing concentrations led to a decrease in luminescence, exhibiting a linear response in the range of 3.00–200.00 ng/mL in human plasma (Salman, 2023). Similarly, nanocarbon dots were synthesized *via* microwave-assisted pyrolysis using orange juice as the carbon source and urea as the nitrogen source for palbociclib assessment *via* fluorescence quenching. The nanosensor demonstrated a strong linear correlation (1.0–20.0 μg/mL) with a correlation coefficient of 0.9997 and a LOD of 0.021 μg/mL (Magdy et al., 2023). The MoS_2-GO/SPE composites were fabricated *via* ultrasonication and functioned as efficient electrochemical sensors for the detection of clenbuterol and 4-nitrophenol (Pham et al., 2021). The GO-g-PCA/DR nanosensor was synthesized by grafting graphene oxide with citric acid, followed by ultrasonication for 15 min and continuous stirring for 80 min at room temperature. This nanosensor was evaluated against varying scopolamine concentrations, demonstrating a linear detection range of 0.65–19.63 μg/mL and a low LOD across different plant parts at various growth stages (Mousavizadeh et al., 2022). Cost-effective AgNPs with low toxicity were synthesized from *Manilkara zapota* L. using ultrasonic vibrations. These NPs were utilized for detecting toxic metal ions, particularly Co^{2+} and Hg^{2+}, with LODs of 54.40 ± 1.43 μM and 10.70 ± 0.16 μM, respectively (Beniwal et al., 2024; Kang et al., 2022).

3.1.3. Sol-gel and hydrothermal methods

The sol-gel method is a bottom-up synthesis method that produces infinite, heavy, and three-dimensional molecules called gels, which can be cast or molded to produce filters or membranes, and can also be used to produce composite or nanocomposite materials (Bokov et al., 2021). Amino-functionalized mesoporous bioactive glass NPs incorporated with the phytotherapeutic *Boswellia sacra* Flueck. extracts were developed using a sol-gel-modified co-precipitation approach and exhibited potent antibacterial effects (Ilyas et al., 2022). Tin oxide (nanorods and nanospheres) was developed from *Tinospora crispa* (L.) Hook. f. & Thomson, stem extract using a sol-gel technique, and the synthesized NPs exhibited anticancer potential (Kaur et al., 2023). Jahnavi et al. (2024) synthesized a nanocomposite of $CaO:MgAl_2O_4$ using a cost-effective sol-gel method and used it to detect paracetamol *via* electrochemical sensing in various methods, including pharmaceutical formulations, body fluids, and water samples. Photoluminescent carbon dot nanostructures synthesized using grapefruit, lemon, and turmeric extracts *via* a hydrothermal method were used for the rapid detection of *E. coli*. An increasing *E. coli* concentration quenched the photoluminescence of a cadmium sulfide (CdS) nanocomposite (Ahmadian-Fard-Fini et al., 2018). A nanoprobe was synthesized using thirsty plant extract *via* a simple hydrothermal method to effectively detect phenobarbital (a linear range between 0 and 750 μM with a LOD of 5 μM) based on fluorescence intensity. The increased luminescence emission of the nanoprobe was enhanced with increasing pH (Mohammadi et al., 2023). Nanozymes were synthesized using *Cinnamomum camphora* L., leaves *via in situ* hydrothermal reaction at 0.3–500 μM with LODs of 0.12, 0.26, 0.07, and 0.075 μM for dopamine, uric acid, guanine, and adenine, respectively (Zhang et al., 2021a). A nanosensor based on nitrogen-doped carbon dots composite was fabricated using *Dregea volubilis* (L.f.) Benth. ex Hook.f., fruit and used for detecting glucose from human blood and urine samples in the pH range of 7–8 and LOD of 0.25 mM (Sahu et al., 2025). Fluorescent carbon quantum dots prepared using mustard seeds *via* a facile one-step hydrothermal treatment exhibited highly selective and sensitive detection of ascorbic acid (in the range of 10–70 μM) with a LOD of 3.26 μM (Chandra et al., 2019). A low-cost, simple, sensitive, and highly selective on-off-on fluorescent nanosensor of water-soluble tea-carbon dots using waste tea extract as the carbon source was used to detect $CrO4^{2-}$, Fe^{3+}, AA, and L-Cys (Chen et al., 2019a).

3.2. Characterization techniques for bio-based nanomaterials

3.2.1. Morphological and structural analysis

The physical and chemical properties of nanomaterials, including their optical, electronic, and catalytic characteristics, are largely influenced by their morphological features such as shape, structure, and size (Kim et al., 2020; Singh et al., 2024). Bio-based nanomaterials exhibit diverse morphologies, including spherical, flat, conical, cylindrical, and irregular shapes. Their surface structures may vary and appear crystalline, amorphous, or irregular (Radnik et al., 2021). Among these characteristics, size is a fundamental parameter in NP characterization. Various techniques are available for morphological analysis, including microscopic methods such as polarized optical microscopy, scanning electron microscopy (SEM), and TEM, which are commonly employed for detailed structural evaluations.

The different characterization techniques are presented in Fig. 3. Recently, in biological specimen analysis and material characterization, SEM and TEM have been widely used (Radnik et al., 2021). SEM is based

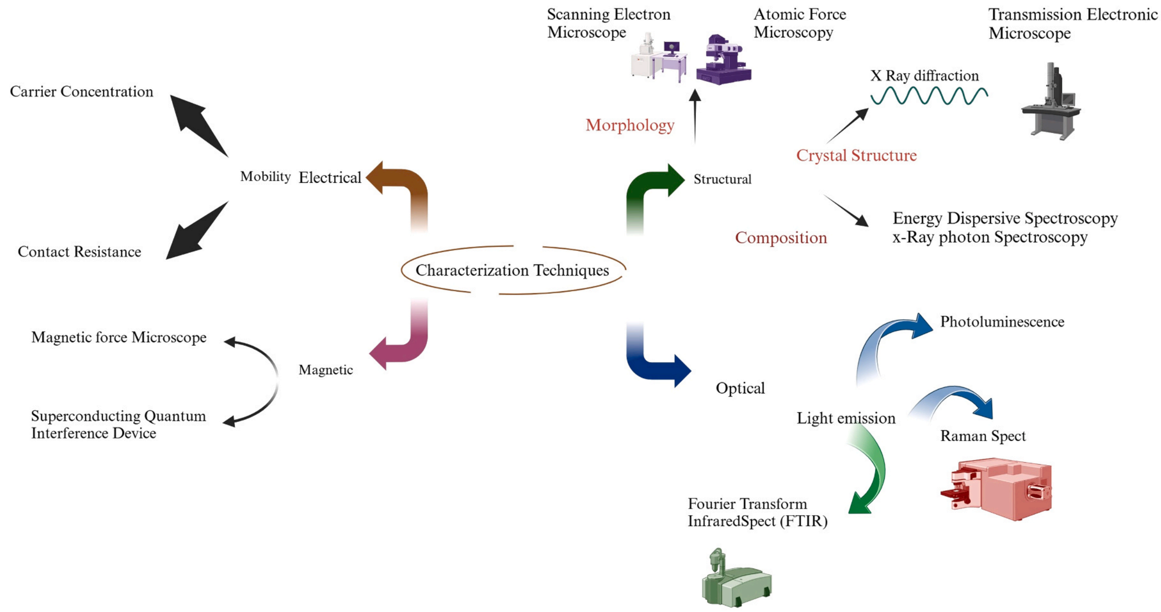

Fig. 3. Various characterization techniques. [Adapted from (Gupta et al., 2020) and created using BioRender].

on the electron scanning principle and creates an image by detecting reflected or knocked-off electrons, whereas TEM creates images using transmitted electrons that pass through the sample (Williams, 2021; Malatesta, 2021). The leaf extract of *Melia azedarach* L. has been used as a reducing agent for silver ions to synthesize AgNPs, and SEM revealed the spherical shape of NPs (Mehmood et al., 2017). Transmission-mode SEM enables high-resolution imaging and enhances the contrast of NPs smaller than 10 nm. The seed extract of *Tectona grandis* L., was used to synthesize AgNPs, and TEM revealed spherical shapes and agglomerates of small grains and dispersed NPs. In the same study, SEM and field emission SEM (FESEM) analyses revealed that the synthesized NPs were spherical in shape and in the range of 10–30 nm (Rautela and Rani, 2019). These structural characteristics aid in understanding the composition, nature, and bulk properties of the subject material. X-ray diffraction (XRD), energy dispersive X-ray spectrometry (EDX), X-ray photoelectron spectroscopy (XPS), IR, Raman spectroscopy, and Zeta-sizer analyzers are commonly used to analyze structural properties of bio-based NPs (Khan et al., 2019). XRD is a powerful technique for understanding the crystalline phases of materials and analyzing their structural properties (strain state, grain size, phase composition, and orientation) (Sagadevan and Koteeswari, 2015). The green synthesis of iron oxide NPs using fern *Cheilanthes* was amorphous, as confirmed by XRD (Seth et al., 2022). EDX is typically fixed with an FESEM or TEM device to understand the elemental composition with an approximate idea of the weight percentage. In one study, the green synthesis of AgNPs using *Mimusops elengi* L showed strong silver signals with weak carbon, oxygen, and nitrogen peaks in the EDX profile, which indicated that biomolecules attached to the AgNP surface were also suggested for the conversion of silver ions to elemental silver (Tiwari et al., 2023). XPS is widely used to determine the elemental ratio and bonding nature of elements in NPs. Green ceramic-based NPs prepared using the sol-gel method were analyzed using XPS, which showed that the silicon percentage was higher than that of other atoms (Chowdhury et al., 2024). Raman spectroscopy helps to determine the structure using light radiation, including the size and crystallization of the NPs. Zinc NPs were synthesized using a hydroalcoholic extract of *Lavandula stoechas* L., and Raman spectroscopy data showed that the size of the NPs ranged from 3 to 25 nm (Mehdipour et al., 2024).

3.2.2. Spectroscopic and thermal properties

Spectrometric techniques are used to identify and characterize NPs based on their particle size, particle number concentration, and chemical composition (Borowska and Jankowski, 2023). Molecular mass spectrometric techniques, including electrospray ionization mass spectrometry, laser desorption/ionization (LDI), and matrix-assisted LDI time-of-flight mass spectrometry, have helped to analyze the mass of ligands present on the surface of NPs (Kruszewska et al., 2021). AgNPs were synthesized using an aqueous propolis extract. UV-Vis absorption analysis showed that SPR peaks exhibited increased absorption at 418 nm for AgNPs, and the photoluminescence spectra of AgNPs exhibited an emission peak at 495 nm (Kabiraj and Rath, 2023). Carrageenan-based bio-nanocomposite films have been developed using silica dioxide and zinc oxide NPs. FTIR analysis revealed that the formulation containing SiO_2-ZnO NPs exhibited new functional groups, named Si−OH bonds, *via* the addition of SDS as a surfactant in aqueous media (Praseptiangga et al., 2020). XPS is a powerful analytical tool that provides information on the chemical characteristics of NPs. AgNPs were synthesized from the Rangoon creeper (*Combretum indicum* L.) aqueous leaf extract, and XPS analysis revealed the presence of C-1s, Ag-3d, N-1s, and O-1s. Moreover, the C-1s binding energy at 283.4 eV relates to the presence of carbon in the phenyl rings present in proteins (Birusanti et al., 2019). ZnO NPs were produced using *Elaeagnus angustifolia* L., leaf extracts, and Raman spectroscopy analysis was performed to study the vibrational modes of the NPs, which are related to the antiferromagnetic nature of Zn^{++} ions, whereas the antiparallel spin behavior of 'Zn^{++}' showed that ZnO NPs are in the nanoscale range (~26 nm) (Iqbal et al., 2021). Eco-friendly synthesis of silver-entecavir NPs was achieved using a green synthesis method, and NMR data revealed that silver-entecavir nanoparticles(Ag-ETR NPs) were shifted to 7.95 ppm and the number of hydrogens in both ETR and Ag-ETR NPs was the same. The data revealed that a bond was formed between silver and the oxygen of the amide group and N-7 of the purine of ETR (Ag-O), thus confirming the synthesis of Ag-ETR NPs synthesis (Shoaib et al., 2021). In one study, the Raman spectra of green-synthesized AgNPs showed blue shifts, confirming that the particle size was changed by altering the NaOH concentration, whereas no changes were observed at varying temperatures (Vasireddy et al., 2012).

Several techniques, including differential scanning calorimetry, differential thermal analysis (DTA), thermogravimetric analysis (TGA), and the transient hot-wire method (THW), have been used to measure the melting point, crystallization, phase transition, and latent heat capacity. In one study, zinc oxide NPs synthesized using *Eucalyptus globulus*

Labill., leaf extract exhibited two endothermic peaks related to water evaporation, whereas the exothermic peaks indicated the crystallization of NPs (Barzinjy and Azeez, 2020). DTA was used to study the phase transition temperature and measure the melting points as well as thermal and oxidative stabilities. The green synthesis of trimetallic CuO/Ag/ZnO nanocomposite exhibited higher weight loss (> 85.92 %) at temperatures between 0 and 250 °C owing to crystallinity of CuO/Ag/ZnO, and final breakdown (10.57 %) occurred between 260 and 500 °C (El-Sawaf et al., 2024). TGA measures the change in the mass of a sample and is used to study the thermal stability of nanomaterials (Ajroudi et al., 2014). ZnO particles were synthesized using aqueous extract of *Epipremnum aureum* (Linden & André) leaves, and TGA showed that 51.59 % weight loss occurred between 250 °C and 485 °C owing to pyrolysis of NPs. From 485–800 °C, no change was observed in the weight-loss of NPs owing to carbonization (Khan et al., 2022). The THW method was used to determine thermal conductivity by placing a heating wire on the test sample. The synthesis of copper oxide NPs using lemon juice and THW analysis showed that the thermal conductivity increased linearly with temperature with an increase in NP concentration (Jebali et al., 2025).

3.2.3. Electrical and electrochemical properties

Electrochemical techniques such as cyclic voltammetry, differential pulse voltammetry, galvanostatic electrolysis, and linear sweep voltammetry have been effectively used to optimize the green synthesis of NPs (Pur et al., 2017). NPs were synthesized using watermelon rind extract, and cyclic voltammetry data revealed that the NPs exhibited distinct oxidation and reduction peaks at + 290 and + 100 mV, respectively (Ndikau et al., 2017). Galvanostatic charge-discharge data of green synthesized Cr_2O_3 NPs by aqueous extract *Cassia fistula* L., showed the highest specific capacitance (454.54 $mAhg^{-1}$) at a current density of 1 mAg^{-1} (Yasmeen et al., 2023). Aloe vera-mediated formation of nickel oxide NPs has also been observed (Selvanathan et al., 2024).

NPs exhibited better electrocatalytic performance, with a Tafel slope of 95 mV dec^{-1} and an overpotential of 413 mV at 10 mA cm^{-2}. This could be attributed to their large surface area, enhanced charge-transfer kinetics, and excellent conductivity, which were measured using electrochemical surface area measurements and electrochemical impedance spectroscopic analysis (Selvanathan et al., 2021). The electrocatalytic activity of the ZnO/PIn-MWCNT/Frt/GOx bioanode was assessed by varying the glucose concentration from 10 mM to 60 mM using linear sweep voltammetry. A previous study showed a gradual increase in the oxidation peak height with an increase in the substrate (glucose) up to 50 mM, and the synthesized nanocomposite showed sufficient binding sites owing to its porous network structure, which enhanced enzyme loading and catalytic activity (Inamuddin et al., 2020). The green tea-synthesized CdO nanomaterial showed excellent rectifying properties in the I–V characteristic graph, exhibiting semiconducting potential for use in electronic devices (Mohanraj et al., 2017).

4. Mechanisms of bio-nanosensors and the role of bio-based nanomaterials

Bio-nanosensors are a revolutionary class of analytical tools that combine biological sensing elements and nanoscale materials to detect and measure biomolecules with high sensitivity and specificity (Ramesh et al., 2023). Recent advances in nanotechnology and bioengineering have resulted in the development of bio-based nanomaterials for sensor construction that are eco-friendly, biocompatible, and cost-effective options (Jafarzadeh et al., 2025). These materials, which are produced from plants, microorganisms, and natural polymers, improve the sensor performance by improving the surface functionality, signal amplification, and target selectivity, thereby enabling a wide range of biomedical and environmental applications. Bio-nanosensors use various transduction methods, including electrochemical, optical, and piezoelectric methods (Naresh and Lee, 2021). Carbon dots, nanocellulose, and chitosan-coated electrodes are bio-based nanomaterials that improve electron transfer rates and biocompatibility, resulting in increased sensitivity and stability.

4.1. Electrochemical mechanisms

Electrochemical biosensors provide label-free detection with a high signal-to-volume ratio by measuring the concentration of targeted molecules and inducing alterations in the current, potential, conductance, or impedance by oxidizing or reducing the analyte at an electrode (Malhotra and Ali, 2018). Nanomaterials can interact with the electrode to increase the surface area, thereby improving the loading capacity and facilitating the efficient mass transport of reactants, resulting in enhanced signal amplification. In addition, they can serve as carriers for redox probes, enabling highly sensitive detection or optimization of redox exchange dynamics, ultimately boosting the detection signal (Quesada-González and Merkoçi, 2018). Electrochemical biosensors are classified into static (zero-current) methods, such as direct potentiometry and potentiometric titration, and dynamic (current-based) methods, including potentiostatic (potential-controlled) and galvanostatic (controlled-flow) techniques (Hu et al., 2020). In certain methods, electrochemical measurements have been combined with immunoassays. The resulting sensors are known as immunosensors (Parlak et al., 2017). Typically, this sensor comprises two control electrodes and a detector (working electrode), which functions as a transducer within the biosensor (Zhu et al., 2019). In potential control methods, the potential of the detector electrode is adjusted relative to that of the control electrode (Huang et al., 2021b). When the current passing through the reference electrode affects its potential, an additional electrode, known as the auxiliary electrode, is employed to carry the current. This arrangement establishes a current flow between the auxiliary electrode and detector, whereas the reference electrode is solely responsible for regulating the potential of the detector electrode (Huang et al., 2021b).

Electrocatalysis is a redox-driven electrochemical process that facilitates the transfer of electrons. When voltage is applied across the electrode to balance the reaction potential, it enables the electrons to flow from a higher to a lower potential. This process can be classified into direct and indirect electrocatalysis (Fu et al., 2023). In direct electrocatalysis, radicals are generated on the electrode surface without the addition of external chemicals, whereas indirect electrocatalysis relies on redox-active mediators or electrochemically active compounds to produce radicals (Fu et al., 2023). El Hajji et al. (2014) used electrochemical deposition to fabricate ZnO, ZnO-CeO_2 and ZnO-Cu_2O nanocomposite thin films as anode materials. These nanocomposites exhibited a methylene blue dye degradation efficiency of 78 %, highlighting their potential as effective anode materials for wastewater treatment.

4.2. Optical mechanisms

Optical nanosensors comprise nanoscale or nanostructured materials that exhibit distinct reactions to electromagnetic excitation at optical frequencies. Optical sensors are influenced by transduction mechanisms such as absorption, visible radiation, luminescence, Raman spectroscopy, SERS, refraction, and qualitative analysis using dispersion (Qu et al., 2012). Luminescence consists of light emission from a material because of absorption at lower wavelengths, which can be categorized as fluorescence and phosphorescence (De Acha et al., 2017a). Luminescent materials, including quantum dots, NPs, and dyes, are fabricated as sensors by entrapping or encapsulating them in different matrices or shells to enable interactions between the analyte molecules and sensing materials (De Acha et al., 2017b). Luminescence has recently emerged as an effective detection method in various fields, particularly biological applications. For luminescent sensors to function optimally, they must exhibit a strong photostability with high selectivity and sensitivity. This was achieved by ensuring the rapid adsorption and desorption of the target analytes on the sensing films. These films can be fabricated using multiple techniques such as dip-coating, spin-coating, sol-gel processing, or xero-gel techniques (Zhao et al., 2011). NPs made of plasmonic materials such as gold, copper, and silver demonstrate localized SPR (LSPR), which is characterized by distinct absorption bands spanning the UV, visible, and near-infrared regions of the spectrum (Reinhard et al., 2020). Colorimetric biosensors based on plasmonic nanomaterials take advantage of the predictable modifications to their optical properties, which generally entail visual color changes (Minopoli et al., 2021).

4.3. Piezoelectric biosensor mechanisms

Piezoelectric biosensors, mainly those that use quartz crystal microbalance (QCM) technology, detect analyte binding by altering the resonant frequency owing to changes in mass or mechanical properties. The use of bio-based nanomaterials, such as peptide-functionalized nanocrystals and polysaccharide-derived films, considerably improves the sensitivity and selectivity of these sensors (Chen et al., 2024). These nanomaterials have high surface-to-volume ratios and excellent biocompatibility, allowing for increased surface-binding affinity and specificity. For example, chitosan nanocrystals integrated into chitosan-based elastomers exhibit improved piezoelectric responses, making them suitable for use in prostheses and wearable devices (Hänninen et al., 2018). Similarly, carbon-based nanomaterials, such as graphene and carbon nanotubes, have been used to develop flexible biosensors with good electrical and mechanical properties, allowing for rapid and sensitive detection of various analytes (Zhu et al., 2017).

Signal transduction in these biosensors is closely related to the physicochemical interactions between the bio-recognition elements and the target analytes. Bio-based nanomaterials enhance these interactions by utilizing specialized binding processes, such as hydrogen bonding, electrostatic interactions, and van der Waals forces (Fu et al., 2024). Their customizable features enable the creation of selected interfaces, which improve the real-time responsiveness of the bio-nanosensors. Advanced biosensors have been applied in food safety, environmental monitoring, and biological diagnostics. Piezoelectric biosensors can detect bacteria such as *E. coli* O157:H7 at limits as low as 1.2×10^2 CFU/mL (Wang et al., 2008). Nanomaterial-based biosensors, including those for pesticides and heavy metals, have been used for toxin detection during environmental monitoring (Sharma et al., 2025). In biomedical diagnostics, QCM-based biosensors have been utilized to detect biomarkers, such as prostate-specific antigens, providing fast and label-free analysis (Pohanka, 2025). The combination of piezoelectric biosensing technology and bio-based nanomaterials has provided substantial developments in analytical techniques, allowing for greater sensitivity, specificity, and real-time detection capabilities in various applications.

5. Applications for bio-based nanomaterials in smart biosensing

5.1. Biosensors for early-stage disease detection

Biosensors enable the detection of different biomarkers for healthcare and environmental monitoring. Biomarkers play a crucial role in the diagnosis of specific diseases. According to the WHO, biomarkers refer to any measurable substance, structure, or biological process within the body or its derivatives that indicate disease occurrence or outcomes. These biomarkers include nucleic acids, proteins, hormones, enzymes, and metabolites. Depending on their type, biomarkers can

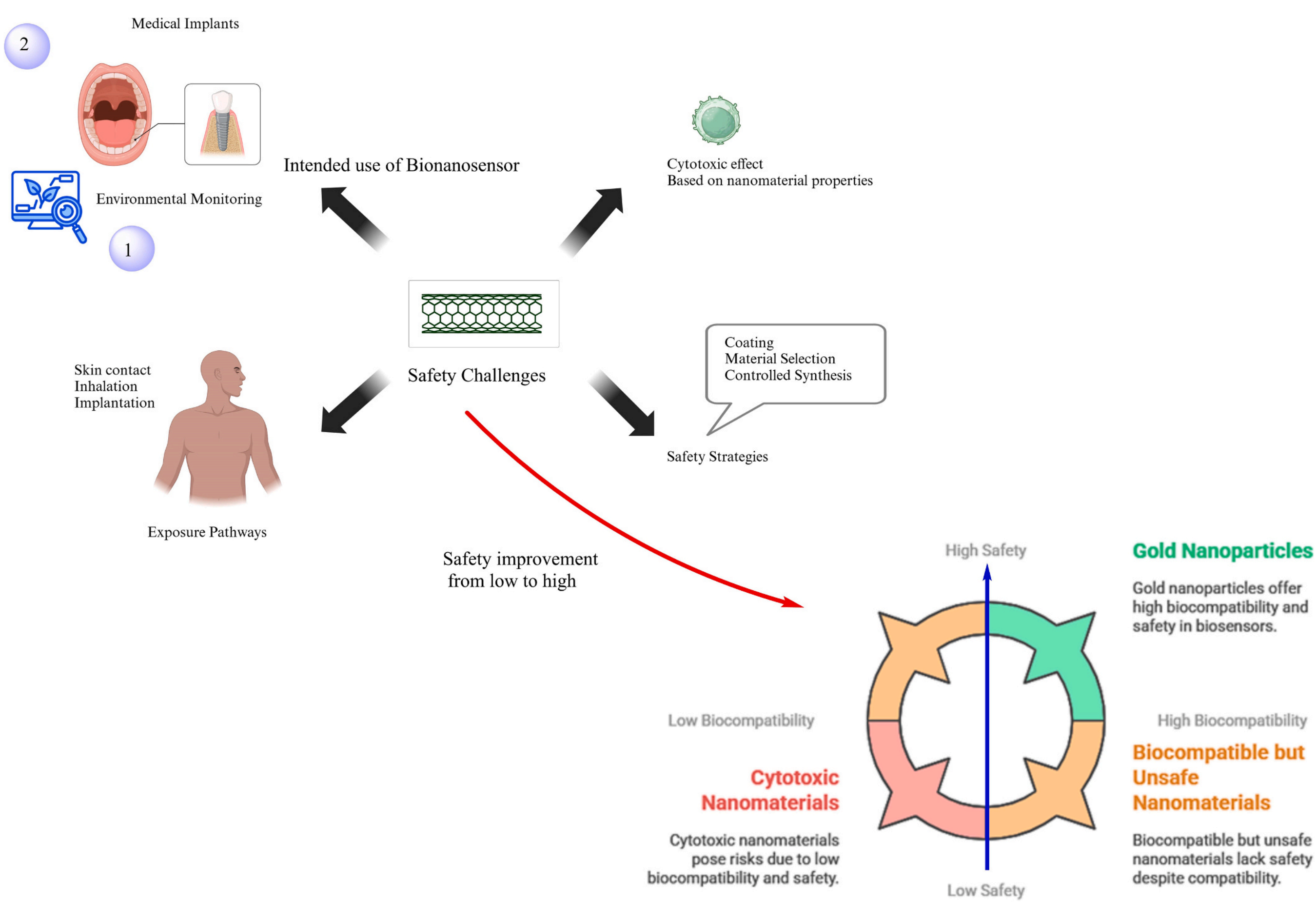

Fig. 4. Biocompatibility and safety concerns are associated with nanomaterials in biosensors. [Created using BioRender].

provide valuable insights into disease prevention, diagnosis, prognosis, and the monitoring of therapeutic responses (Lino et al., 2022). Biosensors have been developed for various detection processes (Fig. 4).

5.1.1. Detection of biomarkers in cancer and diabetes

An electrochemical biosensor was developed to detect carcinoembryonic antigens. Lung cancer markers and sensors are highly sensitive and exhibit high specificity owing to the dual-signal amplification of electrically mediated atom transfer radical polymerization and polyethyleneimine. It showed a linear detection range of 10^{-3}–10^{2} ng/mL and a LOD of 70.17 fg/mL, which could be used for efficient early lung cancer diagnosis application (Zhou et al., 2022). A biosensor was constructed using the fluorescence emission of DNA-templated copper nanoclusters to detect and quantify three significant biomarkers of breast cancer (circulating microRNAs, miR-21, miR-195, and miR-155) that exhibited a detection threshold of 1.7 pM with a linear range between 500 nM and 3 μM (Sadeghi and Rahaie, 2022). Colorimetric biosensors have been constructed to diagnose prostate cancer bone metastases by detecting ALP biomarkers (Li et al., 2023a). To detect prostate cancer, innovative surface-enhanced Raman spectroscopy and lateral flow assay biosensors, together with aptamer recognition, can be used to analyze thrombin and platelet-derived growth factor-BB (Cao et al., 2021b). A triangular AgNP array, LSPR nanosensor, was developed to detect serum p53, which plays a crucial role in head and neck squamous cell carcinoma (Zhou et al., 2011). In one study, AuNPs were combined with blood serum to enhance Raman scattering signals of SERS-active biosensors. These signals are generated by numerous biochemicals and can be used to diagnose parotid gland tumors (Yan et al., 2015). Table 4 and Fig. 5 list the biosensors used for cancer and diabetes diagnoses. Hollow carbon nanofibers functionalized with AgNPs have been fabricated to detect potential biomarkers, including salivary nitrite, and enhance the prediagnosis of oral cancer (Sunil et al., 2024). For the early diagnosis and monitoring of colorectal cancer, an integrated strategy (nanosensors) was developed using target-induced NP coupling and site-specific base oxidation damage for DNA methylation analysis to detect target methylated DNA at concentrations as low as 32 × 10–17 M and with specificity for distinguishing 0.001 % methylation in colorectal cancer samples (Luo et al., 2022). A multivariate-gated catalytic hairpin assembly nanosensor was fabricated to detecting microRNA-21 in human colorectal cancer tissues and to understand miR-21-associated molecular mechanisms (Zhang et al., 2025b).

A fluorescence nanosensor based on a conjugated copolymer (DPA-PFNP-Cu(II)) was designed to assess the severity of diabetes by measuring the homocysteine levels in the kidneys and livers of diabetic mice (Zhang et al., 2020). The nanosensor were fabricated using a terbium (III)-1, 10-phenanthroline (Tb-phen) complex, AgNPs, and a glucose-quenched FRET-based fluorescence system. Glucose-induced quenching of the Tb-phen complex fluorescence enables the rapid and direct screening of glucose residues in real samples, making it a promising tool for clinical diabetes diagnosis (Dehghan et al., 2019). In a diabetic breast cancer model, a novel NIR-II nanosensor, DNPS, exhibited high sensitivity and deep tissue penetration, and showed higher expression levels of nitric oxide than the breast cancer model, which demonstrated that diabetes increased nitric oxide levels in the tumor microenvironment (Zhang et al., 2025a). An enzyme-free triple-readout paper sensor utilizing bismuth-based metal-organic frameworks/AuNPs (Bi-BDC-NH2@Au) was used to detect urine glucose (Jin et al., 2025). NP sensors and viologen quencher-fluorescent dye systems incorporated into poly(2-hydroethyl methacrylate) hydrogels exhibit excellent glucose responses in the physiological range and are a promising tool for real-time glucose tracking (Le et al., 2020). C16-PEG (2000 Da)-ceramide-SWCNT nanosensors have been considered for real-time quantification of insulin secreted by β-cells and provide new opportunities for the rapid assessment of β-cell function (Ehrlich et al., 2021). A nucleic acid-gold nanorod-based nanosensor was developed to noninvasively monitor cellular Lrg1 expression during angiogenesis in a mouse retinal model (Lio et al., 2018). Graphene-doped tin oxide nanofibers and nanoribbon sensors have been developed for the detection of volatile organic compounds (CO and NO responses) corresponding to different chronic diseases, including asthma, chronic obstructive pulmonary disease, cystic fibrosis, and diabetes, demonstrating a fast response time of 50 s, with a recovery phase lasting approximately 10 min (Sánchez-Vicente et al., 2020).

Table 4
Biosensors for diagnosis of cancer and diabetes.

S. No	Biosensors	Cancer/ diabetes	Mechanism	References
1.	NIR-II nanosensor, NIR-II imaging probe	In diabetic breast cancer	To study diabetes-related breast cancer by understanding the expression of Nitric oxide synthase 2, Spp1, Mmp11, and Kitl.	(Zhang et al., 2025a)
2.	FRET nanosensors	Retinal metabolism	Measuring key metabolites at the cellular level	(Calbiague García et al., 2023)
3.	mRNA nanosensors	Diabetic wound healing process	Reveals the dynamic changes of mRNA biomarkers for different stages of wound development	(Hwang et al., 2022)
4.	Quantum dot nanosensors	Cancer	To detect the SIRT1 activity in cancer cells with a detection limit of as low as 3.91 pM	(Hu et al., 2021)
5.	Gold nanosensors	Angiogenesis	Noninvasive monitoring of cellular Lrg1 expression in angiogenesis.	(Lio et al., 2018)
6.	Implantable optical nanosensors	Diabetes	To improve glucose monitoring during diabetes	(Sun et al., 2021)
7.	Sulfide-doped carbon dots /cadmium sulfide quantum dots ratiometric fluorescent nanosensors	Diabetes	Sensitive and selective determination of glibenclamide with the concentration in the range of 0.3 nM−10.0 μM with LOD 0.12 nM.	(Gazizadeh et al., 2023)
8.	DNA-encoded nanosensors	Cancer	Developed a microfluidic platform for densely multiplexed, CRISPR-mediated DNA barcode readout	(Hao et al., 2023)

5.1.2. Pathogen and toxin detection in clinical diagnostics

Magnetically separated plasmonic NPs have been developed as achromatic colorimetric nanosensor for detecting SARS-CoV-2, *Staphylococcus aureus*, and *Salmonella typhimurium*. Different target pathogens induce different colors, such as SARS-CoV-2, *S. aureus*, and *S. typhimurium*, which generate green, purple, and orange colors, respectively, and can be efficiently used to monitor food safety and quality (Wen et al., 2023). Table 5 shows the biosensors used to analyze the pathogens. Multiparametric magnetofluorescent nanosensors have been developed to detect *E. coli* O157:H7 contamination with as little as one colony-forming unit present in solution within a short period of time (< 1 h) and have been proposed as suitable candidates for screening bacterial contaminants in various samples from aquatic reservoirs to packaged foods (Shelby et al., 2017). A dual-modal magnetofluorescent

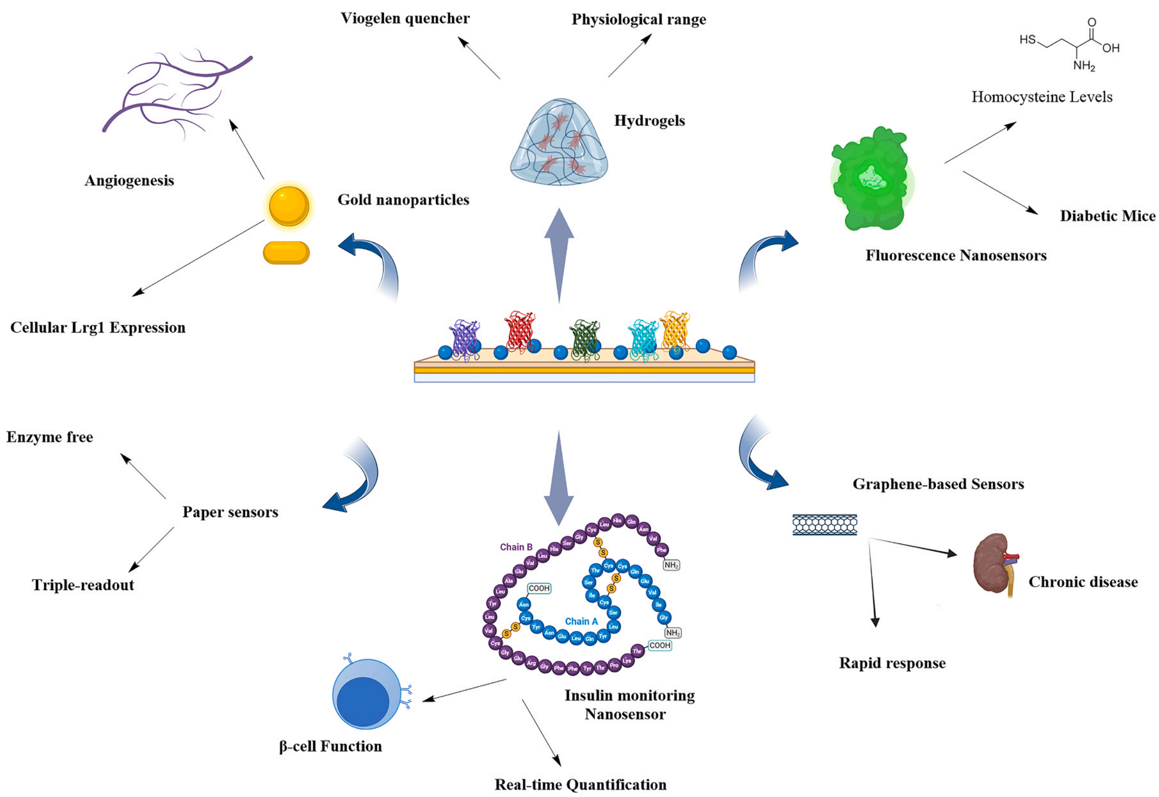

Fig. 5. Applications of biosensors in the diagnosis of cancer and diabetes. [Created using BioRender].

nanosensor was developed to specifically detect *Staphylococcus epidermidis* and *E. coli*, two of the predominant bacterial contaminants in blood and platelet concentrates (Banerjee et al., 2019). Plasmonic NP-based optical biosensors have been developed using functionalized AuNP arrays to capture DNA sequences complementary to the analyte (target) DNA, which ultimately aid in the identification of several fungal pathogens (Zopf et al., 2019). *Staphylococcal* protein A is a key virulence factor that allows *S. aureus* to evade the host immune system. In one study, AuNPs were engineered for the colorimetric detection of the *S. aureus SPA* gene, providing a potential diagnostic approach (Madkour et al., 2023). A smart nanosensor was developed for the detection of HIV and other diseases, including cardiovascular diseases and rheumatoid arthritis, using graphene-based field-effect transistors. This sensor exhibited high sensitivity and showed a linear response to p24 (for HIV), cTn1 (for CVD), and CCP (for RA) from 1 fg/mL to 1 μg/mL with LODs of 100 fg/mL, 10 fg/mL, and 10 fg/mL, respectively (Islam et al., 2019).

5.2. Food safety and quality monitoring

5.2.1. Detection of foodborne pathogens

A NP-based electrochemical biosensor was engineered for the rapid and sensitive detection of plant pathogen DNA, including *Pseudomonas syringae* on disposable screen-printed carbon electrodes. This biosensor is a valuable tool for efficient disease management in agriculture, and enables rapid detection and response (Lau et al., 2017). A graphene-based biosensor was developed using paper electrodes to detect false smut, a fungal disease in rice. This cost-effective biosensor uses probe DNA as a biological recognition element, which hybridizes with the pathogen-target single-stranded DNA (ssDNA). The detection process was analyzed using linear sweep and cyclic voltammetry (Rana et al., 2021). *Citrus tristeza* causes severe diseases in citrus plants. A label-free impedimetric biosensor featuring an electrode modified with AuNPs was developed to detect DNA. This biosensor efficiently identifies target viral DNA, even in the presence of non-specific DNA, and offers improved reproducibility of detection (Khater et al., 2019). Bifunctional and monofunctional AuNP oligo probes have been used to detect viral DNA in tomato leaves using DNA hybridization assays. These probes demonstrate a high level of cost-effectiveness across concentrations of 100 pM–100 M (Dharanivasan et al., 2019). A label-free electrochemical biosensor was developed using an l-cysteine/PAMAM dendrimer combination on a gold electrode to specifically target the internal transcribed spacer sequence of *Mycobacterium simiae.* This biosensor demonstrates exceptional selectivity, a LOD of 1.40 fM, outstanding sensitivity, and high reproducibility (Zare et al., 2022). Europium NPs were developed for the quantitative detection of *Listeria monocytogenes*, *Vibrio parahaemolyticus*, and *E. coli* O157:H7, achieving detection thresholds of 9, 7, and 4 CFU/mL, respectively. The nanosensor demonstrated exceptional sensitivity and specificity, effectively identifying low concentrations of foodborne pathogens (Chen et al., 2021).

5.2.2. Monitoring food freshness and spoilage

A pH-responsive nanofiber was designed to detect *E. coli* in orange juice with a LOD of 102 CFU/mL within 1 h. Nanofibers detect acidic byproducts, such as lactates and acetates, which are generated when *E. coli* metabolizes sugar molecules (Shaibani et al., 2018). An isothermal recombinase polymerase amplification assay using unmodified AuNPs was developed to detect *Salmonella* spp. in milk. This method achieved a detection threshold of 50 CFU and offered a sensitive, rapid, and cost-effective approach for pathogen detection (Chen et al., 2019b). A fluorescence biosensor was designed to detect *E. coli* in adulterated pork samples, achieving a low LOD of approximately 10 CFU/mL with a linear range of 58–58 × 10^6 CFU/mL (Li et al., 2020). Graphene oxide-carbon nanotube nanocomposites were engineered as an aptasensor to detect *S. typhimurium* which exhibited a wide linear dynamic range from 10 to 10^8 CFU/mL with a 10 CFU/mL LOD (Appaturi et al., 2020). Multiplex PCR enhanced with AuNPs has been developed to detect multiple pathogens, including *S. typhimurium,* L. *monocytogenes*, and *E. coli O157:H7.* This method has demonstrated high sensitivity and

Table 5
Biosensors for pathogen detection.

S. No	Biosensors	Pathogens	Detections	References
1.	Gold nanosensors	*Staphylococcal* protein A, a virulence factor of *Staphylococcus aureus*	100 % specificity with a detection limit of 6 fg/μL	(Madkour et al., 2023)
2.	Magnetic nanosensors	ZIKV (ZENV, zika domain III and NS1) and DENV proteins of Dengue virus and Zika virus	Detects at concentrations as low as 20 nM with high specificity, reproducibility, and analytical sensitivity	(Banerjee et al., 2021)
3.	Magneto-plasmonic nanosensors with gold nanoparticles	Food-borne pathogens, particularly *E. coli* O157:H7	Detect as low as 10 CFUs of pathogenic strain of *E. coli* O157:H7 in minutes with no cross-reactivity	(Banerjee et al., 2023)
4.	Innovative fluorescence nanosensors	SARS-CoV−2	Linear detection ranges from 10^{-8} to 10^{-2} μg/mL and a LOD of 5.3 fg/mL	(Apriyani et al., 2025)
5.	Gold nanoparticles	*Proteus mirabilis*	Limit of detection of 10^{1} cells/mL	(Santopolo et al., 2019)
6.	DNA nanosensors	*Escherichia coli* O157:H7 bacterium	To determine 10 pg genomic DNA	(Karimi et al., 2019)
7.	Label free nanosensors	SARS-CoV−2	Detection limit and sensitivity of 0.18×10^{-19}% V/V and 2.14 μA.%V/V.cm^{-2}	(Alireza Hashemi et al., 2021)
8.	Graphene oxide-coated microplates and photoluminescent bioprobes	*Escherichia coli*	Limit of detection of ~2 CFU/mL	(Avila-Huerta et al., 2020)
9.	Magneto-nanosensor biochips	Fungus	Detection limit of ~100 pg/mL	(Kim et al., 2012)

efficiency in identifying pathogenic strains in food samples (Du et al., 2020). A nano-mesoporous SiO_2-based electrochemical immunosensor was developed to detect *S. aureus* in spiked milk samples, achieving LODs of $10^{-2} \times 10^{3}$ and 12 CFU/mL. (Wang et al., 2019a). Multifunctional AuNPs have been developed to detect *L. monocytogenes* in ultra-high-temperature milk (Teixeira et al., 2020). Guanidine-functionalized upconversion NPs (UCNPs@GDNs) have been used to identify various foodborne pathogens, including *E. coli, Shigella flexneri, Salmonella, V. parahaemolyticus, Cronobacter sakazakii, S. aureus,* and *L. monocytogenes* in water, milk, and beef (Yin et al., 2019).

5.3. Environmental monitoring and water quality assessment

5.3.1. Detection of heavy metals and organic pollutants

Multifunctional optical carbon dot-based nanosensor can detect the concentrations of metal ions (Cu^{2+}, Ni^{2+}, and Cr^{3+}) and NO^{3-} anions and help monitor the composition of waste and technological water (Sarmanova et al., 2023). Magnetic Fe_3O_4@SiO_2 NPs have been developed to detect metals, such as Zn^{2+}, Cd^{2+}, Mn^{2+}, Pb^{2+}, Hg^{2+} and Fe^{3+} (Xu et al., 2016). Mesoporous nanosponge NPs fabricated with β-cyclodextrin polymers immobilized with magnetic NPs helped remove organic micropollutants by ~90 % with an efficiency of < 1 min and an enrichment factor reaching ~10^{3} and could be used as a portable and fast detection strategy for detecting organic pollutants (Zhang et al., 2021b). Carbonaceous nanomaterials coated with an intrinsically conductive polymer(polyaniline) were fabricated as thin-film sensors and used to instantly detect organic pollutants with an LOD of 9.6 ppb for aminophenol, with a linearity of 0.997 and sensitivity of 2.3 kΩ/pH at acidic pH (Chajanovsky et al., 2021). Sulfur dioxide is a widely distributed air pollutant that induces respiratory responses and diseases. A novel tetraphenylimidazole compound with aggregation-induced emission enhancement was developed and self-assembled into NPs to detect sulfites with high sensitivity (Gao et al., 2017). Other toxic gases that adversely affect humans include NO_2, and one study developed NO_2 sensors fabricated using Fe_3O_4@rGO-N-(piperidine-4-SO_3H) nanocomposites that were efficient in detecting air (Khaleghiabbasabadi et al., 2024). Magnetic Fe_3O_4@SiO_2 NPs were synthesized to remove metal ions including Zn^{2+}, Cd^{2+}, Mn^{2+}, Pb^{2+}, Hg^{2+}, and Fe^{3+}. Interestingly, the composites showed greater adsorption capabilities for Pb^{2+} and Hg^{2+} and exhibited strong magnetic sensitivity, which helped separate the functionalized magnetic nanocomposites upon capturing heavy metal ions (Xu et al., 2016) (Table 6).

5.3.2. Biosensing of environmental toxins

Nanohybrids of carbon dots and fluorescein isothiocyanate (CDs-FITC-SiO_2@MIP) were synthesized to produce a highly sensitive ratiometric fluorescence sensing platform for microcystins with concentrations in the range of 0.5–500 μg/L and reported to possess great application potential in water quality monitoring (Li et al., 2023). Endotoxins, also known as lipopolysaccharides (LPS), form the outer layers of Gram-negative bacteria, play a key role in bacterial toxicity, and pose significant environmental risks. An AuNP-based optical nanosensor (Cu@AuNPs) was developed for LPS detection, offering a linear detection range of 20–20 ng/mL with an ultralow LOD of 0.2 ag/mL. This

Table 6
Detection of heavy metals and organic pollutants using biosensors.

S. No	Biosensors	Detection of metals/ pollutants	Detection potentials	References
1.	Gold nanorods	Pb^{2+} and Hg^{2+}	LOD 5 nM for Pb^{2+} ions and 1 nM for Hg^{2+} ions	(Ye et al., 2022)
2.	Microfluidic nanosensors	Copper detection	LOD of 396 ppb, a linear range up to 2500 ppb and a sensitivity of 2.3 nA/ppb	(Yang et al., 2022)
3.	Nanocomposite electrochemical nanosensors	Pb^{2+} and Cd^{2+} heavy metal ions	Detection limits were 10.8 nM for Pb^{2+} and 12.4 nM for Cd^{2+}	(He et al., 2020)
4.	Carbon nanodots nanosensors	Hg^{2+}	Low detection limit 15 nM	(Xiao et al., 2020)
5.	Fluorescent sensors	H_2S detection	Good linear response concentration range (0–1 μM), detection limit as low as 32.3 nM	(Liu et al., 2023)
6.	Porous CoS (FP CoS) nanosensor	Trace/ultra-trace chromium species (Cr (VI) and Cr (III))	LOD low to 3.93 μg/L	(Guo et al., 2025)
7.	Nanosensors	Lead (II)	Broad linear span of up to 400.0 nM and ultralow detection limit of 0.6 nM	(Qian et al., 2015)
8.	Nanosensors	Detection of Hg^{2+}, Ag^{+}ions	Detection limits of 6.8 nM and 8.9 nM	(Xuan et al., 2023)

sensor is promising for water quality analysis (Nair et al., 2022). A nanoprobe based on quantum-dot haptens fabricated using aminoethyl-microcystin (MC)-leucine-arginine (LR), with a linear range of 0.10–4.0 μg/L and a LOD of 0.03 μg/L, could be used for the rapid detection of microcystin in real water samples (Feng et al., 2014). Okadaic acid biotoxins act as inhibitors of protein phosphatase and tumor promoters in humans. Another study developed an active biological nanosensor (magnetic Fe_3O_4@MOF@AuNPs) for the highly specific recognition of okadaic acid, which showed an LOD of 0.015 and a LoQ of 0.050 ng/mL for okadaic acid in fortified shellfish samples (Zhou et al., 2024). Improved rare-earth-doped upconversion NPs (NaYF4:Yb/Ho/Gd and NaYF4:Yb/Tm/Gd) were developed for the dual sensing of aflatoxin B1 and deoxynivalenol with a wide sensing range of 0.001–0.1 ng/mL and an LOD of 0.001 ng/mL in adulterated oil samples (Chen et al., 2016).

5.4. Plant pathogen detection in agriculture

To understand biotic stress in plants, a fluorescent nanosensor was developed for the noninvasive detection of extracellular DNA released by invasive pathogens in plant tissues with sensitivity at ng/mL levels (Zhu et al., 2024a). In a previous study, d-AuNPs were stabilized by a ssDNA probe used to detect pathogen DNA at 2.94 fM (Baetsen-Young et al., 2018). The paper electrode biosensor detects plant pathogens with up to 10 fM of the target ssDNA and is considered an effective and low-cost platform for the immobilization of DNA to detect other plant pathogens (Rana et al., 2021). In another study, a lateral flow biosensor was developed to target against *Phytophthora infestans* with a LOD 0.1 pg/μL and in the concentration in the range of 0.1–100 pg/μL (Zhan et al., 2018). Optical biosensors have been engineered to detect *Pseudomonas* spp. with a low LOD of 7.09 log CFU/mL (Mudgal et al., 2020).

6. Challenges and limitations of bio-based nanomaterials in biosensing

6.1. Stability and reproducibility of bio-based nanomaterials

Nanomaterial-based biosensors with high accuracy and precision are in high demand because of their potential for reliable detection. However, their stability and reproducibility present significant challenges, as the biosensor signal strength tends to diminish over time (Fu et al., 2024). Ensuring the stability of these nanomaterials requires rigorous monitoring, high-throughput techniques, and careful assessment of biosensor performance, which depends on biorecognitive elements such as proteins, cDNA, and aptamers (Fathi-Karkan et al., 2023). Despite their high responsiveness, nanomaterial-based biosensors often have a limited shelf-life and can degrade when exposed to air. Additionally, variations in the nanomaterial structures across generations contribute to poor repeatability. Therefore, quality assurance is crucial in clinical applications to ensure that the biosensors provide consistent, precise, and reproducible results (Ramesh et al., 2023).

6.2. Scale-up and commercialization issues

Biosensors have diverse applications in various industries including pharmaceutics and food production. At a commercial level, biosensors are crucial in the separation and processing of various chemicals (Hassan, 2022). However, several challenges hinder its commercialization, including the absence of standardized international regulations for evaluating the effectiveness of nano-biosensors (Li et al., 2024). Additionally, the disconnect between academic research and industrial implementation further slows progress in bringing these sensors to the market. Strengthening collaboration between academia and industry is expected to accelerate commercialization and drive the development of cost-effective and durable nano-biosensors (Sharma et al., 2024). In recent years, point-of-care technologies have gained significant attention owing to their rapid and cost-efficient capabilities for the detection, monitoring, and diagnosis of biomedical samples, particularly foodborne disease detection and environmental pollution control (Kulkarni et al., 2022). The integration of advanced technologies such as cloud computing, deep learning, artificial intelligence, and data analysis can enhance the efficiency of biosensors (Sharma et al., 2024).

6.3. Biocompatibility and safety concerns

The biocompatibility of nanomaterials is essential for the design of biosensors for the detection of bacteria, viruses, and DNA. Sensor chips used in implants interact with complex biological environments, which can lead to a decline in the device performance over time. AuNPs are commonly used in electrochemical biosensors because of their biological compatibility and stability, and they serve as effective signaling molecules (Fu et al., 2024). However, limited research has been conducted on the cytotoxicity of nanomaterials, as indicated in existing literature. The skin and lungs are primarily exposed to nanomaterials *via* inhalation or direct contact. The cytotoxicity of nanocomposites is influenced by their chemical and physical properties, which are shaped during synthesis and by the reagents used (Lin et al., 2021). The misuse of nano-biosensors in environmental monitoring can result in the release of organic compounds or synthetic substances, potentially posing significant risks to human health and the environment (Sharma et al., 2024).

6.4. Integration with existing technologies

The integration of artificial intelligence and regression-based approaches can help monitor the progression of various prognostic markers and enhance the functionality of biosensors. In addition, wearable nano-based biosensors require a continuous power source, making it essential to develop self-sustaining sensors that can harness energy for small-scale power collection. Combining machine learning with portable health monitoring biosensors is crucial for advancing medical capabilities (Kadian et al., 2023). Recently, the Internet of Things (IoT) has been adopted in healthcare systems for disease detection, treatment, and monitoring. With the advent of 5 G technology, new possibilities for IoT applications in healthcare have emerged, offering enhanced opportunities in areas such as treatment, data analysis, diagnostics, and medical imaging (Verma et al., 2022). To further improve the sensor portability, smartphones can leverage their camera functions and computational power for image capture and analysis. This allows smartphones to be transformed into basic spectrophotometric devices by using optical accessories (Preechaburana et al., 2012).

7. Conclusion and future perspectives

In this review, we comprehensively explore the various types of biological nanomaterials used in biosensing, along with their synthesis, characterization, and applications in smart biosensing technologies. Bio-based nanomaterials are promising tools for developing sensitive, selective, and sustainable biosensors. Despite significant progress, several challenges, such as stability, reproducibility, scalability, and biocompatibility, hinder their broader application. A critical area for advancement is the development of biosensors capable of detecting ultralow concentrations of target analytes within complex matrices. Moreover, future biosensors should emphasize on portability, miniaturization, and adaptability for field applications. Designing versatile platforms that can detect a broad spectrum of analytes, including heavy metals, pathogens, and pesticides, will significantly enhance their use in environmental monitoring, healthcare diagnostics, and food safety. Multiplexed biosensing systems capable of simultaneously detecting multiple targets are expected to play pivotal roles in real-time monitoring and rapid diagnostics. The integration of advanced digital technologies, such as artificial intelligence, machine learning, and the IoT has accelerated the commercialization and functionality of next-generation biosensors. Emphasis should be placed on the development of eco-friendly, micro, and disposable biosensors to support point-of-care and personalized healthcare applications. Addressing the potential health and environmental risks associated with nanomaterials is equally important. Regulatory frameworks for safe production, use, and disposal of nanomaterials remain underdeveloped in many countries, highlighting the urgent need for globally harmonized guidelines. The interdisciplinary convergence of nanotechnology, biotechnology, and data science holds immense promise for revolutionizing biosensing platforms. Continued innovation, coupled with responsible research practices and clear regulatory oversight, will be the key to unlocking the full potential of bio-based nanomaterials for a wide range of practical and commercial applications.

CRediT authorship contribution statement

MT: Writing of the original draft. **HYC, HJC, BSJ, SBL, YP, and DJ:** Visualization, collection of materials and writing, review, and editing. **MAS and FC:** Drawing figures, writing, reviewing, and editing. **SHK:** Conceptualization, Investigation, Supervision, writing – review, and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Basic Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education [RS-2024–00412288].

Data availability

Data will be made available on request.

References

Abdi, M.M., Razalli, R.L., Tahir, P.M., Chaibakhsh, N., Hassani, M., Mir, M., 2019. Optimized fabrication of newly cholesterol biosensor based on nanocellulose. Int. J. Biol. Macromol. 126, 1213–1222. https://doi.org/10.1016/j.ijbiomac.2019.01.001.

Adeniyi, O., Nwahara, N., Mwanza, D., Nyokong, T., Mashazi, P., 2021. Nanohybrid electrocatalyst based on cobalt phthalocyanine-carbon nanotube-reduced graphene oxide for ultrasensitive detection of glucose in human saliva. Sens. Actuators B Chem. 348, 130723.

Ahmadian-Fard-Fini, S., Salavati-Niasari, M., Ghanbari, D., 2018. Hydrothermal green synthesis of magnetic Fe_3O_4-carbon dots by lemon and grapefruit extracts and as a photoluminescence sensor for detecting of *E. coli* bacteria. Spectrochim. Acta A Mol. Biomol. Spectrosc. 203, 481–493. https://doi.org/10.1016/j.saa.2018.06.021.

Ajroudi, L., Mliki, N., Bessais, L., Madigou, V., Villain, S., Leroux, C., 2014. Magnetic, electric and thermal properties of cobalt ferrite nanoparticles. Mater. Res. Bull. 59, 49–58.

Akhgari, F., Samadi, N., Farhadi, K., 2017. Fluorescent carbon dot as nanosensor for sensitive and selective detection of cefixime based on inner filter effect. J. Fluor. 27 (3), 921–927. https://doi.org/10.1007/s10895-017-2027-0.

Ali, R., Alfeneekh, B., Chigurupati, S., Saleh, S.M., 2022. Green synthesis of pregabalin-stabilized gold nanoclusters and their applications in sensing and drug release. Arch. Pharm. 355 (4), e2100426. https://doi.org/10.1002/ardp.202100426.

Alireza Hashemi, S., Bahrani, S., Mojtaba Mousavi, S., Omidifar, N., Ghaleh Golab Behbahan, N., Arjmand, M., Ramakrishna, S., Bagheri Lankarani, K., Moghadami, M., Shokripour, M., Firoozsani, M., Chiang, W.H., 2021. Ultra-precise label-free nanosensor based on integrated graphene with Au nanostars toward direct detection of IgG antibodies of SARS-CoV-2 in blood. J. Electroanal. Chem. 894, 115341. https://doi.org/10.1016/j.jelechem.2021.115341.

Antunes, R.S., Thomaz, D.V., Garcia, L.F., Gil, E.S., Lopes, F.M., 2021. Development and optimization of *Solanum lycocarpum* polyphenol oxidase-based biosensor and application towards paracetamol detection. Adv. Pharm. Bull. 11 (3), 469–476. https://doi.org/10.34172/apb.2021.054.

Appaturi, J.N., Pulingam, T., Thong, K.L., Muniandy, S., Ahmad, N., Leo, B.F., 2020. Rapid and sensitive detection of *Salmonella* with reduced graphene oxide-carbon nanotube based electrochemical aptasensor. Anal. Biochem 589, 113489. https://doi.org/10.1016/j.ab.2019.113489.

Apriyani, F., Sari, S.R., Petrus, H.T.B.M., Angelina, M., Manurung, R.V., Septiani, N.L.W., Yuliarto, B., Jenie, S.N.A., 2025. A fluorescence nanosensor based on modified sustainable silica for highly sensitive detection of the SARS-CoV-2 IgG antibody. Nanoscale 17 (9), 5438–5446. https://doi.org/10.1039/d4nr04546g.

Arifin, N.F.T., Yusof, N., Nordin, N.A.H.M., Jaafar, J., Ismail, A.F., Aziz, F., Salleh, W.N. W., 2021. Potential application of biomass derived graphene for COVID-19 pandemic. Mater. Today Proc. 46, 1959–1962. https://doi.org/10.1016/j.matpr.2021.02.379.

Arlyapov, V.A., Kharkova, A.S., Kurbanaliyeva, S.K., Kuznetsova, L.S., Machulin, A.V., Tarasov, S.E., Melnikov, P.V., Ponamoreva, O.N., Alferov, V.A., Reshetilov, A.N., 2021. Use of biocompatible redox-active polymers based on carbon nanotubes and modified organic matrices for development of a highly sensitive BOD biosensor. Enzym. Microb. Technol. 143, 109706. https://doi.org/10.1016/j.enzmictec.2020.109706.

Avila-Huerta, M.D., Ortiz-Riaño, E.J., Mancera-Zapata, D.L., Morales-Narváez, E., 2020. Real-time photoluminescent biosensing based on graphene oxide-coated microplates: A rapid pathogen detection platform. Anal. Chem. 92 (17), 11511–11515. https://doi.org/10.1021/acs.analchem.0c02200.

Baetsen-Young, A.M., Vasher, M., Matta, L.L., Colgan, P., Alocilja, E.C., Day, B., 2018. Direct colorimetric detection of unamplified pathogen DNA by dextrin-capped gold nanoparticles. Biosens. Bioelectron. 101, 29–36. https://doi.org/10.1016/j.bios.2017.10.011.

Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V.S., Easton, A.J., Ahmadian, G., 2021. Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. J. Nanobiotechol. 19 (1), 86. https://doi.org/10.1186/s12951-021-00834-3.

Bai, X., Ga, L., Ai, J., 2023. A fluorescent biosensor based on carbon quantum dots and single-stranded DNA for the detection of *Escherichia coli*. Analyst 148 (16), 3892–3898. https://doi.org/10.1039/d3an01024d.

Banerjee, T., Panchal, N., Sutton, C., Elliott, R., Patel, T., Kajal, K., Arogunyo, E., Koti, N., Santra, S., 2023. Tunable magneto-plasmonic nanosensor for sensitive detection of foodborne pathogens. Biosensors 13 (1), 109. https://doi.org/10.3390/bios13010109.

Banerjee, T., Patel, T., Pashchenko, O., Elliott, R., Santra, S., 2021. Rapid detection and one-step differentiation of cross-reactivity between zika and dengue virus using functional magnetic nanosensors. ACS Appl. Biol. Mater. 4 (5), 3786–3795. https://doi.org/10.1021/acsabm.0c01264.

Banerjee, T., Tummala, T., Elliott, R., Jain, V., Brantley, W., Hadorn, L., Santra, S., 2019. Multimodal magneto-fluorescent nanosensor for rapid and specific detection of blood-borne pathogens. ACS Appl. Nano Mater. 2 (9), 5587–5593. https://doi.org/10.1021/acsanm.9b01158.

Banu, A., Antony, A.M., Sasidhar, B.S., Patil, S.A., Patil, S.A., 2023. Palladium nanoparticles grafted onto phytochemical functionalized biochar: a sustainable nanozyme for colorimetric sensing of glucose and glutathione. Molecules 28 (18), 6676. https://doi.org/10.3390/molecules28186676.

Barzinjy, A.A., Azeez, H.H., 2020. Green synthesis and characterization of zinc oxide nanoparticles using *Eucalyptus globulus* Labill. leaf extract and zinc nitrate hexahydrate salt. SN Appl. Sci. 2 (5), 991. https://doi.org/10.1007/s42452-020-2813-1.

Ben Jaballah, M., Rajendran, A., Prieto-Simón, B., Dridi, C., 2022. Development of a sustainable nanosensor using green Cu nanoparticles for simultaneous determination of antibiotics in drinking water. Anal. Method 14 (20), 2014–2025. https://doi.org/10.1039/d2ay00419d.

Beniwal, A., Singh, S., Rani, J., Moond, M., Kakkar, S., Sangwan, S., Kumari, S., 2024. Waste upcycling of Sapota peels as a green route for the synthesis of silver nanoparticles and their application as catalytic and colorimetric detection of Co^{2+} and Hg^2. Discov. Nano 19 (1), 191. https://doi.org/10.1186/s11671-024-04147-w.

Bhatt, P., Kukkar, D., Yadav, A.K., 2024. Carbon dot-graphene oxide-based luminescent nanosensor for creatinine detection in human urine. Mikrochim Acta 191 (12), 745. https://doi.org/10.1007/s00604-024-06838-8.

Birusanti, A.B., Mallavarapu, U., Nayakanti, D., Espenti, C.S., Mala, S., 2019. Sustainable green synthesis of silver nanoparticles by using Rangoon creeper leaves extract and their spectral analysis and anti-bacterial studies. IET Nanobiotechnol. 13 (1), 71–76. https://doi.org/10.1049/iet-nbt.2018.5117.

Bokov, D., Turki Jalil, A., Chupradit, S., Suksatan, W., Javed Ansari, M., Shewael, I.H., Kianfar, E., 2021. Nanomaterial by sol-gel method: synthesis and application. Adv. Mat. Sci. Eng. 2021 (1), 5102014. https://doi.org/10.1155/2021/5102014.

Bondancia, T.J., Soares, A.C., Popolin-Neto, M., Gomes, N.O., Raymundo-Pereira, P.A., Barud, H.S., Machado, S.A.S., Ribeiro, S.J.L., Melendez, M.E., Carvalho, A.L., Reis, R. M., Paulovich, F.V., Oliveira Jr., O.N., 2022. Low-cost bacterial nanocellulose-based interdigitated biosensor to detect the p53 cancer biomarker. Biomater. Adv. 134, 112676. https://doi.org/10.1016/j.msec.2022.112676.

Bora, K.A., Hashmi, S., Zulfiqar, F., Abideen, Z., Ali, H., Siddiqui, Z.S., Siddique, K.H.M., 2022. Recent progress in bio-mediated synthesis and applications of engineered nanomaterials for sustainable agriculture. Front. Plant Sci. 13, 999505. https://doi.org/10.3389/fpls.2022.999505.

Borowska, M., Jankowski, K., 2023. Basic and advanced spectrometric methods for complete nanoparticles characterization in bio/ecosystems: current status and future prospects. Anal. Bioanal. Chem. 415 (18), 4023–4038. https://doi.org/10.1007/s00216-023-04641-7.

Bounegru, A.V., Apetrei, C., 2022. Sensitive detection of hydroxytyrosol in extra virgin olive oils with a novel biosensor based on single-walled carbon nanotubes and tyrosinase. Int. J. Mol. Sci. 23 (16), 9132. https://doi.org/10.3390/ijms23169132.

Calbiague García, V., Chen, Y., Cádiz, B., Wang, L., Paquet-Durand, F., Schmachtenberg, O., 2023. Imaging of lactate metabolism in retinal Müller cells with

a FRET nanosensor. Exp. Eye Res. 226, 109352. https://doi.org/10.1016/j.exer.2022.109352.
Cao, L., Ding, Q., Liu, M., Lin, H., Yang, D.P., 2021a. Biochar-supported Cu^{2+}/Cu^{+} composite as an electrochemical ultrasensitive interface for ractopamine detection. ACS Appl. Biol. Mater. 4 (2), 1424–1431. https://doi.org/10.1021/acsabm.0c01314.
Cao, X., Song, Q., Sun, Y., Mao, Y., Lu, W., Li, L., 2021b. A SERS-LFA biosensor combined with aptamer recognition for simultaneous detection of thrombin and PDGF-BB in prostate cancer plasma. Nanotechnol 32 (44). https://doi.org/10.1088/1361-6528/ac1754.
Capecchi, E., Piccinino, D., Tomaino, E., Bizzarri, B.M., Polli, F., Antiochia, R., Mazzei, F., Saladino, R., 2020. Lignin nanoparticles are renewable and functional platforms for the concanavalin a oriented immobilization of glucose oxidase-peroxidase in cascade bio-sensing. RSC Adv. 10 (48), 29031–29042. https://doi.org/10.1039/d0ra04485g.
Chajanovsky, I., Cohen, S., Shtenberg, G., Suckeveriene, R.Y., 2021. Development and characterization of integrated nano-sensors for organic residues and pH field detection. Sensors 21 (17), 5842. https://doi.org/10.3390/s21175842.
Chandra, S., Singh, V.K., Yadav, P.K., Bano, D., Kumar, V., Pandey, V.K., Talat, M., Hasan, S.H., 2019. Mustard seeds derived fluorescent carbon quantum dots and their peroxidase-like activity for colorimetric detection of H_2O_2 and ascorbic acid in a real sample. Anal. Chim. Acta 1054, 145–156. https://doi.org/10.1016/j.aca.2018.12.024.
Chen, Q., Hu, W., Sun, C., Li, H., Ouyang, Q., 2016. Synthesis of improved upconversion nanoparticles as ultrasensitive fluorescence probe for mycotoxins. Anal. Chim. Acta 938, 137–145. https://doi.org/10.1016/j.aca.2016.08.003.
Chen, J., Liu, B., Gao, X., Xue, D., 2018. A review of the interfacial characteristics of polymer nanocomposites containing carbon nanotubes. RSC Adv. 8, 28048–28085. https://doi.org/10.1039/C8RA04205E.
Chen, K., Ma, B., Li, J., Chen, E., Xu, Y., Yu, X., Sun, C., Zhang, M., 2021. A rapid and sensitive europium nanoparticle-based lateral flow immunoassay combined with recombinase polymerase amplification for simultaneous detection of three food-borne pathogens. Int. J. Environ. Res. Public Health 18, 4574. https://doi.org/10.3390/ijerph18094574.
Chen, K., Qing, W., Hu, W., Lu, M., Wang, Y., Liu, X., 2019a. On-off-on fluorescent carbon dots from waste tea: Their properties, antioxidant and selective detection of $CrO4^{2-}$, Fe^{3+}, ascorbic acid and L-cysteine in real samples. Spectrochim. Acta A Mol. Biomol. Spectrosc, 213, 228–234. https://doi.org/10.1016/j.saa.2019.01.066.
Chen, S., Tong, X., Huo, Y., Liu, S., Yin, Y., Tan, M.L., Cai, K., Ji, W., 2024. Piezoelectric biomaterials inspired by nature for applications in biomedicine and nanotechnology. Adv. Mat. 36 (35), e2406192. https://doi.org/10.1002/adma.202406192.
Chen, M., Zhang, Z., Liu, M., Qiu, C., Yang, H., Chen, X., 2017. In situ fabrication of label-free optical sensing paper strips for the rapid surface-enhanced Raman scattering (SERS) detection of brassinosteroids in plant tissues. Talanta 165, 313–320. https://doi.org/10.1016/j.talanta.2016.12.072.
Chen, Z.G., Zhong, H.X., Luo, H., Zhang, R.Y., Huang, J.R., 2019b. Recombinase polymerase amplification combined with unmodified gold nanoparticles for *Salmonella* detection in milk. Food Anal. Methods 12, 190–197. https://doi.org/10.1007/s12161-018-1351-6.
Chowdhury, M.A., Iqbal, M.Z., Rana, M.M., Hossain, N., Shahin, M., Islam, M.A., Rahman, M.M., 2024. Green synthesis of novel green ceramic-based nanoparticles prepared by sol-gel technique for diverse industrial application. Results Surf. Inter. 14, 100178. https://doi.org/10.1016/j.rsurfi.2023.100178.
Coelho, J.H., Eisele, A.P.P., Valezi, C.F., Mattos, G.J., Schirmann, J.G., Dekker, R.F.H., Barbosa-Dekker, A.M., Sartori, E.R., 2019. Exploring the exocellular fungal biopolymer botryosphaeran for laccase-biosensor architecture and application to determine dopamine and spironolactone. Talanta 204, 475–483. https://doi.org/10.1016/j.talanta.2019.06.033.
Costa, L.A.D., Diógenes, I.C.N., Oliveira, M.D.A., Ribeiro, S.F., Furtado, R.F., Bastos, M.D.S.R., Benevides, S.D., 2020. Smart film of jackfruit seed starch as a potential indicator of fish freshness. Food Sci. Technol. 41 (2), 489–496. https://doi.org/10.1590/fst.06420.
Coutinho, M.S., Latocheski, E., Neri, J.M., Neves, A.C., Domingos, J.B., Cavalcanti, L.N., Menezes, F.G., 2019. Rutin-modified silver nanoparticles as a chromogenic probe for the selective detection of Fe^{3+} in aqueous medium. RSC Adv. 9 (51), 30007–30011. https://doi.org/10.1039/C9RA06653E.
Dadkhah, S., Mehdinia, A., Jabbari, A., Manbohi, A., 2022. Nicotinamide-functionalized carbon quantum dot as new sensing platform for portable quantification of vitamin B12 in fluorescence, UV-Vis and smartphone triple mode. J. Fluor. 32 (2), 681–689. https://doi.org/10.1007/s10895-021-02863-5.
Dayakar, T., Rao, K.V., Bikshalu, K., Malapati, V., Sadasivuni, K.K., 2018. Non-enzymatic sensing of glucose using screen-printed electrode modified with novel synthesized CeO_2@CuO core shell nanostructure. Biosens. Bioelectron. 111, 166–173. https://doi.org/10.1016/j.bios.2018.03.063.
De Acha, N., Elosua, C., Matias, I., Arregui, F.J., 2017a. Luminescence-based optical sensors fabricated by means of the layer-by-layer nano-assembly technique. Sensors 17 (12), 2826. https://doi.org/10.3390/s17122826.
De Acha, N., Elosúa, C., Martínez, D., Hernáez, M., Matías, I.R., Arregui, F.J., 2017b. Comparative study of polymeric matrices embedding oxygen-sensitive fluorophores by means of Layer-by-Layer nanosassembly. Sens. Actuators B Chem. 239, 1124–1133. https://doi.org/10.1016/j.snb.2016.08.077.
Dehghan, G., Shaghaghi, M., Alizadeh, P., 2019. A novel ultrasensitive and non-enzymatic "turn-on-off" fluorescence nanosensor for direct determination of glucose in the serum: As an alternative approach to the other optical and electrochemical methods. Spectrochim. Acta A Mol. Biomol. Spectrosc. 214, 459–468. https://doi.org/10.1016/j.saa.2019.02.054.
Dharanivasan, G., Jesse, D.M.I., Rajamuthuramalingam, T., Rajendran, G., Shanthi, S., Kathiravan, K., 2019. Scanometric detection of tomato leaf curl New Delhi viral DNA using mono- and bifunctional AuNP-conjugated oligonucleotide probes. ACS Omega 4, 10094–10107. https://doi.org/10.1021/acsomega.9b00340.
Díez-Pascual, A.M., 2021. Carbon-based nanomaterials. Int. J. Mol. Sci. 22 (14), 7726. https://doi.org/10.3390/ijms22147726.
Du, J., Wu, S., Niu, L., Li, J., Zhao, D., Bai, Y., 2020. A gold nanoparticles-assisted multiplex PCR assay for simultaneous detection of *Salmonella typhimurium*, *Listeria monocytogenes* and *Escherichia coli* O157: H7. Anal. Methods 12, 212–217. https://doi.org/10.1039/C9AY02282A.
Durrani, S., Zhang, J., Yang, Z., Pang, A.P., Zeng, J., Sayed, S.M., Khan, A., Zhang, Y., Wu, F.G., Lin, F., 2022. Plant-derived Ca, N, S-Doped carbon dots for fast universal cell imaging and intracellular Congo red detection. Anal. Chim. Acta 1202, 339672. https://doi.org/10.1016/j.aca.2022.339672.
Ehrlich, R., Hendler-Neumark, A., Wulf, V., Amir, D., Bisker, G., 2021. Optical nanosensors for real-time feedback on insulin secretion by β-cells. Small 17 (30), e2101660. https://doi.org/10.1002/smll.202101660.
El Hajji, M., Hallaoui, A., Bazzi, L., Benlhachemi, A., Jbara, O., Tara, A., Bakiz, B., 2014. Nanostructured ZnO, ZnO-CeO_2, ZnO-Cu_2O thin films electrodes prepared by electrodeposition for electrochemical degradation of dye. Int. J. Electrochem. Sci. 9 (8), 4297–4314. https://doi.org/10.1016/s1452-3981(23)08093-8.
El Hamd, M.A., El-Maghrabey, M., Almawash, S., El-Shaheny, R., Magdy, G., 2023. Self-ratiometric fluorescence approach based on plant extract-assisted synthesized silver nanoparticles for the determination of vanillin. Mikrochim. Acta 191 (1), 16. https://doi.org/10.1007/s00604-023-06093-3.
El-Sawaf, A.K., El-Moslamy, S.H., Kamoun, E.A., Hossain, K., 2024. Green synthesis of trimetallic CuO/Ag/ZnO nanocomposite using *Ziziphus spina-christi* plant extract: characterization, statistically experimental designs, and antimicrobial assessment. Sci. Rep. 14 (1), 19718. https://doi.org/10.1038/s41598-024-67579-5.
Fathi-Karkan, S., Mirinejad, S., Ulucan-Karnak, F., Mukhtar, M., Ghahramani Almanghadim, H., Sargazi, S., Rahdar, A., Díez-Pascual, A.M., 2023. Biomedical applications of aptamer-modified chitosan nanomaterials: An updated review. Int. J. Biol. Macromol. 238, 124103. https://doi.org/10.1016/j.ijbiomac.2023.124103.
Feng, L., Zhu, A., Wang, H., Shi, H., 2014. A nanosensor based on quantum-dot haptens for rapid, on-site immunoassay of cyanotoxin in environmental water. Biosens. Bioelectron. 53, 1–4. https://doi.org/10.1016/j.bios.2013.09.018.
Figueroa, V., Velasco, B., Arellano, L.G., Domínguez-Arca, V., Cambón, A., Pardo, A., Taboada, P., 2024. Role of surface functionalization and biomolecule structure on protein corona adsorption and conformation onto anisotropic metallic nanoparticles. J. Mole. Liq. 398, 124240. https://doi.org/10.1016/j.molliq.2024.124240.
Fu, Y., Liu, T., Wang, H., Wang, Z., Hou, L., Jiang, J., Xu, T., 2024. Applications of nanomaterial technology in biosensing. J. Sci. Adv. Mat. Dev. 9 (2), 100694. https://doi.org/10.1016/j.jsamd.2024.100694.
Fu, R., Zhang, P.S., Jiang, Y.X., Sun, L., Sun, X.H., 2023. Wastewater treatment by anodic oxidation in an electrochemical advanced oxidation process: Advances in mechanism, direct, and indirect oxidation detection methods. Chemosphere 311 (Pt1), 136993. https://doi.org/10.1016/j.chemosphere.2022.136993.
Furtado, R.F., Alves, C.R., Moreira, A.C., Azevedo, R.M., Dutra, R.F., 2012. Novel xyloglucan film-based biosensor for toxicity assessment of ricin in castor seed meal. Carbohydr. Polym. 89 (2), 586–591. https://doi.org/10.1016/j.carbpol.2012.03.053.
Gao, T., Cao, X., Ge, P., Dong, J., Yang, S., Xu, H., Wu, Y., Gao, F., Zeng, W., 2017. Self-assembled fluorescent organic nanoprobe and their application for sulfite detection in food samples and living systems. Org. Biomol. Chem. 15 (20), 4375–4382. https://doi.org/10.1039/c7ob00580f.
Gao, Y., Guo, M., Wang, D., Zhao, D., Wang, M., 2023a. Advances in extraction, purification, structural characteristics, and biological activities of hemicelluloses: a review. Int. J. Biol. Macromol. 225, 467–483. https://doi.org/10.1016/j.ijbiomac.2022.11.099.
Gao, L., Li, H., Dong, X., Li, W., Deng, H., 2024. High-sensitivity QCM humidity sensor based on chitosan/carboxymethylated multiwalled carbon nanotube composites for non-contact respiratory monitoring. Int. J. Biol. Macromol. 279 (Pt2), 135156. https://doi.org/10.1016/j.ijbiomac.2024.135156.
Gao, Y., Wu, Y., Huang, P., Wu, F.Y., 2023b. Colorimetric and photothermal immunosensors for the sensitive detection of cancer biomarkers based on enzyme-mediated growth of gold nanostars on polydopamine. Anal. Chim. Acta 1279, 341775. https://doi.org/10.1016/j.aca.2023.341775.
Gazizadeh, M., Dehghan, G., Soleymani, J., 2023. Dual-emission ratiometric fluorescent biosensor for ultrasensitive detection of glibenclamide using S-CDs/CdS quantum dots. Spectrochim. Acta A Mol. Biomol. Spectrosc, 297, 122714. https://doi.org/10.1016/j.saa.2023.122714.
Ghosh, T., Raj, G.V.S.B., Dash, K.K., 2022. A comprehensive review on nanotechnology based sensors for monitoring quality and shelf life of food products. Meas. Food 7, 100049. https://doi.org/10.1016/j.meafoo.2022.100049.
Guo, C., Huo, H., Han, X., Xu, C., Li, H., 2014. Ni/CdS bifunctional Ti@TiO_2 core-shell nanowire electrodes for high-performance nonenzymatic glucose sensing. Anal. Chem. 86 (1), 876–883. https://doi.org/10.1021/ac4034467.
Guo, J., Wu, J., Yang, J., He, J., 2025. Colorimetric and electrochemical dual-mode system for identifying and detecting various Cr species based on fungus-like porous CoS nanosensor. Talanta 285, 127379. https://doi.org/10.1016/j.talanta.2024.127379.
Gupta, M., Tomar, R.S., Mishra, R.K., 2020. Factors affecting the biosynthesis of green nanoparticles. Our Herit. 68 (30), 10530–10555.
Hänninen, A., Sarlin, E., Lyyra, I., Salpavaara, T., Kellomäki, M., Tuukkanen, S., 2018. Nanocellulose and chitosan based films as low cost, green piezoelectric materials. Carbohydr. Polym. 202, 418–424. https://doi.org/10.1016/j.carbpol.2018.09.001.

Hao, L., Zhao, R.T., Welch, N.L., Tan, E.K.W., Zhong, Q., Harzallah, N.S., Ngambenjawong, C., Ko, H., Fleming, H.E., Sabeti, P.C., Bhatia, S.N., 2023. CRISPR-Cas-amplified urinary biomarkers for multiplexed and portable cancer diagnostics. Nat. Nanotechnol. 18 (7), 798–807. https://doi.org/10.1038/s41565-023-01372-9.

Hassan, R.Y.A., 2022. Advances in electrochemical nano-biosensors for biomedical and environmental applications: From the current work to future perspectives. Sensors 22 (19), 7539. https://doi.org/10.3390/s22197539.

He, Y., Ma, L., Zhou, L., Liu, G., Jiang, Y., Gao, J., 2020. Preparation and Application of Bismuth/MXene nano-composite as electrochemical sensors for heavy metal ion detection. Nanomaterials 10 (5), 866. https://doi.org/10.3390/nano10050866.

Hemdan, M., Abuelhaded, K., Shaker, A.A.S., Ashour, M.M., Abdelaziz, M.M., Dahab, M. I., Ragab, A.H., 2025. Recent advances in nano-enhanced biosensors: Innovations in design, applications in healthcare, environmental monitoring, and food safety, and emerging research challenges. Sens. BioSens. Res. 48, 100783. https://doi.org/10.1016/j.sbsr.2025.100783.

Hooshmand, S., Es'haghi, Z., 2017b. Simultaneous quantification of arginine, alanine, methionine, and cysteine amino acids in supplements using a novel bioelectro-nanosensor based on a CdSe quantum dot/modified carbon nanotube hollow fiber pencil graphite electrode via the Taguchi method. J. Pharm. Biomed. Anal. 146, 226–235. https://doi.org/10.1016/j.jpba.2017.08.034.

Hooshmand, S., Es'haghi, Z., 2017a. Microfabricated disposable nanosensor based on CdSe quantum dot/ionic liquid-mediated hollow fiber-pencil graphite electrode for simultaneous electrochemical quantification of uric acid and creatinine in human samples. Anal. Chim. Acta 972, 28–37. https://doi.org/10.1016/j.aca.2017.04.035.

Hu, C.Y., Bai, L., Song, F., Wang, Y.L., Wang, Y.Z., 2022. Cellulose nanocrystals and β-cyclodextrin chiral nematic composite films were used as selective sensors for methanol discrimination. Carbohydr. Polym. 296, 119929. https://doi.org/10.1016/j.carbpol.2022.119929.

Hu, J., Pan, L.Y., Li, Y., Zou, X., Liu, B.J., Jiang, B., Zhang, C.Y., 2021. Deacetylation-activated construction of a single quantum dot-based nanosensor for the sirtuin 1 assay. Talanta 224, 121918. https://doi.org/10.1016/j.talanta.2020.121918.

Hu, J., Zhang, H., Liu, L., Zhu, X., Zhao, C., Pan, Q., 2020. Convergent multiagent formation control with collision avoidance. EEE Trans. Robot. 36 (6), 1805–1818. https://doi.org/10.1109/TRO.2020.2998766.

Huang, L., Chen, F., Zong, X., Lu, Q., Wu, C., Ni, Z., Liu, M., Zhang, Y., 2021a. Near-infrared light-excited UCNP-DNAzyme nanosensor for selective detection of Pb^{2+} and in vivo imaging. Talanta 227, 122156. https://doi.org/10.1016/j.talanta.2021.122156.

Huang, Y., Zhu, F., Guan, J., Wei, W., Zou, L., 2020. Label-free Amperometric immunosensor based on a versatile carbon nanofibers network coupled with au nanoparticles for aflatoxin B1 detection. Biosensors 11 (1), 5. https://doi.org/10.3390/bios11010005.

Huang, X., Zhu, Y., Kianfar, E., 2021b. Nano biosensors: properties, applications, and electrochemical techniques. J. mat. res. technol. 12, 1649–1672. https://doi.org/10.1016/j.jmrt.2021.03.048.

Hwang, J., Seo, Y., Jeong, D., Ning, X., Wiraja, C., Yang, L., Tan, C.T., Lee, J., Kim, Y., Kim, J.W., Kim, D.H., Choi, J., Lim, C.Y., Pu, K., Jang, W.Y., Xu, C., 2022. Monitoring wound healing using topically applied optical nanoflare mRNA nanosensors. Adv. Sci. 9 (18), e2104835. https://doi.org/10.1002/advs.202104835.

Ilyas, K., Singer, L., Akhtar, M.A., Bourauel, C.P., Boccaccini, A.R., 2022. *Boswellia sacra* extract-loaded mesoporous bioactive glass nanoparticles: synthesis and biological effects. Pharmaceutics 14 (1), 126. https://doi.org/10.3390/pharmaceutics14010126.

Inamuddin, N., Shakeel, M., Ahamed, M., Kanchi, S., Kashmery, H., 2020. Green synthesis of ZnO nanoparticles decorated on polyindole-functionalized MCNTs and used as anode material for enzymatic biofuel cell applications. Sci. Rep. 10 (1), 5052. https://doi.org/10.1038/s41598-020-61831-4.

Iqbal, J., Abbasi, B.A., Yaseen, T., Zahra, S.A., Shahbaz, A., Shah, S.A., Ahmad, P., 2021. Green synthesis of ZnO oxide nanoparticles using *Elaeagnus angustifolia* L. leaf extracts and their multiple in vitro biological applications. Sci. Rep. 11, 20988. https://doi.org/10.1038/s41598-021-99839-z.

Islam, S., Shukla, S., Bajpai, V.K., Han, Y.K., Huh, Y.S., Kumar, A., Ghosh, A., Gandhi, S., 2019. Smart nanosensor for the detection of human immunodeficiency virus and associated cardiovascular and arthritis diseases using functionalized graphene-based transistors. Biosens. Bioelectron. 126, 792–799. https://doi.org/10.1016/j.bios.2018.11.041.

Iwunze, M.O., McEwan, D., 2007. Characterization of sol-gel-encapsulated curcumin as a possible sensor for biologically important small molecules. Cell Mol. Biol. 53 (4), 81–87.

Jafarzadeh, S., Oladzadabbasabadi, N., Dheyab, M.A., Lalabadi, M.A., Sheibani, S., Ghasemlou, M., Timms, W., 2025. Emerging trends in smart and sustainable nano-biosensing: The role of green nanomaterials. Ind. Crops Prod. 223, 120108. https://doi.org/10.1016/j.indcrop.2024.120108.

Jahnavi, H.K., Prasad, S.R., Nagaswarupa, H.P., Naik, R., Basavaraju, N., Ravikumar, C. R., Goud, B.S., Kim, J.H., 2024. Exploring the diverse applications of sol-gel-synthesized CaO:$MgAl_2O_4$ nanocomposite from morphological, photocatalytic, and electrochemical perspectives. Discov. Nano 19 (1), 147. https://doi.org/10.1186/s11671-024-04093-7.

Jayaramudu, T., Varaprasad, K., Pyarasani, R.D., Reddy, K.K., Akbari-Fakhrabadi, A., Carrasco-Sánchez, V., Amalraj, J., 2021. Hydroxypropyl methylcellulose-copper nanoparticle and nanocomposite hydrogel films for antibacterial application. S. Carbohydr. Polym. 254, 117302. https://doi.org/10.1016/j.carbpol.2020.117302.

Jebali, M., Gómez-Merino, A.I., Colangelo, G., 2025. Influence of lemon (*Citrus limon* L.) juice amount on the green synthesis of CuO nanoparticles: characterization, stability, and thermal conductivity. Ceram. Int. 51 (1), 72–84. https://doi.org/10.1016/j.ceramint.2024.10.330.

Jebril, S., Fdhila, A., Dridi, C., 2021. Nanoengineering of eco-friendly silver nanoparticles using five different plant extracts and development of cost-effective phenol nanosensor. Sci. Rep. 11 (1), 22060. https://doi.org/10.1038/s41598-021-01609-4.

Jędrzak, A., Rębiś, T., Kuznowicz, M., Jesionowski, T., 2019. Bio-inspired magnetite/lignin/polydopamine-glucose oxidase biosensing nanoplatforms. Sensing assays were used for comparison with other glucose-testing techniques. Int. J. Biol. Macromol. 127, 677–682. https://doi.org/10.1016/j.ijbiomac.2019.02.008.

Jimenez-Falcao, S., Joga, N., García-Fernández, A., Llopis Lorente, A., Torres, D., de Luis, B., Sancenón, F., Martínez-Ruiz, P., Martínez-Máñez, R., Villalonga, R., 2019. Janus nanocarriers are powered by a bienzymatic cascade system for smart delivery. J. Mater. Chem. B. 7 (30), 4669–4676. https://doi.org/10.1039/c9tb00938h.

Jin, C., Yang, S., Zheng, J., Chai, F., Tian, M., 2025. Paper-based triple-readout nanosensor for the point-of-care detection of glucose in urine. Biosens. Bioelectron. 269, 116931. https://doi.org/10.1016/j.bios.2024.116931.

Joshi, D.J., Lalrinhlupuii, Malek, M.I., Muthukumaran, R.B., Kailasa, S.K., 2022. Microwave-assisted synthesis of red-emitting copper nanoclusters using trypsin as a ligand for sensing Pb^{2+} and Hg^{2+} ions in water and tobacco samples. Appl. Spectrosc. 76 (10), 1234–1245. https://doi.org/10.1177/00037028221100544.

Kabiraj, A., Rath, S., 2023. Green synthesis of silver nanoparticles: Optical and rheological properties. In: In J. Phy. Conf. Series, 2663, 012026. https://doi.org/10.1088/1742-6596/2663/1/012026.

Kadian, S., Kumari, P., Shukla, S., Narayan, R., 2023. Recent advancements in machine learning have enabled the development of portable wearable biosensors. Talanta Open 8, 100267. https://doi.org/10.1016/j.talo.2023.100267.

Kalinke, C., de Oliveira, P.R., Marcolino-Júnior, L.H., Bergamini, M.F., 2024. Nanostructures of Prussian blue-supported activated biochar for the development of a glucose biosensor. Talanta 274, 126042. https://doi.org/10.1016/j.talanta.2024.126042.

Kamel, S., Khattab, T.A., 2020. Recent advances in cellulose-based biosensors for medical diagnosis. Biosensors 10 (6), 67. https://doi.org/10.3390/bios10060067.

Kamil, M., Al-Rekabi, S.H., Yaacob, M.H., Syahir, A., Chee, H.Y., Mahdi, M.A., Abu Bakar, M.H., 2019. Detection of dengue using the PAMAM dendrimer-integrated tapered optical fiber sensor. Sci. Rep. 9 (1), 13483. https://doi.org/10.1038/s41598-019-49891-7.

Kang, W., Lin, H., Jiang, R., Yan, Y., Ahmad, W., Ouyang, Q., Chen, Q., 2022. Emerging applications of nano-optical sensors combined with near-infrared spectroscopy for detecting tea extract fermentation aroma under ultrasound-assisted sonication. Ultrason. Sonochem. 88, 106095. https://doi.org/10.1016/j.ultsonch.2022.106095.

Kareem, F., Mohd-Naim, N.F., Ahmed, M.U., 2024. A novel and ultrasensitive electrochemical immunosensor based on a nanocellulose-Ti_3C_2Tx@ZrO_2 nanoframework for the detection of ovalbumin. Int. J. Biol. Macromol. 257 (Pt 2), 128657. https://doi.org/10.1016/j.ijbiomac.2023.128657.

Karimi, F., Balazadeh, N., Eftekhari-Sis, B., 2019. 3' end of the eae gene-based fluorescence DNA nanosensor for detection of *E. coli* O157:H7. J. Appl. Genet 60 (3-4), 417–426. https://doi.org/10.1007/s13353-019-00511-0.

Kaur, M., Prasher, D., Sharma, A., Ghosh, D., Sharma, R., 2023. Natural sunlight-driven photocatalytic dye degradation by biogenically synthesized tin oxide (SnO_2) nanostructures using *Tinospora crispa* stem extract and its anticancer and antibacterial applications. Environ. Sci. Pollut. Res. Int. 30 (13), 38869–38885. https://doi.org/10.1007/s11356-022-25028-8.

Ke, Y., Garg, B., Ling, Y.C., 2016. A novel graphene-based label-free fluorescence 'turn-on' nanosensor for selective and sensitive detection of phosphorylated species in biological samples and living cells. Nanoscale 8 (8), 4547–4556. https://doi.org/10.1039/c5nr07261a.

Khaleghiabbasabadi, M., Taghavian, H., Gholami, P., Khodabakhshi, S., Gheibi, M., Wacławek, S., Černík, M., Silvestri, D., Raczak, K.B., Moezzi, R., 2024. A novel organic-inorganic-nanocomposite-based reduced was used as an efficient nanosensor for NO_2 detection. Nanomaterials 14 (24), 1983. https://doi.org/10.3390/nano14241983.

Khan, T., Abbas, S., Fariq, A., Yasmin, A., 2018. Microbes: Natural cell factories for nanoparticles synthesis. In: Prasad, R., Jha, A.K., Prasad, K. (Eds.), Exploring the Realms of Nature for Nanosynthesis. Springer, Cham, pp. 25–50. https://doi.org/10.1007/978-3-319-99570-0_2.

Khan, M.S., Dhavan, P.P., Ratna, D., Shimpi, N.G., 2022. Ultrasonic-assisted biosynthesis of ZnO nanoparticles using *Sonneratia alba* leaf extract and investigation of its photocatalytic and biological activities. J. Clust. Sci. 33, 1007–1023. https://doi.org/10.1007/s10876-021-02036-1.

Khan, I., Saeed, K., Khan, I., 2019. Nanoparticles: properties, applications, and toxicities. Arab. J. Chem. 12 (7), 908–931. https://doi.org/10.1016/j.arabjc.2017.05.011.

Khater, M., de la Escosura-Muñiz, A., Quesada-González, D., Merkoçi, A., 2019. Electrochemical detection of plant viruses using AuNP-modified electrodes. Anal. Chim. Acta 1046, 123–131. https://doi.org/10.1016/j.aca.2018.09.031.

Khattab, T.A., Fouda, M.M.G., Abdelrahman, S.I., Bin-Jumah, M., Alqaraawi, M.A., Al Fassam, H., Allam, A.A., 2019. Development of illuminant glow-in-the-dark cotton fabric coated with a luminescent composite with antimicrobial activity and ultraviolet protection. J. Fluor. 29, 703–710. https://doi.org/10.1007/s10895-019-02384-2.

Kim, D., Wang, S.X., 2012. A magneto-nanosensor immunoassay for the sensitive detection of *Aspergillus fumigatus* allergen Asp f 1. IEEE Trans. Magn. 48 (11), 3266–3268. https://doi.org/10.1109/TMAG.2012.2195163.

Kim, G.W., Yoon, S., Lee, J., Lee, J.H., Ha, J.W., 2020. High-throughput characterization and in situ control of the three-dimensional orientations of single gold nanorods

coated with spherical mesoporous silica shell. S. J. Phys. Chem. C. 124 (26), 14279–14286. https://doi.org/10.1021/acs.jpcc.0c03652.
Krishnan, V., Pandey, G.R., Babu, K.A., Paramasivam, S., Kumar, S.S., Balasubramanian, S., Ravichandiran, V., Pazhani, G.P., Veerapandian, M., 2021. Chitosan-grafted butein: a metal-free transducer for electrochemical genosensing of exosomal CD24. Carbohydr. Polym. 269, 118333. https://doi.org/10.1016/j.carbpol.2021.118333.
Kruszewska, J., Zajda, J., Matczuk, M., 2021. How can we effectively prepare a sample for bottom-up proteomic analysis of nanoparticle protein corona? A critical review. Talanta 226, 122153. https://doi.org/10.1016/j.talanta.2021.122153.
Kulkarni, Madhusudan, Narasimha, B., Ayachit, H., Tejraj, M., Aminabhavi, 2022. Recent advancements in nano. Biosens. Incl. Curr. Trends Chall. Future Appl. Biosens. 12 (10), 892. https://doi.org/10.3390/bios12100892.
Lau, H.Y., Wu, H., Wee, E.J., Trau, M., Wang, Y., Botella, J.R., 2017. Specific and sensitive isothermal electrochemical biosensors for plant pathogen DNA detection using colloidal gold nanoparticles as probes. Sci. Rep. 7, 38896. https://doi.org/10.1038/srep38896.
Le, L.V., Chendke, G.S., Gamsey, S., Wisniewski, N., Desai, T.A., 2020. Near-infrared optical nanosensors for continuous detection of glucose. J. Diabetes Sci. Technol. 14 (2), 204–211. https://doi.org/10.1177/1932296819886928.
Lee, H.N., Ryu, J.S., Shin, C., Chung, H.J., 2017. A carbon-dot-based fluorescent nanosensor for simple visualization of bacterial nucleic acids. Macromol. Biosci. 17 (9), 1700086. https://doi.org/10.1002/mabi.201700086.
Li, H., Ahmad, W., Rong, Y., Chen, Q., Zuo, M., Ouyang, Q., Guo, Z., 2020. Designing an aptamer-based magnetic and upconversion nanoparticles conjugated fluorescence sensor for screening *Escherichia coli* in food. Food Cont. 107, 106761. https://doi.org/10.1016/j.foodcont.2019.106761.
Li, M., Ding, C., Zhang, D., Chen, W., Yan, Z., Chen, Z., Guo, Z., Guo, L., Huang, Y., 2023a. Distinguishable colorimetric biosensors for the diagnosis of prostate cancer bone metastases. Adv. Sci. 10 (32), e2303159. https://doi.org/10.1002/advs.202303159.
Li, P., Fu, H., Bai, Z., Feng, X., Qi, J., Song, X., Hu, X., Chen, L., 2023. Dummy molecularly imprinted ratiometric fluorescence nanosensor for the sensitive detection of guanidyl microcystins in environmental water. Analyst 148 (3), 573–582. https://doi.org/10.1039/d2an01928k.
Li, Y., Ren, J., Sun, R., Wang, X., 2018. Fluorescent lignin carbon dots for reversible responses to high-valence metal ions and their bioapplications. J. Biomed. Nanotechnol. 14 (9), 1543–1555. https://doi.org/10.1166/jbn.2018.2610.
Li, L., Wang, T., Zhong, Y., Li, R., Deng, W., Xiao, X., Xu, Y., Zhang, J., Hu, X., Wang, Y., 2024. A review of nanomaterials for biosensing applications. J. Mat. Chem. B 12 (5), 1168–1193. https://doi.org/10.1039/d3tb02648e.
Liang, N., Hu, X., Li, W., Wang, Y., Guo, Z., Huang, X., Li, Z., Zhang, X., Zhang, J., Xiao, J., Zou, X., Shi, J., 2022. Dual-signal fluorescent sensor based on MoS2 and CdTe quantum dots for tetracycline detection in milk. Food Chem. 378, 132076. https://doi.org/10.1016/j.foodchem.2022.132076.
Liang, Y., Xiao, M., Wu, D., Lin, Y., Liu, L., He, J., Zhang, Z., 2020. Wafer-scale uniform carbon nanotube transistors for ultrasensitive and label-free detection of disease biomarkers. ACS Nano 14 (7), 8866–8874. https://doi.org/10.1021/acsnano.0c03523.
Liao, L., Wang, S., Xiao, J., Bian, X., Zhang, Y., Scanlon, M.D., Girault, H.H., 2014. A nanoporous molybdenum carbide nanowire was used as an electrocatalyst for hydrogen evolution reaction. Energy Env. Sci. 7 (1), 387–392. https://doi.org/10.1039/C3EE42441C.
Lin, L.P., Tham, S.Y., Loh, H.S., Tan, M.T.T., 2021. Biocompatible graphene-zirconia nanocomposite as a cyto-safe immunosensor for the rapid detection of carcinoembryonic antigen. S. Sci. Rep. 11 (1), 22536. https://doi.org/10.1038/s41598-021-99498-0.
Lin, H., Wang, X., Wu, J., Li, H., Li, F., 2019. Equipment-free and visualized biosensor for rapid transcription factor assay based on dopamine-functionalized cellulose paper. J. Mater. Chem. B. 7 (36), 5461–5464. https://doi.org/10.1039/c9tb01455a.
Ling, Z., Xu, F., Edwards, J.V., Prevost, N.T., Nam, S., Condon, B.D., French, A.D., 2019. Nanocellulose is a colorimetric biosensor for effective and facile detection of human neutrophil elastase. Carbohydr. Polym. 216, 360–368. https://doi.org/10.1016/j.carbpol.2019.04.027.
Lino, C., Barrias, S., Chaves, R., Adega, F., Martins-Lopes, P., Fernandes, J.R., 2022. Biosensors as diagnostic tools in clinical applications. BBA Rev. Cancer 1877 (3), 188726. https://doi.org/10.1016/j.bbcan.2022.188726.
Lio, D.C.S., Liu, C., Wiraja, C., Qiu, B., Fhu, C.W., Wang, X., Xu, C., 2018. Molecular beacon gold nanosensors for leucine-rich alpha-2-glycoprotein-1 detection in pathological angiogenesis. ACS Sens 3 (9), 1647–1655. https://doi.org/10.1021/acssensors.8b00321.
Liu, R.H., 2004. Potential synergy of phytochemicals in cancer prevention: Mechanisms of action. J. Nutr. 134 (12), 3479S–3485S.
Liu, Y., Chen, X., Ma, Q., 2018. A novel amplified electrochemiluminescence biosensor based on Au NPs@ PDA @CuInZnS QDs nanocomposites for ultrasensitive detection of the p53 gene. Biosens. Bioelectron. 117, 240–245. https://doi.org/10.1016/j.bios.2018.06.023.
Liu, X., Lei, H., Hu, Y., Fan, X., Zhang, Y., Xie, L., Huang, J., Cai, Q., 2023. Turn-on fluorescent nanosensor for H2S detection and imaging in inflammatory cells and mice. Spectrochim. Acta A Mol. Biomol. Spectrosc 297, 122739. https://doi.org/10.1016/j.saa.2023.122739.
Liu, L., Qin, K., Yin, S., Zheng, X., Li, H., Yan, H., Song, P., Ji, X., Zhang, Q., Wei, Y., Zhao, L., 2021. Bifunctional carbon dots derived from an anaerobic bacterium *Porphyromonas gingivalis* for the selective detection of Fe^{3+} and bioimaging. Photochem. Photobio. 97 (3), 574–581. https://doi.org/10.1111/php.13360.
Liu, X., Xu, C., Fu, C., Xia, D., Wang, F., Yin, H., Peng, J., 2022. Graphene oxide-sensitized surface plasmon resonance biosensor for porcine reproductive and respiratory syndrome viruses. Molecules 27 (12), 3942. https://doi.org/10.3390/molecules27123942.
Liu, Y., Yao, L., He, L., Liu, N., Piao, Y., 2019. Electrochemical enzyme biosensor bearing biochar nanoparticles as a signal enhancer for BPA detection in water. Sensors 19 (7), 1619. https://doi.org/10.3390/s19071619.
Liu, J.X., Zhou, W.J., Gong, J.L., Tang, L., Zhang, Y., Yu, H.Y., Wang, B., Xu, X.M., Zeng, G.M., 2008. An electrochemical sensor for the detection of laccase activity from *Penicillium simplicissimum* in compost based on a carbon nanotube-modified glassy carbon electrode. Bioresour. Technol. 99 (18), 8748–8751. https://doi.org/10.1016/j.biortech.2008.04.029.
Luo, B., Zhou, J., Li, Z., Song, J., An, P., Zhang, H., Chen, Y., Lan, F., Ying, B., Wu, Y., 2022. Ultrasensitive DNA methylation ratio detection based on target-induced nanoparticle coupling and site-specific base oxidation damage in colorectal cancer. Anal. Chem. 94 (16), 6261–6270. https://doi.org/10.1021/acs.analchem.2c00104.
Lv, M., Li, Y., Qiao, X., Zeng, X., Luo, X., 2024. An antifouling electrochemical biosensor based on oxidized bacterial cellulose and quaternized chitosan was developed for the reliable detection of involucrin in wound exudate. S. Anal. Chim. Acta 1316, 342821. https://doi.org/10.1016/j.aca.2024.342821.
Madkour, E., Abou Zeid, A., Abdel Ghany, S., Alshehrei, F.M., El-Ghareeb, D., Abdel-Hakeem, M., 2023. Sensitive and selective colorimetric detection of Staphylococcus aureus-SPA using an engineered gold nanosensor. Saudi. J. Biol. Sci. 30 (2), 103559. https://doi.org/10.1016/j.sjbs.2023.103559.
Magar, H.S., Ghica, M.E., Abbas, M.N., Brett, C.M.A., 2017. Novel sensitive amperometric choline biosensors based on multiwalled carbon nanotubes and gold nanoparticles. Talanta 167, 462–469. https://doi.org/10.1016/j.talanta.2017.02.048.
Magdy, G., Aboelkassim, E., El-Domany, R.A., Belal, F., 2022. Green synthesis, characterization, and antimicrobial applications of silver nanoparticles as fluorescent nanoprobes for spectrofluorimetric determination of ornidazole and miconazole. Sci. Rep. 12 (1), 21395. https://doi.org/10.1038/s41598-022-25830-x.
Magdy, G., Belal, F., Elmansi, H., 2023. Rapid microwave-assisted synthesis of nitrogen-doped carbon quantum dots as fluorescent nanosensors for spectrofluorimetric determination of palbociclib: application for cellular imaging and selective probing in living cancer cells. RSC Adv. 13 (7), 4156–4167. https://doi.org/10.1039/d2ra05759j.
Malatesta, M., 2021. Transmission electron microscopy is a powerful tool for investigating the interaction of nanoparticles with subcellular structures. Int. J. Mol. Sci. 26, 2789. https://doi.org/10.3390/ijms222312789.
Malhotra, B.D., Ali, Md.A., 2018. Nanomaterials in biosensors. Nanomater. Biosens. 1–74. https://doi.org/10.1016/b978-0-323-44923-6.00001-7.
Malik, M., Chaudhary, R., Pundir, C.S., 2020. An amperometric pyruvate biosensor based on pyruvate oxidase nanoparticles was immobilized on a pencil graphite electrode. Process Biochem. 93, 12–20. https://doi.org/10.1016/j.procbio.2020.03.008.
Maqsood, M.F., Shahbaz, M., Khalid, F., Rasheed, Y., Asif, K., Naz, N., Zulfiqar, U., Zulfiqar, F., Moosa, A., Alamer, K.H., Attia, H., 2023. Biogenic nanoparticles application in agriculture for ROS mitigation and abiotic stress tolerance: a review. Plant Stress 10, 100281. https://doi.org/10.1016/j.stress.2023.100281.
Marquitan, M., Ruff, A., Bramini, M., Herlitze, S., Mark, M.D., Schuhmann, W., 2020. Polymer/enzyme-modified HF-etched carbon nanoelectrodes for single-cell analysis. Bioelectrochem 133, 107487. https://doi.org/10.1016/j.bioelechem.2020.107487.
Mayol, B., Pradana-López, S., García, A., de la Torre, C., Díez, P., Villalonga, A., Anillo, C., Vilela, D., Sánchez, A., Martínez-Ruiz, P., Martínez-Máñez, R., Villalonga, R., 2024. Self-propelled enzyme-controlled IR-mesoporous silica Janus nanomotors for smart delivery. J. Colloid Interface Sci. 671, 294–302. https://doi.org/10.1016/j.jcis.2024.05.134.
Mazzarino, L., Otsuka, I., Halila, S., Bubniak, Ldos, S., Mazzucco, S., Santos-Silva, M.C., Lemos-Senna, E., Borsali, R., 2014. Xyloglucan-block-poly(ϵ-caprolactone) copolymer nanoparticles coated with chitosan are a biocompatible mucoadhesive drug delivery system. Macromol. Biosci. 14 (5), 709–719. https://doi.org/10.1002/mabi.201300465.
Mehdipour, A., Reza, M.A.S., Rasouli, A., Baravati, M.H.J., Jafari, G.A., Heidari, F., 2024. Green synthesis of zinc nanoparticles by hydroalcoholic extract of lavender (*Lavandula stoechas* L.), characterization, and cytotoxic effects on human breast and colon cancer. Sci. Rep. 14 (1), 29543. https://doi.org/10.1038/s41598-024-81295-0.
Mehmood, A., Murtaza, G., Bhatti, T.M., Kausar, R., 2017. Phyto-mediated synthesis of silver nanoparticles from *Melia azedarach* L. leaf extract: Characterization and antibacterial activity. Arab. J. Chem. 10, S3048–S3053. https://doi.org/10.1016/j.arabjc.2013.11.046.
Meng, L., Chirtes, S., Liu, X., Eriksson, M., Mak, W.C., 2022. Green route for lignin-derived graphene electrodes: a disposable platform for electrochemical biosensors. Biosens. Bioelectron. 218, 114742. https://doi.org/10.1016/j.bios.2022.114742.
Minopoli, A., Acunzo, A., Della Ventura, B., Velotta, R., 2021. Nanostructured surfaces as plasmonic biosensors: a review. Adv. Mater. Interfaces, 2101133. https://doi.org/10.1002/admi.202101133.
Mohammadi, A., Haghnazari, N., Karami, C., 2023. Nano-probe for determination of phenobarbital in green synthesized fluorescent carbon dots using *Scrophularia striata*. J. Mater. Sci. Mater. Electron 34 (4), 251. https://doi.org/10.1007/s10854-022-09439-4.
Mohanraj, K., Balasubramanian, D., Jhansi, N., Bakkiyaraj, R., Chandrasekaran, J., 2017. Structural, Optical, and electrical properties of green synthesized CdO nanoparticles and its Ag/CdO/P-Si junction diode fabricated via the JNS pyrolysis technique. Int. J. Thin Films Sci. Technol. 6, 87–91. https://doi.org/10.18576/ijtfst/060207.

Moreno, A., Sipponen, M.H., 2020. Lignin-based smart materials: a roadmap for processing and synthesis for current and future applications. Mater. Horiz. 7, 2237–2257. https://doi.org/10.1039/D0MH00798F.
Mousavizadeh, F.S., Sarlak, N., Ghorbanpour, M., Ghafarzadegan, R., 2022. Rapid detection and determination of scopolamine in the leaf extract of black henbane (*Hyoscyamus niger* L.) plants using a novel nanosensor. J. AOAC Int. 105 (6), 1730–1740. https://doi.org/10.1093/jaoacint/qsac061.
Mudgal, N., Yupapin, P., Ali, J., Singh, G., 2020. $BaTiO_3$-graphene-affinity layer–based surface plasmon resonance (SPR) biosensor for *Pseudomonas* bacterial detection. Plasmonics 15, 1221–1229. https://doi.org/10.1007/s11468-020-01146-2.
Naghdi, T., Faham, S., Mahmoudi, T., Pourreza, N., Ghavami, R., Golmohammadi, H., 2020. Phytochemicals toward green (bio) bio-sensing. ACS Sens 5 (12), 3770–3805. https://doi.org/10.1021/acssensors.0c02101.
Nair, R.V., Thomas, T., Kuttoth, H., Karthikeyan, A., Nair, B.G., Sandhyarani, N., 2022. Cu^{2+}-mediated aggregation of gold nanoparticles as an optical probe for the detection of endotoxins. Langmuir 38 (35), 10826–10835. https://doi.org/10.1021/acs.langmuir.2c01436.
Naresh, V., Lee, N., 2021. A review of biosensors and recent developments in nanostructured material-enabled biosensors. Sensors 21 (4), 1109. https://doi.org/10.3390/s21041109.
Nasrollahpour, H., Khalilzadeh, B., Naseri, A., Mamaghani, S., Isildak, I., Rashidi, M.R., 2023. Chitosan/luminol/AgNP nanocomposite for electrochemiluminescent determination of prostate-specific antigens. Mikrochim Acta 190 (3), 90. https://doi.org/10.1007/s00604-023-05680-8.
Nasrollahpour, H., Naseri, A., Rashidi, M.R., Khalilzadeh, B., 2021. Application of green-synthesized WO3-poly glutamic acid nanobiocomposites for early stage biosensing of breast cancer using an electrochemical approach. Sci. Rep. 11 (1), 23994. https://doi.org/10.1038/s41598-021-03209-8.
Nawaz, H., Zhang, J., Tian, W., Jin, K., Jia, R., Yang, T., Zhang, J., 2020. Cellulose-based fluorescent sensors for the visual and versatile detection of amines and anions. J. Hazard Mater. 387, 121719. https://doi.org/10.1016/j.jhazmat.2019.121719.
Nayak, S., Borse, S., Jha, S., Mehta, V.N., Murthy, Z.V.P., Park, T.J., Kailasa, S.K., 2025. Development of a copper nanoclusters-based turn-off nanosensor for fluorescence detection of two pyrethroid pesticides (Cypermethrin and Lambda-Cyhalothrin). J. Fluor. 35 (1), 509–520. https://doi.org/10.1007/s10895-023-03537-0.
Ndikau, M., Noah, N.M., Andala, D.M., Masika, E., 2017. Green synthesis and characterization of silver nanoparticles using *Citrullus lanatus* fruit rind extract. Int. J. Anal. Chem. 2017 (1), 8108504. https://doi.org/10.1155/2017/8108504.
Nguyen, T.H.A., Nguyen, V.C., Phan, T.N.H., Le, V.T., Vasseghian, Y., Trubitsyn, M.A., Nguyen, A.T., Chau, T.P., Doan, V.D., 2022. Novel biogenic silver and gold nanoparticles for multifunctional applications: green synthesis, catalytic and antibacterial activity, and colorimetric detection of Fe(III) ions. Chemosphere 287 (Pt3), 132271. https://doi.org/10.1016/j.chemosphere.2021.132271.
Noah, N.M., Ndangili, P.M., 2022. Green synthesis of nanomaterials from sustainable materials for biosensors and drug delivery. Sens. Int. 3, 100166. https://doi.org/10.1016/j.sintl.2022.100166.
Omar, N.A.S., Fen, Y.W., Abdullah, J., Kamil, Y.M., Daniyal, W.M.E.M.M., Sadrolhosseini, A.R., Mahdi, M.A., 2020. Sensitive detection of dengue virus type 2 E-protein signals using self-assembled monolayer/reduced graphene oxide-PAMAM dendrimer thin-film SPR optical sensor. Sci. Rep. 10 (1), 2374. https://doi.org/10.1038/s41598-020-59388-3.
Öztürk, D., Durmuş, M., 2025. N-doped carbon quantum dot-based ratiometric fluorescent nanosensor platforms for the detection of gastric cancer-associated *Helicobacter pylori* genes. Mikrochim. Acta 192 (3), 147. https://doi.org/10.1007/s00604-025-07004-4.
Parlak, O., İncel, A., Uzun, L., Turner, A.P.F., Tiwari, A., 2017. Structure of Au nanoparticles on two-dimensional MoS_2 nanosheets for electrochemical glucose biosensors. Biosens. Bioelectron. 89 (Pt 1), 545–550. https://doi.org/10.1016/j.bios.2016.03.024.
Pham, T.N., Xuan, D.N., Van, T.H., Khanh, V.L., Minh, T.L., Nguyen, V.Q., Vu, D.L., Le, A. T., 2021. Insight into the influence of the analyte molecular structure targeted on MoS_2-GO-coated electrochemical nanosensors. Langmuir 37 (41), 12059–12070. https://doi.org/10.1021/acs.langmuir.1c01853.
Plekhanova, Y., Tarasov, S., Bykov, A., Prisyazhnaya, N., Kolesov, V., Sigaev, V., Signore, M.A., Reshetilov, A., 2019. Multiwalled carbon nanotubes and the electrocatalytic activity of *Gluconobacter oxydans* were used as the basis of a biosensor. Biosensors 9 (4), 137. https://doi.org/10.3390/bios9040137.
Pohanka, M., 2025. Piezoelectric chemosensors and biosensors in medical diagnostics. Biosensors 15 (3), 197. https://doi.org/10.3390/bios15030197.
Praharaj, C., Saloni, Patel, G.K., Nara, S., 2025. Plant biomass-derived nanomaterials for biosensing and bioimaging applications. Ind. Crops Prod. 230, 121074. https://doi.org/10.1016/j.indcrop.2025.121074.
Praseptiangga, D., Zahara, H.L., Widjanarko, P.I., Joni, I., Panatarani, C., 2020. Preparation and FTIR spectroscopic studies of SiO2-ZnO nanoparticles suspensions for the development of carrageenan-based bio-nanocomposite films. In AIP Conf. Proc. 2219 (1). AIP Publishing. https://doi.org/10.1063/5.0003434.
Preechaburana, P., Gonzalez, M., Suska, A., Filippini, D., 2012. Surface plasmon resonance chemical sensing on cell phones. Angew. Chem. Int. Ed. 51 (46), 11585–11588. https://doi.org/10.1002/anie.201206804.
Pur, M.R.K., Hosseini, M., Faridbod, F., Ganjali, M.R., 2017. Highly sensitive label-free electrochemiluminescence aptasensor for the early detection of myoglobin, a biomarker of myocardial infarction. Microchim. Acta 184, 3529–3537. https://doi.org/10.1007/s00604-017-2385-y.
Qian, Z.S., Shan, X.Y., Chai, L.J., Chen, J.R., Feng, H., 2015. A fluorescent nanosensor based on a graphene quantum dot–aptamer probe and graphene oxide platform for the detection of lead (II) ions. Biosens. Bioelectron. 68, 225–231. https://doi.org/10.1016/j.bios.2014.12.057.
Qu, S., Wang, X., Lu, Q., Liu, X., Wang, L., 2012. Biocompatible fluorescent ink based on water-soluble luminescent carbon nanodots. Angew. Chem. 51 (49), 12215–12218. https://doi.org/10.1002/anie.201206791.
Quesada-González, D., Merkoçi, A., 2018. Nanomaterial-based devices for point-of-care diagnostic applications. Chem. Soc. Rev. 47, 4697–4709. https://doi.org/10.1039/C7CS00837F.
Radnik, J., Kersting, R., Hagenhoff, B., Bennet, F., Ciornii, D., Nymark, P., Grafström, R., Hodoroaba, V.D., 2021. Reliable surface analysis data of nanomaterials to support risk assessment based on minimum information requirements. Nanomaterials 11 (3), 639. https://doi.org/10.3390/nano11030639.
Rahman, M.A., Pal, R.K., Islam, N., Freeman, R., Berthiaume, F., Mazzeo, A., Ashraf, A., 2023. A facile graphene conductive polymer paper-based biosensor for the detection of dopamine. TNF-α, and IL-6. Sensors 23 (19), 8115. https://doi.org/10.3390/s23198115.
Ramesh, M., Janani, R., Deepa, C., Rajeshkumar, L., 2023. Nanotechnology-enabled biosensors: a review of fundamentals, design principles, materials, and applications. Biosensors 13 (1), 40. https://doi.org/10.3390/bios13010040.
Rana, K., Mittal, J., Narang, J., Mishra, A., Pudake, R.N., 2021. Graphene-based electrochemical DNA biosensor for detection of false smut of rice (*Ustilaginoidea virens*). Plant Pathol. J. 37, 291–298. https://doi.org/10.5423/PPJ.OA.11.2020.0207.
Rautela, A., Rani, J., 2019. Green synthesis of silver nanoparticles from *Tectona grandis* seed extract: characterization and mechanism of antimicrobial action on different microorganisms. J. Anal. Sci. Technol. 10 (1), 1–10. https://doi.org/10.1186/s40543-018-0163-z.
Reinhard, I., Miller, K., Diepenheim, G., Cantrell, K., Hall, W.P., 2020. Nanoparticle design rules for colorimetric plasmonic sensors. ACS Appl. Nano Mat. 3 (5), 4342–4350. https://doi.org/10.1021/acsanm.0c00475.
Sadeghi, S., Rahaie, M., 2022. Design and fabrication of a DNA-copper nanocluster-based biosensor for the multiple detection of circulating miRNAs in early screening of breast cancer. J. Fluor. 32 (6), 2297–2307. https://doi.org/10.1007/s10895-022-03023-z.
Sagadevan, S., Koteeswari, P., 2015. Analysis of the structure, surface morphology, and optical and electrical properties of copper nanoparticles. J. Nanomed. Res. 2 (5), 00040–00048. https://doi.org/10.15406/jnmr.2015.02.00040.
Sahu, Y., Patel, R., Singh, A.K., Singh, S., Sahu, V., Susan, M.A.B.H., 2025. Highly fluorescent ZnO composite of N-doped carbon dots from *Dregea volubilis* for fluorometric determination of glucose in biological samples. J. Fluor. 35 (2), 805–818. https://doi.org/10.1007/s10895-023-03538-z.
Saithongdee, A., Praphairaksit, N., Imyim, A., 2014. Electrospun curcumin-loaded zein membranes for iron(III) ion sensing. Sens. Actuators B Chem. 202, 935–940. https://doi.org/10.1016/j.snb.2014.06.036.
Salman, B.I., 2023. Green microwave quantum dots as luminescent probes for quantifying prucalopride: Consistency of content and application to pharmacokinetic studies. BMC Chem. 17 (1), 83. https://doi.org/10.1186/s13065-023-01002-4.
Sanad, M.F., Chava, V.S.N., Shalan, A.E., Enriquez, L.G., Zheng, T., Pilla, S., Sreenivasan, S.T., 2021. Engineering of electron affinity and interfacial charge transfer of graphene for self-powered nonenzymatic biosensor applications. ACS Appl. Mater. Inter. 13 (34), 40731–40741. https://doi.org/10.1021/acsami.1c12423.
Sánchez-Vicente, C., Santos, J.P., Lozano, J., Sayago, I., Sanjurjo, J.L., Azabal, A., Ruiz-Valdepeñas, S., 2020. Graphene-doped tin oxide nanofibers and nanoribbons have been used as gas. Sens. Detect Biomark. Differ. Dis. Breath. Sens. 20 (24), 7223. https://doi.org/10.3390/s20247223.
Santiago, A.M., Santos, C.I.M., Lourenço, L.M.O., Mariz, I.F.A., Tomé, J.P.C., Maçôas, E., 2022. Graphene quantum dots and phthalocyanines Turn-OFF-ON photoluminescence nanosensor for ds-DNA. Nanomaterials 12 (11), 1892. https://doi.org/10.3390/nano12111892.
Santopolo, G., Doménech-Sánchez, A., Russell, S.M., de la Rica, R., 2019. Ultra-fast and ultrasensitive naked-eye detection of urease-positive bacteria using plasmonic nanosensors. ACS Sens 4 (4), 961–967. https://doi.org/10.1021/acssensors.9b00063.
Sarkar, N., Sharma, R.S., Kaushik, M., 2020. Green synthesis and physiochemical characterization of nickel oxide nanoparticles: Interaction studies with calf thymus DNA. Luminescence 35 (2), 178–186. https://doi.org/10.1002/bio.3709.
Sarmanova, O.E., Laptinskiy, K.A., Burikov, S.A., Chugreeva, G.N., Dolenko, T.A., 2023. Implementing a neural network approach to create carbon-based optical nanosensor for heavy metal ions in liquid media. Spectrochim. Acta A Mol. Biomol. Spectrosc 286, 122003. https://doi.org/10.1016/j.saa.2022.122003.
Savk, A., Özdil, B., Demirkan, B., Nas, M.S., Calimli, M.H., Alma, M.H., Inamuddin, A.M., Şen, F., 2019. Multi-walled carbon nanotube-based nanosensor for ultrasensitive detection of uric acid, dopamine, and ascorbic acid. Mater. Sci. Eng. C. Mater. Biol. Appl. 99, 248–254. https://doi.org/10.1016/j.msec.2019.01.113.
Selvanathan, V., Islam, M.A., Kiong, T.S., Razali, S.A., Alharbi, H.F., Akhtaruzzaman, M., 2024. *Aloe vera* extract-assisted sol-gel synthesis of NiOx nanopyramids for supercapacitor application. Ceram. Int. 50 (7), 10843–10853. https://doi.org/10.1016/j.ceramint.2023.12.400.
Selvanathan, V., Shahinuzzaman, M., Selvanathan, S., Sarkar, D.K., Algethami, N., Alkhammash, H.I., Akhtaruzzaman, M., 2021. Phytochemical-assisted green synthesis of nickel oxide nanoparticles for application as electrocatalysts in the oxygen evolution reaction. Catalysts 11 (12), 1523. https://doi.org/10.3390/catal11121523.

Sen, S., Sarkar, P., 2024. Impedance nanobiosensor based on enzyme-conjugated biosynthesized gold nanoparticles for the detection of gram-positive bacteria. Biotechnol. Prog. 40 (2), e3421. https://doi.org/10.1002/btpr.3421.

Seth, A., Devi, E., Thakur, K., Attri, C., Singh, V., Bhandari, A., Seth, M.K., 2022. Himalayan fern cheilanthes bicolor-mediated fabrication and characterization of iron nanoparticles with antimicrobial potential. BioNanoScience 12 (2), 486–495. https://doi.org/10.1007/s12668-022-00969-z.

Sha, T., Liu, J., Sun, M., Li, L., Bai, J., Hu, Z., Zhou, M., 2019. Green and low-cost synthesis of nitrogen-doped graphene-like mesoporous nanosheets from okara biomass waste for amperometric detection of vitamin C in real samples. Talanta 200, 300–306. https://doi.org/10.1016/j.talanta.2019.03.071.

Shaibani, P.M., Etayash, H., Jiang, K., Sohrabi, A., Hassanpourfard, M., Naicker, S., Sadrzadeh, M., Thundat, T., 2018. Portable nanofiber-light-addressable potentiometric sensor for rapid *Escherichia coli* detection in orange juice. ACS Sens 3, 815–822. https://doi.org/10.1021/acssensors.8b00063.

Sharma, M., Mahajan, P., Alsubaie, A.S., Khanna, V., Chahal, S., Thakur, A., Singh, G., 2024. Next-generation nanomaterial-based biosensors: real-time biosensing devices for detecting emerging environmental pollutants. Mater. Today Sustain, 101068. https://doi.org/10.1016/j.mtsust.2024.101068.

Sharma, M., Mahajan, P., Alsubaie, A.S., Khanna, V., Chahal, S., Thakur, A., Singh, G., 2025. Next-generation nanomaterials-based biosensors: real-time biosensing devices for detecting emerging environmental pollutants. Mater. Today Sustain 29, 101068. https://doi.org/10.1016/j.mtsust.2024.101068.

Sharma, A., Thakur, M., Bhattacharya, M., Mandal, T., Goswami, S., 2019. Commercial applications of cellulose nano-composites: A review. Biotech. Rep. 21, e00316. https://doi.org/10.1016/j.btre.2019.e00316.

Shelby, T., Sulthana, S., McAfee, J., Banerjee, T., Santra, S., 2017. Foodborne pathogen screening using magneto-fluorescent nanosensor: rapid detection of *E. coli* O157:H7. J. Vis. Exp. 2017 (127), 55821. https://doi.org/10.3791/55821.

Shoaib, M., Naz, A., Osra, F.A., Abro, S.H., Qazi, S.U., Siddiqui, F.A., Mirza, A.Z., 2021. Green synthesis and characterization of silver-entecavir nanoparticles with stability determination. Arab. J. Chem. 14 (3), 102974. https://doi.org/10.1016/j.arabjc.2020.102974.

Silva, H.M.D., Mageste, A.B., Silva, S.J.B.E., Dias Ferreira, G.M., Ferreira, G.M., 2020. Anthocyanin immobilization in carboxymethylcellulose/starch films: a sustainable sensor for the detection of Al(III) ions in aqueous matrices. Carbohydr. Polym. 230, 115679. https://doi.org/10.1016/j.carbpol.2019.115679.

Singh, A., Sharma, A., Singh, O., Rajput, V.D., Movsesyan, H., Minkina, T., Alexiou, A., Papadakis, M., Singh, R.K., Singh, S., Sousa, J.R., El-Ramady, H.R., Zulfiqar, F., Kumar, R., Al-Ghamdi, A.A., Ghazaryan, K., 2024. In-depth exploration of nanoparticles for enhanced nutrient use efficiency and abiotic stresses management: present insights and future horizons. Plant Stress 14, 100576. https://doi.org/10.1016/j.stress.2024.100576.

Singh, H., Singh, S., Bhardwaj, S.K., Kaur, G., Khunk, M., Deep, A., Bhardwaj, N., 2022. Development of a carbon quantum dot-based lateral flow immunoassay for the sensitive detection of aflatoxin M1 in milk. Food Chem. 393, 133374. https://doi.org/10.1016/j.foodchem.2022.133374.

Sobhan, A., Jia, F., Kelso, L.C., Biswas, S.K., Muthukumarappan, K., Cao, C., Wei, L., Li, Y., 2022. Novel activated biochar-based immunosensor for the rapid detection of *E. coli* O157:H7. Biosensors 12 (10), 908. https://doi.org/10.3390/bios12100908.

Sobhan, A., Muthukumarappan, K., Cen, Z., Wei, L., 2019. Characterization of biosensing properties of nanocellulose and activated carbon nanocomposite films for smart packaging. Carbohydr. Polym. 225, 115189. https://doi.org/10.1016/j.carbpol.2019.115189.

Solangi, A.G., Tahira, A., Waryani, B., Chang, A.S., Pirzada, T., Nafady, A., Dawi, E.A., Saleem, L.M.A., Padervand, M., Haj Ismail, A.A.K., Lv, K., Vigolo, B., Ibupoto, Z.H., 2023. Green-mediated synthesis of $NiCo_2O_4$ nanostructures using radish white peel extract for sensitive and selective enzyme-free detection of uric acid. Biosensors 13 (8), 780. https://doi.org/10.3390/bios13080780.

Soni, M., Mehta, P., Soni, A., Goswami, G.K., 2018. Green nanoparticles: Synthesis and applications. IOSR J. Biotechnol. Biochem. 4, 78–83.

Sun, K., Ding, Z., Zhang, J., Chen, H., Qin, Y., Xu, S., Wu, C., Yu, J., Chiu, D.T., 2021. Enhancing the long-term stability of a polymer dot glucose transducer using an enzymatic cascade reaction system. Adv. Healthc. Mater. 10 (4), e2001019. https://doi.org/10.1002/adhm.202001019.

Sun, L., Li, C., Zhang, C., Liang, T., Zhao, Z., 2019. Strain transfer mechanism of fiber Bragg grating sensor for extra-large strain monitoring. Sensors 19 (8), 1851. https://doi.org/10.3390/s19081851.

Sun, Q., Yu, W., Gong, M., Ma, J., Liu, G., Mei, T., Luo, X., 2024. Xanthine oxidase-immobilized cellulose membrane-based colorimetric biosensor for screening and detecting bioactivity of xanthine oxidase inhibitors. Int. J. Biol. Macromol. 275 (Pt1), 133450. https://doi.org/10.1016/j.ijbiomac.2024.133450.

Sunil, N., Unnathpadi, R., Pullithadathil, B., 2024. Ag nanoisland-functionalized hollow carbon nanofibers are a non-invasive, label-free SERS salivary biosensor platform for salivary nitrite detection for the pre-diagnosis of oral cancer. Analyst 149 (17), 4443–4453. https://doi.org/10.1039/d4an00641k.

Tai, M.J.Y., Perumal, V., Gopinath, S.C.B., Raja, P.B., Ibrahim, M.N.M., Jantan, I.N., Suhaimi, N.S.H., Liu, W.W., 2021. Laser-scribed graphene nanofiber decorated with oil palm lignin-capped silver nanoparticles: A green biosensor. Sci. Rep. 11 (1), 5475. https://doi.org/10.1038/s41598-021-85039-2.

Tang, B., He, Y., Liu, J., Zhang, J., Li, J., Zhou, J., Wang, X., 2019. Kinetic investigation of the pH-dependent color of anthocyanin and its sensing performance. Dyes Pigments 170, 107643.

Teixeira, A., Paris, J.L., Roumani, F., Diéguez, L., Prado, M., Espiña, B., Abalde-Cela, S., Garrido-Maestu, A., Rodriguez-Lorenzo, L., 2020. Multifunctional gold nanoparticles for SERS detection of pathogens combined with a LAMP-in-microdroplet approach. Materials 13 (8), 1934. https://doi.org/10.3390/ma13081934.

Tiwari, H., Samal, K., Geed, S.R., Bera, S., Das, C., Mohanty, K., 2023. Green synthesis of silver nanoparticles for ultrafiltration membrane surface modification and antimicrobial activity. Sustain. Chem. Clim. Action 3, 100031.

Tortolini, C., Capecchi, E., Tasca, F., Pofi, R., Venneri, M.A., Saladino, R., Antiochia, R., 2021. Novel Nanoarchitectures based on lignin Nanoparticles for eco-friendly electrochemical biosensing development. Nanomaterials 11 (3), 718. https://doi.org/10.3390/nano11030718.

Trang, N.L.N., Nga, D.T.N., Hoang, V.T., Ngo, X.D., Nhung, P.T., Le, A.T., 2022. Bio-AgNP-based electrochemical nanosensors for the sensitive determination of 4-nitrophenol in tomato samples: The roles of natural plant extracts in physicochemical parameters and sensing performance. RSC Adv. 12 (10), 6007–6017. https://doi.org/10.1039/D1RA09202B.

Umar, A., Haque, M., Ansari, S.G., Seo, H.K., Ibrahim, A.A., Alhamami, M.A.M., Algadi, H., Ansari, Z.A., 2022. Label-free myoglobin biosensors based on pure and copper-doped titanium dioxide nanomaterials. Biosensors 12 (12), 1151. https://doi.org/10.3390/bios12121151.

Valenga, M.G.P., Martins, G., Martins, T.A.C., Didek, L.K., Gevaerd, A., Marcolino-Junior, L.H., Bergamini, M.F., 2022. Biochar: An environmentally friendly platform for the construction of a SARS-CoV-2 electrochemical immunosensor. Sci. Total Environ. 858 (Pt 2), 159797. https://doi.org/10.1016/j.scitotenv.2022.159797.

Vasireddy, R., Paul, R., Mitra, A.K., 2012. Green synthesis of silver nanoparticles and study of their optical properties. Nanomat. Nanotechnol. 2, 8.

Vasudevan, M., Perumal, V., Raja, P.B., Ibrahim, M.N.M., Lee, H.L., Gopinath, S.C.B., Ovinis, M., Karuppanan, S., Ang, P.C., Arumugam, N., Kumar, R.S., 2023. A quadruplet 3-D laser scribed graphene/MoS2, functionalized N2-doped graphene quantum dots, and lignin-based Ag-nanoparticles were used for biosensing. Int. J. Biol. Macromol. 253 (Pt2), 126620. https://doi.org/10.1016/j.ijbiomac.2023.126620.

Verma, D., Singh, K.R., Yadav, A.K., Nayak, V., Singh, J., Solanki, P.R., Singh, R.P., 2022. Internet of things (IoT) in nanointegrated wearable biosensor devices for healthcare applications. Biosens. Bioelectron. X 11, 100153.

Wadhwani, S.A., Shedbalkar, U.U., Singh, R., Karve, M.S., Chopade, B.A., 2014. Novel polyhedral gold nanoparticles: Green synthesis, optimization, and characterization by environmental isolates of *Acinetobacter* sp. SW30. World J. Microbiol. Biotechnol. 30 (10), 2723–2731. https://doi.org/10.1007/s11274-014-1696-y.

Wang, L., Wei, Q.S., Wu, C.S., Hu, Z.Y., Ji, J., Wang, P., 2008. The *Escherichia coli* O157: H7 DNA detection on a gold nanoparticle-enhanced piezoelectric biosensor. Chin. Sci. Bull. 53, 1175–1184. https://doi.org/10.1007/s11434-007-0529-x.

Wang, H., Xiu, Y., Chen, Y., Sun, L., Yang, L., Chen, H., Niu, X., 2019a. Electrochemical immunosensor based on antibody-hierarchical mesoporous SiO_2 for the detection of Staphylococcus aureus. RSC Adv. 9 (28), 16278–16287. https://doi.org/10.1039/c9ra00907h.

Wang, L., Zhang, Q., Chen, S., Xu, F., Chen, S., Jia, J., Tan, H., Hou, H., Song, Y., 2014a. Electrochemical sensing and biosensing platforms based on biomass-derived macroporous carbon materials. Anal. Chem. 86 (3), 1414–1421. https://doi.org/10.1021/ac401563m.

Wang, R.J., Zhang, L.W., Liu, R., Liu, L., Yao, J.M., 2019b. Ultra-fast and probe-free cellulose biosensors for visual detection of Cu^{2+} ions in biological samples. Carbohydr. Polym. 223, 115117. https://doi.org/10.1016/j.carbpol.2019.115117.

Wei, S., Dou, Y., Song, S., Li, T., 2023b. Functionalized-graphene field-effect transistor-based biosensor for ultrasensitive and label-free detection of β-galactosidase produced by *Escherichia coli*. Biosensors 13 (10), 925. https://doi.org/10.3390/bios13100925.

Wei, D., Liu, Q., Liu, Z., Liu, J., Zheng, X., Pei, Y., Tang, K., 2019. Modified nano-microfibrillated cellulose/carboxymethyl chitosan composite hydrogel with a giant network structure and quick gelation ability. Int. J. Biol. Macromol. 135, 561–568. https://doi.org/10.1016/j.ijbiomac.2019.05.091.

Wei, Q., Wu, L., Zhu, M., Wang, Z., Huang, Z.H., Wang, M.X., 2023a. Porous nitrogen-doped reduced graphene oxide-supported CuO@Cu_2O hybrid electrodes for highly sensitive enzyme-free glucose biosensor. S. Isc. 26 (3), 106155. https://doi.org/10.1016/j.isci.2023.106155.

Wei, Q., Zhang, P., Liu, T., Pu, H., Sun, D.W., 2021. Fluorescence biosensors based on single-stranded DNA and carbon quantum dots for acrylamide detection. Food Chem. 356, 129668. https://doi.org/10.1016/j.foodchem.2021.129668.

Wen, C.Y., Liang, X., Liu, J., Zhao, T.Y., Li, X., Zhang, Y., Guo, G., Zhang, Z., Zeng, J., 2023. An achromatic colorimetric nanosensor for the sensitive detection of multiple pathogens by coupling plasmonic nanoparticles with magnetic separation. Talanta 256, 124271. https://doi.org/10.1016/j.talanta.2023.124271.

Williams, H., 2021. SEM for conductive and nonconductive specimens. Phys. Educ. 56, 055034. https://doi.org/10.1088/1361-6552/ac1503.

Xi, X., Wu, Z., Zhang, X., Li, Y., Zhao, Y., Wen, W., Wang, S., 2023. Endogenous protease-activatable nanosensor based on PNA-peptide-DNA engineering for AND-gated and dual-model detection of microRNAs in single living tumor cells. ACS Appl. Mater. Inter. 15 (18), 21917–21928. https://doi.org/10.1021/acsami.3c02012.

Xiao, Z., Cheng, B., Wang, C., Wang, Z., 2020. High stability and strong fluorescence of carbon Nanodots as Nanosensor for Hg^{2+} in environmental water. Bull. Environ. Contam. Toxicol. 104 (1), 57–63. https://doi.org/10.1007/s00128-019-02753-4.

Xu, C., Li, G., Zhou, M., Hu, Z., 2022. Coral-like hierarchical meso-macroporous carbon nanorods were assembled as sustainable materials for efficient biosensing and biofuel cells. Anal. Chim. Acta 1220, 339994. https://doi.org/10.1016/j.aca.2022.339994.

Xu, Y., Zhou, Y., Li, R., 2016. Colorimetric fluorescent nanosensor based on hexamethylene diisocyanate for fluorescent response and adsorption of heavy metal

ions. J. Nanosci. Nanotechnol. 16 (3), 2853–2860. https://doi.org/10.1166/jnn.2016.10779.
Xuan, Y., Li, X., Yan, C., Wang, G., 2023. Fluorescence off-on nanosensor based on MoS2 nanosheets and oligonucleotides for the alternative detection of mercury(II) or silver (I) ions. Spectrochim. Acta A Mol. Biomol. Spectrosc. 293, 122479. https://doi.org/10.1016/j.saa.2023.122479.
Yan, B., Li, B., Wen, Z., Luo, X., Xue, L., Li, L., 2015. Label-free blood serum detection using surface-enhanced Raman spectroscopy and a support vector machine for the preoperative diagnosis of parotid gland tumors. BMC Cancer 15, 650. https://doi.org/10.1186/s12885-015-1653-7.
Yang, J., Li, W., Guo, L., Luo, F., Qiu, B., Lin, Z., Wang, L., 2022a. Highly sensitive photoelectrochemical biosensor for MicroRNA-21 based on a dumbbell-shaped heterostructure AuNRs@end-TiO_2 combined with carbon dots as photosensitizers and duplex-specific nuclease-assisted signal amplification. Anal. Chem. 94 (39), 13575–13581. https://doi.org/10.1021/acs.analchem.2c03230.
Yang, Q., Rosati, G., Abarintos, V., Aroca, M.A., Osma, J.F., Merkoçi, A., 2022. Wearable and fully printed microfluidic nanosensor for sweat rate, conductivity, and copper detection in healthcare applications. Biosens. Bioelectron. 202, 114005. https://doi.org/10.1016/j.bios.2022.114005.
Yasmeen, G., Hussain, S., Tajammal, A., Mustafa, Z., Sagir, M., Shahid, M., Iqbal, M., 2023. Green synthesis of Cr_2O_3 nanoparticles by *Cassia fistula* and their electrochemical and antibacterial potential. Arab. J. Chem. 16 (8), 104912. https://doi.org/10.1016/j.arabjc.2023.104912.
Ye, W., Yu, M., Wang, F., Li, Y., Wang, C., 2022. Multiplexed detection of heavy-metal ions using single plasmonic nanosensors. Biosens. Bioelectron. 196, 113688. https://doi.org/10.1016/j.bios.2021.113688.
Yin, M., Wu, C., Li, H., Jia, Z., Deng, Q., Wang, S., Zhang, Y., 2019. Simultaneous sensing of seven pathogenic bacteria using guanidine-functionalized up-conversion fluorescent nanoparticles. ACS Omega 4 (5), 8953–8959. https://doi.org/10.1021/acsomega.9b00775.
Yu, Y., Zhu, Q., Xiang, F., Hu, Y., Zhang, L., Xu, X., Huang, S., 2020. AuNP/SWCNT was used to fabricate an electrical nanogap device for DNA hybridization detection. Carbon 157, 40–46. https://doi.org/10.1016/j.carbon.2019.10.017.
Yuan, C., Lou, Z., Wang, W., Yang, L., Li, Y., 2019. Synthesis of Fe_3C@C from pyrolysis of Fe_3O_4-lignin clusters and its application for quick and sensitive detection of PrPSc through a sandwich SPR detection assay. Int. J. Mol. Sci. 20 (3), 741. https://doi.org/10.3390/ijms20030741.
Yuan, W., Yuan, H., Li, R., Yong, R., Mitrovic, I., Lim, E.G., Duan, S., Song, P., 2024. SERS nanocellulose-paper-based analytical device for ultrasensitive detection of Alzheimer's disease. Anal. Chim. Acta 1301, 342447. https://doi.org/10.1016/j.aca.2024.342447.
Zare, H., Meshkat, Z., Hatamluyi, B., Rezayi, M., Ghazvini, K., Derakhshan, M., Sankian, M., Neshani, A., Aryan, E., 2022. This is the first diagnostic test for the specific detection of *Mycobacterium simiae* using an electrochemical label-free DNA nanobiosensor. Talanta 238, 123049. https://doi.org/10.1016/j.talanta.2021.123049.
Zhan, F., Wang, T., Iradukunda, L., Zhan, J., 2018. A gold nanoparticle-based lateral flow biosensor for sensitive visual detection of the potato late blight pathogen *Phytophthora infestans*. Anal. Chim. Acta 1036, 153–161.
Zhang, X., Chen, W., Wan, S., Qu, B., Liao, F., Cheng, D., Zhang, Y., Ding, Z., Yang, Y., Yuan, Q., 2025b. Spatially selective miRNA imaging in human colorectal cancer tissues using a multivariate-gated signal amplification nanosensor. J. Am. Chem. Soc. 147 (8), 6679–6687. https://doi.org/10.1021/jacs.4c16001.
Zhang, S., Geryak, R., Geldmeier, J., Kim, S., Tsukruk, V.V., 2017. Synthesis, assembly, and application of hybrid nanostructures for biosensing. Chem. Rev. 117 (20), 12942–13038. https://doi.org/10.1021/acs.chemrev.7b00088.
Zhang, L., Guo, Y., Hao, R., Shi, Y., You, H., Nan, H., Dai, Y., Liu, D., Lei, D., Fang, J., 2021b. Ultra-rapid and highly efficient enrichment of organic pollutants via magnetic mesoporous nanosponges for ultrasensitive nanosensors. Nat. Commun. 12 (1), 6849. https://doi.org/10.1038/s41467-021-27100-2.
Zhang, H., Li, X., Zhou, X., Zhang, Y., Zhao, Y., 2024. A lipase-conjugated carbon nanotube fiber-optic SPR sensor for the sensitive and specific detection of tributyrin. Nanoscale 16 (6), 3113–3120. https://doi.org/10.1039/d3nr05129c.
Zhang, R.R., Ran, X.Y., Yu, K.K., Zhao, Y., Zhang, L.N., Lv, X.F., Zhang, H., Yu, X.Q., Li, K., 2025a. Rational design of an NIR-II fluorescence/photoacoustic nanosensor tailored for mechanisms of diabetes-related breast cancer. Adv. Mater. 37 (8), e2415891. https://doi.org/10.1002/adma.202415891.
Zhang, W., Zhang, H., Wang, M., Li, P., Ding, C., Zhang, W., Wang, H., Tang, B., 2020. Copolymer-based fluorescence nanosensor for in situ imaging of homocysteine in the livers and kidneys of diabetic mice. Anal. Chem. 92 (24), 16221–16228. https://doi.org/10.1021/acs.analchem.0c04068.
Zhang, K., Zhuo, Z., Fan, G., Wang, Z., Chen, S., Xu, L., Wen, Y., Wang, P., 2021a. Nano-ZnS decorated hierarchically porous carbon electrocatalysts with multiple enzyme-like activities were used as a nanozyme sensing platform for the simultaneous detection of dopamine, uric acid, guanine, and adenine. Nanoscale 13 (47), 20078–20090. https://doi.org/10.1039/d1nr06017a.
Zhao, Z., Lu, P., Lam, J.W.Y., Wang, Z., Chan, C.Y.K., Sung, H.H.Y., Williams, I.D., Ma, Y., Tang, B.Z., 2011. Molecular anchors in the solid state: the restriction of intramolecular rotation increases the emission efficiency of luminogen aggregates to unity. Chem. Sci. 2, 672–675. https://doi.org/10.1039/C0SC00521E.
Zhao, N., Zhang, H., Yang, S., Sun, Y., Zhao, G., Fan, W., Yan, Z., Lin, J., Wan, C., 2023. Direct induction of porous graphene from mechanically strong and waterproof biopaper for on-chip multifunctional flexible electronics. Small 19 (43), e2300242. https://doi.org/10.1002/smll.202300242.
Zheng, H., Han, X., Wei, Q., Liu, X., Li, Y., Zhou, J., 2022. A green, flexible, and wearable biosensor based on carbon nanofibers for the sensitive detection of uric acid in artificial urine. J. Mater. Chem. B. 10 (41), 8450–8461. https://doi.org/10.1039/D2TB01547A.
Zhong, Y., Huang, L.X., Lin, M.T., Zhang, Z.Y., Liu, A.L., Lei, Y.A., 2023. Y-shape-structured electrochemiluminescence biosensors based on carbon quantum dots and locked nucleic acid probes for microRNA determination with single-base resolution. Biosens. Bioelectron. 238, 115583. https://doi.org/10.1016/j.bios.2023.115583.
Zhou, Y., Chen, Q., Huang, G., Huang, S., Lin, C., Lin, X., Xie, Z., 2024. Oriented aptamer-encoded magnetic nanosensor with laser-induced fluorescence for ultrasensitive testing of okadaic acid. Talanta 266 (Pt 1), 124984. https://doi.org/10.1016/j.talanta.2023.124984.
Zhou, Y., Li, M., Wang, H., Sun, S., 2022. Dual-signal amplified electrochemical biosensor based on eATRP and PEI for early detection of lung cancer. Bioelectrochem 148, 108224. https://doi.org/10.1016/j.bioelechem.2022.108224.
Zhou, W., Ma, Y., Yang, H., Ding, Y., Luo, X., 2011. A label-free biosensor based on silver nanoparticles array for clinical detection of serum p53 in head and neck squamous cell carcinoma. Int. J. Nanomed. 6 381–386. https://doi.org/10.2147/IJN.S13249.
Zhu, Z., 2017. An overview of carbon nanotubes and graphene for biosensing applications. NanoMicro Lett. 9, 25. https://doi.org/10.1007/s40820-017-0128-6.
Zhu, C., Kang, S., Wu, S., Sun, Q., Zhang, Z., Hu, J., Liu, J., Li, C., Wang, F., 2024a. Self-reporting nanosensor for detecting bacterial exploitation in plants using extracellular DNA. Nano Lett. 24 (48), 15464–15472. https://doi.org/10.1021/acs.nanolett.4c05168.
Zhu, L., Li, D., Lu, H., Zhang, S., Gao, H., 2022. Lignin-based fluorescence-switchable graphene quantum dots for Fe_3^+ and ascorbic acid detection. Int. J. Biol. Macromol. 194, 254–263. https://doi.org/10.1016/j.ijbiomac.2021.11.199.
Zhu, J., Wang, X., Chen, M., Wu, P., Kim, M.J., 2019. Integration of BIM and GIS. IFC Geom. Transform. shapefile Using Enhanc. OpenSource Approach Auto. Constr. 106, 102859. https://doi.org/10.1016/j.autcon.2019.102859.
Zhu, X., Xiang, Q., Chen, L., Chen, J., Wang, L., Jiang, N., Hao, X., Zhang, H., Wang, X., Li, Y., Omer, R., Zhang, L., Wang, Y., Zhuang, Y., Huang, J., 2024b. Engineered *Bacillus subtilis* Biofilm@Biochar living materials for in situ sensing and bioremediation of heavy metal ion pollution. J. Hazard Mater. 465, 133119. https://doi.org/10.1016/j.jhazmat.2023.133119.
Zopf, D., Pittner, A., Dathe, A., Grosse, N., Csáki, A., Arstila, K., Toppari, J.J., Schott, W., Dontsov, D., Uhlrich, G., Fritzsche, W., Stranik, O., 2019. Plasmonic nanosensor array for multiplexed DNA-based pathogen detection. ACS Sens 4 (2), 335–343. https://doi.org/10.1021/acssensors.8b01073.
Zubkovs, V., Schuergers, N., Lambert, B., Ahunbay, E., Boghossian, A.A., Mediatorless, 2017. Reversible optical nanosensor enabled by enzymatic pocket doping. Small 13 (42). https://doi.org/10.1002/smll.201701654.
Zuhrotun, A., Oktaviani, D.J., Hasanah, A.N., 2023. Biosynthesis of AuNPs and silver nanoparticles using phytochemicals. Molecules 28 (7), 3240. https://doi.org/10.3390/molecules28073240.