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Review Article

Nanotechnology-Based Biosensors for Infectious Disease Detection: A Narrative Review

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ABSTRACT

Background: Infectious diseases remain a major global health burden, particularly in resource-limited settings where delayed diagnosis contributes to poor clinical outcomes, continued transmission, and ineffective outbreak control. Conventional diagnostic methods such as culture, enzyme-linked immunosorbent assay, polymerase chain reaction, and serological testing are reliable but often require specialized infrastructure, trained personnel, longer turnaround times, and higher operational costs. Nanotechnology-based biosensors have emerged as promising diagnostic tools because nanoscale materials can enhance signal amplification, target recognition, sensitivity, portability, and suitability for point-of-care testing. **Objective:** This narrative review aimed to synthesize current and foundational evidence on nanotechnology-based biosensors for infectious disease detection, focusing on nanomaterial classes, biosensor mechanisms, disease-specific applications, diagnostic advantages, and translational challenges. **Methods:** A narrative literature search was conducted using PubMed, Google Scholar, ScienceDirect, and IEEE Xplore. Peer-reviewed studies published primarily between 2018 and 2023 were prioritized, with selected earlier foundational studies included when directly relevant to biosensor development or nanomaterial-enabled infectious disease diagnostics. Evidence was synthesized thematically according to biosensor platform, nanomaterial type, target pathogen, diagnostic application, and implementation barriers. **Results:** Thirty-five studies were synthesized. Electrochemical, optical, fluorescence-based, colorimetric, surface plasmon resonance, field-effect transistor, magnetic, piezoelectric, and CRISPR-assisted biosensors were identified across applications including COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis, influenza, Zika virus infection, Salmonella, and Escherichia coli. Gold nanoparticles, graphene, graphene oxide, carbon nanotubes, quantum dots, magnetic nanoparticles, silver nanoparticles, nanowires, and gold nanorods enhanced biosensor performance through improved conductivity, fluorescence, plasmonic response, magnetic enrichment, and biomolecular immobilization. **Conclusion:** Nanotechnology-based biosensors show strong potential for rapid, sensitive, portable, and multiplexed infectious disease detection. Their clinical translation requires standardized validation, reproducible fabrication, biosafety evaluation, scalable manufacturing, regulatory approval, and real-world point-of-care assessment. **Keywords:** Nanotechnology; Biosensors; Infectious Disease Detection; Nanomaterials; Point-of-Care Testing; Electrochemical Biosensors; Gold Nanoparticles; Molecular Diagnostics.

INTRODUCTION

Infectious diseases remain a persistent cause of morbidity, mortality, and health-system strain worldwide, particularly in low- and middle-income settings where timely access to accurate diagnostic services is often limited (1). Viral, bacterial, parasitic, and fungal infections such as COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis, influenza, and foodborne bacterial infections continue to challenge public health systems through delayed case recognition, ongoing transmission, antimicrobial resistance, and recurrent outbreaks. Early diagnosis is therefore central not only to individual patient management but also to infection control, surveillance, outbreak containment, and rational antimicrobial use (2).

Conventional diagnostic approaches, including microbial culture, enzyme-linked immunosorbent assay, polymerase chain reaction, and other nucleic acid amplification or serological methods, remain essential in clinical microbiology because of their established analytical validity and diagnostic reliability.

However, these methods often require centralized laboratory infrastructure, skilled personnel, cold-chain-dependent reagents, prolonged turnaround times, and relatively high operational costs (3). Culture-based methods may require days to yield actionable results, whereas molecular tests, although faster and highly sensitive, may be difficult to deploy at scale in field conditions or resource-constrained health systems. These limitations have intensified the demand for diagnostic platforms that are rapid, sensitive, specific, affordable, portable, and suitable for point-of-care use (4).

Nanotechnology-based biosensors have emerged as a promising response to these diagnostic needs. Biosensors combine a biological recognition element, such as an antibody, aptamer, nucleic acid probe, enzyme, or receptor, with a transducer capable of converting a target-binding event into a measurable signal. When nanomaterials are incorporated into biosensing platforms, they can enhance diagnostic performance through high surface-area-to-volume ratios, improved electron transfer, tunable optical behavior, magnetic responsiveness, catalytic activity, and efficient surface functionalization. Gold nanoparticles, silver nanoparticles, graphene and graphene oxide, carbon nanotubes, quantum dots, magnetic nanoparticles, nanowires, and other nanoscale materials have therefore been widely investigated for infectious disease detection across electrochemical, optical, fluorescence-based, surface plasmon resonance, field-effect transistor, piezoelectric, and colorimetric platforms (5,6).

The diagnostic appeal of nanotechnology-enabled biosensors lies in their ability to detect low concentrations of pathogen-derived nucleic acids, antigens, antibodies, metabolites, or whole organisms using small sample volumes and shortened assay times. During the COVID-19 pandemic, for example, plasmonic, graphene-based, CRISPR-assisted, and colorimetric nanobiosensors were investigated as alternatives or complements to laboratory-based RT-PCR testing (1–6). Similar approaches have been explored for tuberculosis DNA detection, HIV p24 antigen identification, malaria biomarker detection, dengue virus antigen or RNA detection, hepatitis virus monitoring, influenza typing, Zika virus surveillance, and bacterial pathogen detection in clinical and food-safety contexts (7,8). These platforms suggest a broad technological shift from centralized, equipment-intensive diagnostics toward miniaturized, portable, and potentially multiplexed systems capable of supporting decentralized care.

Despite this promise, the evidence base for nanotechnology-based biosensors remains heterogeneous. Many reported platforms demonstrate excellent analytical performance under controlled laboratory conditions, yet fewer have progressed through large-scale clinical validation, regulatory evaluation, manufacturing standardization, or implementation in real-world point-of-care settings. Important translational barriers include reproducibility of nanomaterial synthesis, batch-to-batch variability, sensor stability, biocompatibility and toxicity concerns, matrix effects in complex clinical samples, lack of standardized performance benchmarks, cost of scalable production, and uncertain pathways for regulatory approval (9,10). As a result, the field requires not only technological innovation but also integrated synthesis that distinguishes proof-of-concept performance from clinically deployable diagnostic value.

Several reviews have addressed biosensors, nanomaterials, or pathogen detection individually; however, a focused narrative synthesis remains valuable because the field is rapidly evolving across multiple disease categories, nanomaterial classes, and sensing modalities (11,12). A narrative approach is particularly appropriate for integrating diverse experimental, technological, and translational evidence where formal pooling is not feasible because of variation in pathogens, targets, sample types, biosensor architectures, outcome measures, and validation standards (13). Such a synthesis can clarify how different nanomaterials contribute to biosensor function, which infectious disease applications are most developed, and what methodological and implementation gaps must be addressed before these technologies can be adopted more widely.

Therefore, this narrative review aims to synthesize current and foundational evidence on nanotechnology-based biosensors for infectious disease detection. Specifically, it examines major nanomaterial classes, biosensing mechanisms, disease-specific diagnostic applications, comparative

advantages over conventional diagnostic methods, and key barriers to clinical and point-of-care translation. By organizing the evidence around diagnostic platforms, pathogen targets, and translational challenges, this review seeks to provide a balanced overview of the potential and limitations of nano biosensors as next-generation tools for infectious disease diagnosis.

MATERIALS AND METHODS

This study was designed as a narrative review to synthesize evidence on the role of nanotechnology-based biosensors in infectious disease detection. A narrative approach was selected because the available literature spans diverse pathogens, nanomaterial classes, biosensor architectures, sample types, analytical targets, and validation stages, making formal quantitative pooling inappropriate. The review focused on biosensors incorporating nanoscale materials for the detection of viral, bacterial, parasitic, and other clinically relevant infectious agents, with emphasis on diagnostic principles, disease-specific applications, advantages, limitations, and translational barriers.

A literature search was conducted using PubMed, Google Scholar, ScienceDirect, and IEEE Xplore. The search prioritized peer-reviewed articles published between 2018 and 2023, while selected earlier foundational studies were included when they introduced widely cited biosensor platforms, nanomaterial applications, or diagnostic principles directly relevant to infectious disease detection. Search terms were used individually and in combination, including “nanotechnology-based biosensors,” “nanobiosensors,” “infectious disease detection,” “point-of-care diagnostics,” “electrochemical biosensors,” “optical biosensors,” “surface plasmon resonance,” “field-effect transistor biosensor,” “graphene biosensor,” “gold nanoparticles,” “silver nanoparticles,” “carbon nanotubes,” “quantum dots,” “magnetic nanoparticles,” “COVID-19,” “tuberculosis,” “HIV,” “malaria,” “dengue,” “hepatitis,” “influenza,” “Zika virus,” “Salmonella,” and “Escherichia coli.”

Articles were considered eligible when they addressed nanomaterial-enabled biosensing platforms for infectious disease diagnosis, described the use of nanoscale materials in signal amplification or target recognition, evaluated biosensor performance for pathogen or biomarker detection, or discussed translational issues relevant to point-of-care diagnostics.

Studies focusing on electrochemical, optical, fluorescence-based, colorimetric, surface plasmon resonance, piezoelectric, magnetic, field-effect transistor, CRISPR-assisted, or microfluidic biosensing approaches were included when they were relevant to infectious disease detection. Review articles, experimental studies, analytical validation studies, and selected technology-development reports were considered when they contributed directly to understanding biosensor design, diagnostic performance, or clinical applicability.

Articles were excluded when they were unrelated to infectious disease diagnostics, did not involve nanotechnology or nanomaterial-assisted biosensing, focused exclusively on therapeutic nanomedicine without diagnostic relevance, lacked sufficient methodological or technical detail, were non-peer-reviewed, or duplicated information already captured in more relevant sources. Studies focused only on general nanomaterial synthesis without a biosensing or diagnostic application were also excluded. Conference abstracts, editorials, opinion pieces, and inaccessible full-text records were not used as primary evidence sources.

The initial search retrieved approximately 120 records. After removal of duplicates and screening of titles and abstracts for relevance, 65 articles were retained for full-text consideration. Thirty-five peer-reviewed studies were selected for detailed synthesis based on their relevance to nanotechnology-based biosensors, infectious disease detection, biosensor mechanism, nanomaterial type, diagnostic target, and contribution to point-of-care or translational diagnostics. Selection was performed through iterative reading and thematic relevance assessment rather than formal dual-screening, consistent with the narrative review design.

Data were extracted narratively from eligible studies using a structured thematic approach. Extracted information included infectious disease target, pathogen or biomarker detected, nanomaterial used, biosensor platform, detection principle, reported diagnostic advantages, detection time where available, and major limitations.

Particular attention was given to nanomaterials commonly used in biosensor fabrication, including gold nanoparticles, silver nanoparticles, graphene and graphene oxide, carbon nanotubes, quantum dots, magnetic nanoparticles, nanowires, and nanorods. Biosensor platforms were grouped according to their principal transduction mechanisms, including electrochemical, optical, fluorescence-based, colorimetric, surface plasmon resonance, field-effect transistor, magnetic, piezoelectric, and CRISPR-assisted systems.

The synthesis was organized conceptually and thematically rather than statistically. First, biosensors were classified by detection mechanism and nanomaterial type. Second, disease-specific applications were summarized for major infectious diseases, including COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis B and C, influenza, Zika virus infection, Salmonella infection, and Escherichia coli infection.

Third, the diagnostic advantages of nanotechnology-based biosensors were analyzed in relation to sensitivity, specificity, assay speed, portability, sample-volume requirements, multiplexing capacity, and suitability for point-of-care testing. Finally, implementation challenges were synthesized, including reproducibility, large-scale fabrication, standardization, nanomaterial safety, biocompatibility, cost, regulatory approval, and clinical validation.

Because this was a narrative review, no meta-analysis, pooled diagnostic accuracy estimate, or formal risk-of-bias assessment was performed. Differences in biosensor design, pathogen targets, sample matrices, analytical endpoints, and reporting standards limited direct quantitative comparison across studies. The review therefore emphasizes descriptive and interpretive synthesis, with attention to patterns across the literature, recurring technological advantages, and barriers affecting clinical translation. Potential selection bias was addressed by using multiple databases, broad search terms, and inclusion of both recent and foundational literature relevant to the development and application of nanotechnology-based biosensors for infectious disease detection.

RESULTS

The literature search identified approximately 120 records across PubMed, Google Scholar, ScienceDirect, and IEEE Xplore. After removal of duplicate and irrelevant records through title and abstract screening, 65 articles were retained for full-text assessment. Thirty-five peer-reviewed studies were selected for narrative synthesis based on their relevance to nanotechnology-based biosensors, infectious disease detection, nanomaterial type, sensing mechanism, diagnostic application, and point-of-care potential. The included evidence covered electrochemical, optical, fluorescence-based, colorimetric, surface plasmon resonance, field-effect transistor, magnetic, piezoelectric, and CRISPR-assisted biosensing platforms. The principal infectious disease applications included COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis B and C, influenza, Zika virus infection, Salmonella infection, and Escherichia coli infection.

Table 1. Classification of Nanotechnology-Based Biosensors Used for Infectious Disease Detection

Biosensor Class	Signal Transduction Principle	Common Nanomaterials Used	Main Diagnostic Strengths	Representative Infectious Disease Applications
Electrochemical biosensors	Measure changes in current, voltage, impedance, or electron transfer after target binding	Graphene oxide, carbon nanotubes, gold nanoparticles, magnetic nanoparticles	High sensitivity, rapid response, low sample volume, compatibility with portable devices	Tuberculosis, COVID-19, hepatitis, Salmonella, E. coli

Biosensor Class	Signal Transduction Principle	Common Nanomaterials Used	Main Diagnostic Strengths	Representative Infectious Disease Applications
Optical biosensors	Detect changes in light absorption, fluorescence, color, or refractive index	Gold nanoparticles, silver nanoparticles, quantum dots, gold nanorods	Visual detection, high analytical sensitivity, multiplexing potential	COVID-19, dengue, influenza, HIV, Zika virus
Surface plasmon resonance biosensors	Detect refractive index changes at a nanostructured metal surface after biomolecular binding	Gold nanoparticles, gold nanoislands, gold nanorods	Label-free detection, real-time monitoring, high sensitivity	COVID-19, Zika virus, viral antigen detection
Fluorescence-based biosensors	Measure fluorescence emission changes after pathogen or biomarker recognition	Quantum dots, fluorescent nanoprobes, carbon-based nanomaterials	Strong signal intensity, multiplexed detection, high photostability	HIV, influenza, malaria, dengue
Field-effect transistor biosensors	Detect electrical changes caused by target binding on a semiconductor or graphene surface	Graphene, reduced graphene oxide, nanowires	Label-free detection, rapid response, high sensitivity	COVID-19, influenza, viral antigen detection
Magnetic biosensors	Use magnetic separation or enrichment to concentrate target pathogens or biomarkers	Magnetic nanoparticles, iron oxide nanoparticles	Target enrichment, improved detection in complex samples, reduced assay time	Malaria, bacterial infections
Piezoelectric biosensors	Detect mass or mechanical changes after pathogen binding to a sensor surface	Nanowires, carbon-based nanomaterials	Real-time detection, label-free monitoring, wearable potential	Viral and bacterial pathogen detection
CRISPR-assisted nanobiosensors	Combine nucleic acid amplification or recognition with CRISPR-mediated target detection	Gold nanoparticles, lateral-flow nanomaterials, nanostructured platforms	High sequence specificity, rapid molecular detection, point-of-care potential	COVID-19 and emerging viral infections

Table 2. Common Nanomaterials and Their Functional Roles in Infectious Disease Biosensors

Nanomaterial	Major Physicochemical Properties	Functional Role in Biosensors	Key Diagnostic Advantages	Main Disease Applications
Gold nanoparticles	Surface plasmon resonance, high conductivity, biocompatibility, easy functionalization	Signal amplification, optical/colorimetric detection, antibody or probe immobilization	Visual readout, enhanced sensitivity, rapid antigen or nucleic acid detection	COVID-19, dengue, E. coli, viral infections
Silver nanoparticles	Strong optical properties, plasmonic behavior, antimicrobial activity	Colorimetric signal generation and optical enhancement	Rapid visual detection, low-cost assay potential	SARS-CoV-2 and other viral targets
Graphene and graphene oxide	High surface area, excellent electron mobility, strong adsorption capacity	Electrode modification, DNA hybridization, antigen detection	Improved electron transfer, high sensitivity, miniaturization	Tuberculosis, COVID-19, hepatitis, influenza
Carbon nanotubes	High electrical conductivity, mechanical strength, large surface area	Electrochemical signal enhancement and biomolecule immobilization	Improved sensitivity, rapid signal response, suitability for wearable sensors	Salmonella, HIV, bacterial detection
Quantum dots	Size-tunable fluorescence, high brightness, photostability	Fluorescent labeling and multiplexed detection	Strong fluorescence signal, simultaneous biomarker detection	HIV, influenza, malaria
Magnetic nanoparticles	Magnetic responsiveness, enrichment capacity, modifiable surface chemistry	Pathogen separation, concentration, and signal amplification	Improved detection in blood or complex matrices, reduced detection time	Malaria, bacterial infections
Nanowires	High aspect ratio, strong electrical response, nanoscale conductivity	Label-free electrical sensing and field-effect detection	Real-time detection, high surface interaction, low detection limit potential	Hepatitis, influenza, viral detection
Gold nanorods / nanoislands	Tunable plasmonic response, strong optical enhancement	SPR and LSPR-based pathogen recognition	Highly sensitive optical detection, real-time monitoring	COVID-19, Zika virus

Table 3. Disease-Wise Applications of Nanotechnology-Based Biosensors

Infectious Disease	Target Detected	Biosensor Platform	Nanomaterial Used	Detection Principle	Reported Detection Time / Performance Feature	Diagnostic Relevance
COVID-19	SARS-CoV-2 RNA, spike protein, nucleocapsid gene, viral particles	Plasmonic, graphene FET, colorimetric, CRISPR-assisted, electrochemical	Gold nanoislands, graphene, gold nanoparticles, silver nanoparticles	LSPR, electrical signal change, visual color shift, CRISPR-mediated nucleic acid recognition	Results reported within minutes in several platforms; some systems enabled amplification-free or visual detection	Rapid screening, point-of-care testing, outbreak management
Tuberculosis	Mycobacterium tuberculosis DNA or biomarkers	Electrochemical DNA biosensor	Graphene, graphene oxide, gold nanoparticles	DNA hybridization and electrochemical signal transduction	Detection reported within approximately 20 minutes in selected graphene-based systems	Early TB diagnosis, resource-limited settings
HIV	p24 antigen and HIV-associated biomarkers	Fluorescence biosensor, electrochemical biosensor, CNT-based biosensor	Quantum dots, carbon nanotubes, nanostructured electrodes	Fluorescence emission or electrochemical signal amplification	Detection of low-concentration biomarkers with enhanced sensitivity	Early diagnosis and disease monitoring
Malaria	Plasmodium falciparum antigens, parasite-derived biomarkers	Magnetic, fluorescent, paper-based, electrochemical biosensor	Magnetic nanoparticles, quantum dots, gold nanoparticles	Magnetic enrichment, fluorescence detection, nucleic acid amplification, electrochemical sensing	Rapid field-suitable detection reported in portable platforms	Screening in endemic and low-resource regions
Dengue fever	Dengue virus antigen, antibody, or RNA	Optical immunosensor, fluorescence biosensor, graphene biosensor	Gold nanoparticles, graphene, optical nanomaterials	Optical signal amplification, fluorescence response, electrical signal change	Rapid antigen or RNA detection reported in early-stage infection contexts	Outbreak surveillance and early diagnosis
Hepatitis B/C	Viral nucleic acids and surface antigens	Electrochemical and nanowire biosensors	Graphene, nanowires, nanoparticles	Electron transfer enhancement and label-free nucleic acid detection	Reduced diagnostic time compared with conventional immunoassays in selected studies	Viral monitoring and early detection
Influenza	Influenza viral particles or strain-specific targets	Fluorescence biosensor, nanowire FET, graphene immunosensor	Quantum dots, nanowires, graphene, gold nanoparticle-CNT hybrids	Fluorescence, field-effect sensing, electrochemical response	Rapid, label-free, and multiplexed detection reported	Respiratory virus screening and strain identification
Zika virus	Viral RNA or viral particles	SPR and electrochemical biosensors	Gold nanorods, nanostructured electrodes	Plasmonic signal enhancement and electrochemical detection	Real-time monitoring and sensitive viral detection reported	Emerging viral outbreak surveillance
Salmonella	Salmonella enterica cells or antigens	Electrochemical and multiplexed nanosensors	Carbon nanotubes, nanostructured electrodes	Antibody immobilization and electrochemical signal response	Detection within approximately 30 minutes in selected systems	Food safety and bacterial infection monitoring

Infectious Disease	Target Detected	Biosensor Platform	Nanomaterial Used	Detection Principle	Reported Detection Time / Performance Feature	Diagnostic Relevance
Escherichia coli	E. coli cells or bacterial antigens	Electrochemical biosensor	Gold nanoparticles, screen-printed electrodes	Current or impedance measurement after bacterial binding	Detection within minutes in AuNP-enhanced platforms	Rapid bacterial identification in clinical and food-safety settings

Table 4. Diagnostic Advantages and Translational Challenges of Nanotechnology-Based Biosensors

Domain	Main Findings from the Synthesized Evidence	Practical Implication
Sensitivity	Nanomaterials increase surface area, improve electron transfer, and amplify optical or electrochemical signals	Enables detection of low pathogen or biomarker concentrations
Specificity	Functionalization with antibodies, aptamers, nucleic acid probes, or ligands improves target recognition	Supports pathogen-specific diagnosis and reduces nonspecific signal
Detection speed	Many platforms report detection within minutes to less than 30 minutes	Supports rapid triage, screening, and outbreak response
Sample volume	Nanoscale platforms often require small sample volumes	Useful for point-of-care testing, pediatric sampling, and field diagnostics
Portability	Miniaturized electrochemical, paper-based, and handheld biosensors are compatible with decentralized testing	Supports use in remote and low-resource settings
Multiplexing	Quantum dots, optical platforms, and nanostructured arrays can support simultaneous detection of multiple targets	Useful for syndromic testing and outbreak differentiation
Scalability	Complex nanomaterial synthesis and sensor fabrication may limit large-scale production	Manufacturing reproducibility remains a major translational barrier
Reproducibility	Small variations in nanoparticle size, shape, surface charge, or functionalization can alter performance	Standardized fabrication and quality control are essential for clinical use
Biosafety	Nanomaterial toxicity, biocompatibility, and environmental impact remain important concerns	Safety evaluation is necessary before widespread deployment
Regulation	Lack of harmonized validation standards and regulatory pathways slows translation	Clinical adoption requires standardized performance benchmarks
Cost	Some nanobiosensors are designed for low-cost use, but advanced fabrication may increase production expense	Economic feasibility depends on material, platform, and scale
Clinical validation	Many systems remain at proof-of-concept or analytical validation stages	Real-world diagnostic utility depends on performance in clinical samples

The selected studies collectively demonstrate that nanotechnology-based biosensors represent a diverse and rapidly developing diagnostic field rather than a single uniform technology. Across the included evidence, biosensors were most commonly classified according to their signal transduction mechanism, with electrochemical, optical, fluorescence-based, surface plasmon resonance, field-effect transistor, magnetic, piezoelectric, and CRISPR-assisted systems forming the major categories. Electrochemical biosensors were the most frequently described because of their compatibility with portable devices, low sample-volume requirements, rapid signal generation, and ability to integrate conductive nanomaterials such as graphene, carbon nanotubes, and gold nanoparticles. Optical and plasmonic biosensors were also prominent, particularly for viral detection, because gold and silver nanostructures can produce visible colorimetric changes or enhanced refractive-index responses after target binding.

Nanomaterial selection strongly influenced biosensor function. Gold nanoparticles were repeatedly used for signal amplification, antibody or nucleic acid probe immobilization, surface plasmon resonance enhancement, and colorimetric readout. Their optical behavior and ease of functionalization made them especially relevant for COVID-19, dengue, viral pathogen detection, and bacterial assays. Graphene and graphene oxide were mainly incorporated into electrochemical and field-effect transistor platforms because their large surface area and electrical conductivity improved electron transfer and target-induced signal changes. Carbon nanotubes contributed similar conductivity and surface-area advantages, particularly in bacterial detection and electrochemical sensing. Quantum dots were primarily used in fluorescence-based biosensors because of their high brightness, photostability, and suitability for multiplexed detection, while magnetic nanoparticles improved pathogen concentration and separation in complex biological samples such as blood.

COVID-19 represented the most extensively discussed disease application. The reviewed evidence included plasmonic biosensors using gold nanoislands for SARS-CoV-2 nucleic acid detection, graphene-based field-effect transistor biosensors targeting viral spike protein, colorimetric assays based on gold or silver nanoparticles, and CRISPR-assisted molecular platforms. These systems were reported to reduce detection time and increase suitability for decentralized testing compared with conventional laboratory-dependent diagnostic approaches. Some COVID-19 biosensors enabled visual readout within minutes, while others supported amplification-free or real-time detection of viral proteins or RNA. Collectively, these findings suggest that SARS-CoV-2 accelerated the development of rapid nanobiosensor platforms and demonstrated their potential for outbreak diagnostics.

For tuberculosis, the synthesized studies emphasized graphene and graphene oxide-based electrochemical biosensors for the detection of Mycobacterium tuberculosis DNA or disease-associated biomarkers. These platforms used nanomaterial-enhanced electron transfer and DNA hybridization to shorten diagnostic turnaround time compared with culture-based methods. Some graphene-based systems reported detection within approximately 20 minutes, supporting their relevance for early-stage diagnosis in settings where conventional culture is slow and molecular infrastructure is limited. However, the evidence was mainly concentrated on analytical sensitivity and prototype performance rather than broad clinical deployment.

HIV detection was commonly associated with fluorescence-based and electrochemical nanobiosensors targeting p24 antigen or other HIV-associated biomarkers. Quantum dots enabled strong fluorescence signals at low biomarker concentrations, while carbon nanotubes and nanostructured electrodes improved electrochemical signal amplification. These platforms were particularly relevant to early diagnosis because conventional antibody-based detection may be limited during early infection. The synthesized evidence indicates that nanotechnology-based HIV biosensors may improve sensitivity and reduce detection time, especially when combined with portable or low-volume testing formats.

Malaria biosensors used magnetic nanoparticles, quantum dots, gold nanoparticles, paper-based systems, and electrochemical platforms to detect Plasmodium falciparum antigens or parasite-derived biomarkers. Magnetic nanoparticles were especially useful because they enabled parasite enrichment and separation from blood, improving detection efficiency in complex samples. Paper-based and portable nanosensors were relevant to malaria-endemic regions because they reduced dependence on centralized laboratory infrastructure. These findings indicate that nanobiosensors may be particularly valuable where rapid field diagnosis is essential for treatment initiation and disease control.

Dengue fever detection was mainly represented by gold nanoparticle-based immunosensors, graphene biosensors, and fluorescence-based optical nanosensors. These platforms targeted dengue antigens, antibodies, or viral RNA and were reported to improve optical signal amplification and early-stage detection. Because dengue diagnosis is often complicated by overlapping symptoms with other febrile illnesses, rapid and sensitive biosensors may support outbreak surveillance and timely clinical differentiation. The reviewed evidence also shows that fluorescence and optical nanobiosensors are suitable for early viral detection when antigen or RNA levels are diagnostically informative.

Hepatitis B and C detection relied largely on graphene-based electrochemical biosensors and nanowire platforms targeting viral nucleic acids or surface antigens. These systems offered label-free or rapid electrochemical detection through enhanced electron transfer and high surface interaction. Compared with conventional immunological assays, nanotechnology-assisted platforms were reported to shorten detection time and improve analytical sensitivity. Similarly, influenza detection was supported by quantum dot fluorescence biosensors, nanowire field-effect transistor systems, graphene-based immunosensors, and gold nanoparticle-carbon nanotube hybrids. These platforms enabled rapid, label-free, or multiplexed detection of influenza viruses and may be useful for respiratory pathogen screening.

For emerging viral infections such as Zika virus, surface plasmon resonance biosensors using gold nanorods and electrochemical platforms demonstrated sensitive and real-time detection potential. The use of plasmonic nanomaterials was especially relevant because signal amplification can improve detection of low viral loads. Bacterial pathogen detection was represented mainly by Salmonella and Escherichia coli biosensors. Carbon nanotube-based electrochemical platforms improved Salmonella detection through increased antibody immobilization and enhanced signal response, while gold nanoparticle-modified electrochemical sensors supported rapid E. coli identification. These bacterial platforms are relevant not only to clinical diagnostics but also to food safety and environmental monitoring.

Across disease categories, several shared advantages were evident. Nanotechnology-based biosensors consistently improved analytical performance through signal amplification, increased pathogen-sensor interaction, high surface-area effects, and enhanced optical or electrical responsiveness. Many platforms required small sample volumes and generated results within minutes to less than 30 minutes, making them suitable for point-of-care testing. The potential for multiplex detection was especially important for syndromic diagnosis, where multiple pathogens may produce similar clinical presentations. However, the reviewed evidence also showed important translational challenges. Reproducibility of nanomaterial synthesis, large-scale fabrication, sensor stability, biocompatibility, toxicity, standardization, regulatory approval, and clinical validation remain major barriers to routine implementation.

Overall, the synthesis indicates that nanotechnology-based biosensors have substantial potential to transform infectious disease detection by enabling rapid, sensitive, portable, and potentially multiplexed diagnostics. The strongest evidence supports their analytical promise across viral, bacterial, and parasitic infections, particularly in applications requiring rapid screening or decentralized testing. At the same time, the clinical maturity of these platforms varies considerably. Many systems remain at the laboratory or early validation stage, and their transition into routine practice depends on reproducible manufacturing, standardized performance assessment, biosafety evaluation, and demonstration of effectiveness in real-world clinical and field settings.

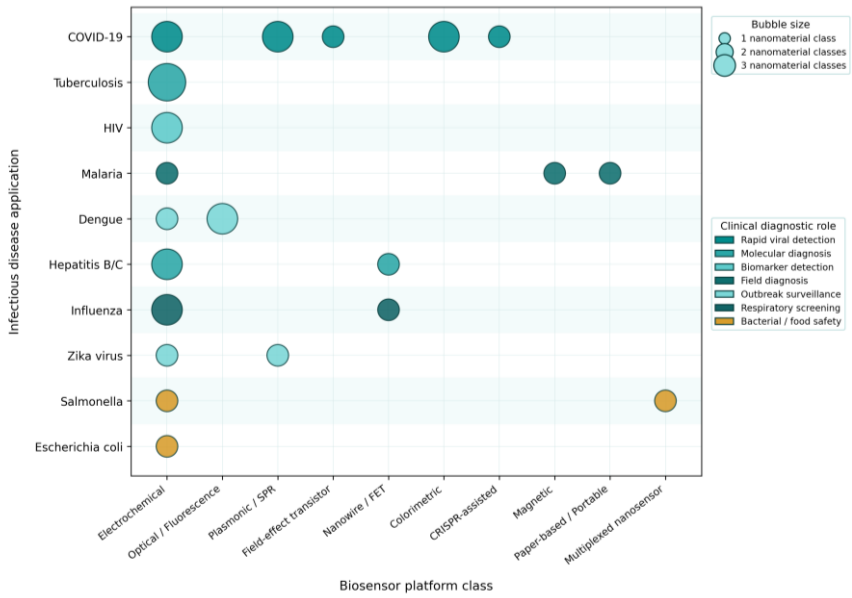

Figure 1. Nanotechnology-Enabled Biosensor Evidence Gradient Across Infectious Disease Applications

The figure presents a disease-by-platform evidence-gradient matrix derived from the synthesized review findings. Electrochemical biosensors show the broadest cross-disease applicability, appearing across COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis B/C, influenza, Zika virus, Salmonella, and Escherichia coli. COVID-19 shows the most diversified biosensor landscape, with five platform categories

represented: electrochemical, plasmonic/SPR, field-effect transistor, colorimetric, and CRISPR-assisted systems. Tuberculosis shows a concentrated electrochemical profile with three nanomaterial classes, mainly reflecting graphene, graphene oxide, and gold nanoparticle-enhanced approaches. Viral outbreak-related applications such as COVID-19, dengue, influenza, and Zika virus cluster around optical, plasmonic, fluorescence, and electrochemical platforms, whereas bacterial detection is concentrated in electrochemical and multiplexed nanosensor systems. This distribution highlights electrochemical biosensing as the most versatile platform class, while optical and plasmonic approaches appear especially important for rapid viral and outbreak surveillance applications.

DISCUSSION

This narrative review synthesized current and foundational evidence on nanotechnology-based biosensors for infectious disease detection, with emphasis on nanomaterial classes, biosensor mechanisms, disease-specific applications, diagnostic advantages, and translational challenges. The principal finding is that nanotechnology-enabled biosensors offer a highly adaptable diagnostic framework capable of improving sensitivity, reducing detection time, supporting miniaturization, and enabling point-of-care testing across viral, bacterial, and parasitic infections. Electrochemical biosensors emerged as the most broadly applicable platform, particularly because conductive nanomaterials such as graphene, graphene oxide, carbon nanotubes, and gold nanoparticles enhance electron transfer, increase functional surface area, and allow rapid signal generation. Optical, fluorescence-based, colorimetric, surface plasmon resonance, field-effect transistor, magnetic, piezoelectric, and CRISPR-assisted platforms also showed important disease-specific strengths, especially for rapid viral detection, outbreak surveillance, biomarker identification, and field-based diagnosis (14).

The findings indicate that the diagnostic value of nanobiosensors is closely linked to the physicochemical properties of the incorporated nanomaterials. Gold nanoparticles and gold nanostructures were especially useful in optical, colorimetric, and plasmonic biosensors because of their surface plasmon resonance behavior, biocompatibility, conductivity, and ease of functionalization. These properties supported rapid detection of SARS-CoV-2, dengue virus, Zika virus, and bacterial pathogens (15). Graphene and graphene oxide were prominent in electrochemical and field-effect transistor platforms because their high surface area and strong electrical conductivity improve biomolecular interaction and signal transduction. Carbon nanotubes contributed similar advantages in electrochemical bacterial and viral detection systems, whereas quantum dots were valuable in fluorescence-based assays because of their brightness, photostability, and multiplexing potential (16). Magnetic nanoparticles added a different diagnostic function by enabling target enrichment and separation, which is particularly relevant for complex biological samples such as blood in malaria and bacterial detection.

Across the synthesized evidence, COVID-19 represented the most diversified application area, reflecting the rapid expansion of diagnostic innovation during the pandemic. Plasmonic biosensors, graphene-based field-effect transistor systems, colorimetric nanoparticle assays, electrochemical platforms, and CRISPR-assisted nanobiosensors all demonstrated potential for rapid SARS-CoV-2 detection. This diversity suggests that pandemic conditions accelerated the development and testing of decentralized diagnostic technologies (17). However, the COVID-19 evidence also illustrates a broader pattern in the field: many platforms show excellent analytical performance in controlled settings, but fewer have undergone large-scale clinical validation or routine implementation (18). Therefore, the strongest conclusion is not that nanobiosensors have replaced conventional diagnostics, but that they provide a technologically promising foundation for faster, smaller, and more adaptable infectious disease testing systems.

For tuberculosis, the evidence was concentrated mainly around graphene-based and electrochemical DNA biosensors. These platforms are clinically relevant because tuberculosis diagnosis remains limited

by slow culture methods and uneven access to molecular testing in many high-burden settings. Rapid electrochemical detection of Mycobacterium tuberculosis DNA or biomarkers could reduce diagnostic delay and support earlier treatment initiation. Similarly, HIV nanobiosensors targeting p24 antigen and other early biomarkers may help address the diagnostic window period by improving sensitivity at low biomarker concentrations. In both tuberculosis and HIV, the most important contribution of nanotechnology lies in signal amplification and early detection rather than simple replacement of existing laboratory assays (19,20).

Malaria, dengue, influenza, hepatitis, Zika virus infection, Salmonella infection, and Escherichia coli detection further demonstrate the breadth of nanobiosensor applications. Magnetic nanoparticle-based enrichment and paper-based nanosensors are especially relevant for malaria because field diagnosis often occurs in settings with limited laboratory infrastructure. Dengue and Zika virus applications highlight the usefulness of optical and plasmonic platforms for outbreak surveillance, where rapid differentiation from clinically similar febrile illnesses is important (21). Influenza applications show the potential of fluorescence, nanowire, graphene, and electrochemical systems for respiratory pathogen screening and strain-sensitive detection. Bacterial biosensors for Salmonella and E. coli extend the relevance of nanobiosensing beyond clinical diagnosis into food safety, environmental monitoring, and public health surveillance.

A consistent advantage across platforms was reduced detection time. Several nanobiosensor systems were reported to generate results within minutes to less than 30 minutes, which is substantially more compatible with point-of-care decision-making than conventional culture-based methods. Small sample-volume requirements, portability, and potential compatibility with handheld or paper-based devices further strengthen their relevance for decentralized testing. Multiplexing is another important advantage, especially for infectious disease syndromes in which multiple pathogens produce overlapping clinical features (22). Quantum dot fluorescence, nanostructured sensor arrays, and multiplexed electrochemical platforms may allow simultaneous detection of several pathogens or biomarkers, improving triage during outbreaks and reducing diagnostic uncertainty in settings where broad laboratory panels are unavailable.

Despite these advantages, the evidence base remains uneven. Many studies focus on analytical sensitivity, detection time, signal amplification, or proof-of-concept feasibility, whereas fewer provide full clinical performance data such as sensitivity, specificity, predictive values, performance across diverse sample matrices, reproducibility across batches, or comparison against established diagnostic standards. This distinction is essential because analytical detectability does not automatically translate into clinical diagnostic utility. A biosensor that performs well in buffer or spiked samples may show reduced performance in nasopharyngeal swabs, blood, serum, saliva, stool, or other complex clinical matrices because of nonspecific binding, matrix interference, variable pathogen load, or sample-processing requirements. Therefore, the clinical promise of nanobiosensors depends not only on nanoscale material performance but also on assay robustness under real-world conditions.

Reproducibility remains one of the most important translational challenges. Nanomaterial properties such as particle size, morphology, surface charge, aggregation state, functional group density, and binding chemistry can strongly influence biosensor performance. Small variations during synthesis or functionalization may alter signal intensity, target affinity, stability, and background noise. This issue is particularly relevant for large-scale manufacturing, where batch-to-batch consistency is essential. Electrochemical platforms may be easier to miniaturize and integrate into portable devices, but they still require reproducible electrode fabrication and stable biomolecule immobilization (23). Optical and plasmonic platforms may offer strong signal enhancement, but they require careful control of nanostructure geometry and optical response. These manufacturing and quality-control challenges remain central barriers to clinical translation.

Safety and biocompatibility are also important considerations. Although diagnostic biosensors often involve limited patient exposure compared with therapeutic nanomedicine, nanomaterials may still pose concerns related to toxicity, environmental persistence, disposal, operator exposure, and biological interaction. The safety profile depends on material composition, size, surface coating, concentration, route of exposure, and assay format. Gold nanoparticles and carbon-based nanomaterials are widely used because of favorable functional properties, but long-term biosafety and environmental implications remain important for large-scale deployment (24). For point-of-care and field settings, safe handling, storage stability, waste management, and ease of use are as important as analytical performance.

The regulatory pathway for nanotechnology-based biosensors is another major challenge. Diagnostic devices require consistent manufacturing, defined performance benchmarks, analytical validation, clinical validation, quality management, and usability assessment. Nanobiosensors often combine biological recognition elements, engineered nanomaterials, microfabricated components, and electronic or optical readout systems, making regulatory evaluation more complex than for simpler assays (25). In addition, the absence of standardized reporting across studies makes comparison difficult. Many reports do not consistently provide sample type, limit of detection, linear detection range, cross-reactivity, interference testing, storage stability, reproducibility, or comparator performance. More harmonized reporting would strengthen the field by allowing meaningful comparison between platforms and clearer assessment of clinical readiness.

The integration of nanobiosensors with artificial intelligence, machine learning, microfluidics, smartphone-based readouts, and internet-connected diagnostic systems represents an important future direction. Artificial intelligence may improve interpretation of complex electrochemical, optical, or multiplexed signals, particularly when sensor outputs require pattern recognition rather than a single positive-or-negative threshold. Microfluidic integration can reduce reagent use, automate sample handling, and improve portability (26). Smartphone-based detection may support decentralized data capture, telemedicine linkage, and real-time surveillance. However, these advances should be viewed as enabling technologies rather than guaranteed solutions. Their usefulness will depend on affordability, user training, data security, device calibration, and performance in the intended clinical or field environment.

This review has several limitations inherent to its narrative design. The synthesis was intentionally broad and covered multiple pathogens, nanomaterials, and biosensor mechanisms, which allowed conceptual integration but limited direct quantitative comparison. The included studies varied widely in design, diagnostic target, sample matrix, validation depth, and performance reporting, making meta-analysis inappropriate. The review also prioritized recent literature while incorporating selected foundational studies, which may introduce selection bias despite the use of multiple databases and broad search terms. In addition, because many nanobiosensor studies remain at experimental or analytical validation stages, conclusions about clinical implementation must be interpreted cautiously. The review therefore provides an integrated overview of technological potential and translational barriers rather than a pooled estimate of diagnostic accuracy.

The practical implication of this synthesis is that nanotechnology-based biosensors are best understood as a promising diagnostic platform family rather than a single mature replacement for conventional testing. Their greatest near-term value may lie in settings where speed, portability, low sample volume, and decentralized access are essential, including outbreak response, rural clinics, emergency screening, field surveillance, and resource-limited health systems. Electrochemical platforms appear particularly versatile for broad infectious disease testing, while optical, fluorescence, plasmonic, and colorimetric systems may be especially useful for rapid viral and outbreak-related applications. Magnetic and paper-based systems may offer additional benefits where sample preparation and field deployment are major constraints.

Future research should focus on moving beyond proof-of-concept demonstrations toward standardized clinical validation. Priority areas include head-to-head comparison with established diagnostic methods, evaluation in real clinical samples, testing across diverse populations and pathogen loads, assessment of cross-reactivity and matrix interference, long-term stability studies, scalable manufacturing methods, and cost-effectiveness analysis. Research should also define minimum reporting standards for nanobiosensor studies, including target analyte, sample type, detection limit, assay time, reproducibility, comparator method, clinical sensitivity and specificity, and intended-use setting. By addressing these gaps, future work can help determine which nanotechnology-based biosensors are most likely to progress from laboratory innovation to reliable point-of-care infectious disease diagnostics.

CONCLUSION

Nanotechnology-based biosensors represent a promising advancement in infectious disease diagnostics by combining nanoscale signal amplification, biomolecular recognition, and portable sensing formats to support rapid, sensitive, and potentially point-of-care detection of viral, bacterial, and parasitic pathogens. Across the synthesized evidence, electrochemical, optical, fluorescence-based, plasmonic, magnetic, field-effect transistor, colorimetric, and CRISPR-assisted platforms demonstrated value for detecting clinically important infections, including COVID-19, tuberculosis, HIV, malaria, dengue, hepatitis, influenza, Zika virus infection, Salmonella, and Escherichia coli. Their major diagnostic relevance lies in reduced detection time, small sample-volume requirements, improved analytical sensitivity, multiplexing potential, and suitability for decentralized testing in outbreak, field, and resource-limited settings. However, routine clinical implementation remains limited by challenges related to reproducible nanomaterial synthesis, scalable manufacturing, assay standardization, biosafety, regulatory approval, cost, and real-world clinical validation. Future research should therefore prioritize robust validation in clinical samples, standardized performance reporting, scalable fabrication, and integration with user-friendly point-of-care systems so that nanotechnology-based biosensors can move from experimental innovation toward reliable infectious disease diagnosis and surveillance.

REFERENCES

1. Qiu G, Gai Z, Tao Y, Schmitt J, Kullak-Ublick GA, Wang J. Dual-functional plasmonic photothermal biosensors for highly accurate severe acute respiratory syndrome coronavirus 2 detection. ACS Nano. 2020;14(5):5268–5277.

2. Seo G, Lee G, Kim MJ, Baek SH, Choi M, Ku KB, et al. Rapid detection of COVID-19 causative virus SARS-CoV-2 in human nasopharyngeal swab specimens using field-effect transistor-based biosensor. ACS Nano. 2020;14(4):5135–5142.

3. Ahmadivand A, Gerislioglu B, Ramezani Z, Kaushik A, Manickam P, Ghoreishi SA. Functionalized terahertz plasmonic metasensors: femtomolar-level detection of SARS-CoV-2 spike proteins. Biosens Bioelectron. 2021;177:112971.

4. Shan B, Broza YY, Li W, Wang Y, Wu S, Liu Z, et al. Multiplexed nanomaterial-based sensor array for detection of COVID-19 in exhaled breath. ACS Nano. 2020;14(9):12125–12132.

5. Torrente-Rodríguez RM, Lukas H, Tu J, Min J, Yang Y, Xu C, et al. SARS-CoV-2 RapidPlex: a graphene-based multiplexed telemedicine platform for rapid and low-cost COVID-19 diagnosis and monitoring. Matter. 2020;3(6):1981–1998.

6. Moitra P, Alafeef M, Dighe K, Frieman MB, Pan D. Selective naked-eye detection of SARS-CoV-2 mediated by N gene targeted antisense oligonucleotide capped plasmonic nanoparticles. ACS Nano. 2020;14(6):7617–7627.

7. Layqah LA, Eissa S. An electrochemical immunosensor for the corona virus associated with the Middle East respiratory syndrome using an array of gold nanoparticle-modified carbon electrodes. Microchim Acta. 2019;186(4):224.

8. Kaushik A, Tiwari S, Jayant RD, Marty A, Nair M. Electrochemical biosensors for early stage Zika diagnostics. TrAC Trends Anal Chem. 2016;79:21–28.

9. Draz MS, Shafiee H. Applications of gold nanoparticles in virus detection. Theranostics. 2018;8(7):1985–2017.

10. Mokhtarzadeh A, Eivazzadeh-Keihan R, Pashazadeh P, Hejazi M, Gharaatifar N, Hasanzadeh M, et al. Nanomaterial-based biosensors for detection of pathogenic virus. TrAC Trends Anal Chem. 2017;97:445–457.

11. Sheikhzadeh E, Beni V, Zourob M. Nanomaterial application in bio/sensors for the detection of infectious diseases. Talanta. 2021;230:122026.

12. Castillo-Henríquez L, Brenes-Acuña M, Castro-Rojas A, Cordero-Salmerón R, Lopretti-Correa M, Vega-Baudrit JR. Biosensors for the detection of bacterial and viral clinical pathogens. Sensors (Basel). 2020;20(23):6926.

13. Song M, Yang M, Hao J. Pathogenic virus detection by optical nanobiosensors. Cell Rep Phys Sci. 2021;2(1):100288.

14. Sposito AJ, Kurdekar A, Zhao J, Hewlett I. Application of nanotechnology in biosensors for enhancing pathogen detection. Wiley Interdiscip Rev Nanomed Nanobiotechnol. 2018;10(5):e1512.

15. Qureshi A, Niazi JH. Biosensors for detecting viral and bacterial infections using host biomarkers. Analyst. 2021;145(24):7825–7848.

16. Saxena S, Punjabi K, Ahamad N, Singh S, Bendale P, Banerjee R. Nanotechnology approaches for rapid detection and theranostics of antimicrobial resistant bacterial infections. ACS Biomater Sci Eng. 2022;8(6):2232–2257.

17. Yoo SM, Lee SY. Optical biosensors for the detection of pathogenic microorganisms. TrAC Trends Anal Chem. 2016;82:337–353.

18. Choi JR. Development of point-of-care biosensors for COVID-19. Front Chem. 2020;8:517.

19. Bhalla N, Pan Y, Yang Z, Payam AF. Opportunities and challenges for biosensors and nanoscale analytical tools for pandemics: COVID-19. ACS Nano. 2020;14(7):7783–7807.

20. Udugama B, Kadhiresan P, Kozlowski HN, Malekjahani A, Osborne M, Li VYC, et al. Diagnosing COVID-19: the disease and tools for detection. ACS Nano. 2020;14(4):3822–3835.

21. Hassan EM, de la Escosura-Muñiz A, Merkoçi A. Highly sensitive and rapid determination of Escherichia coli O157:H7 by electrochemical impedance spectroscopy using gold nanoparticle modified screen-printed electrodes. Biosens Bioelectron. 2014;49:520–526.

22. Kumar S, Kumar S, Ali MA, Anand P, Agrawal VV, John R, et al. Malaria disease detection using a novel graphitic carbon nitride quantum dot fluorescent probe. Sens Actuators B Chem. 2020;325:128778.

23. Jain S, Nehra M, Kumar R, Dilbaghi N, Hu TY, Kumar S, et al. Internet of medical things-integrated biosensors for point-of-care testing of infectious diseases. Biosens Bioelectron. 2021;179:113074.

24. Peeling RW, Olliaro P, Boeras DI, Fongwen N. Scaling up COVID-19 rapid antigen tests: promises and challenges. Lancet Infect Dis. 2021;21(9):e290–e295.

25. Cady NC, Stelick S, Batt CA. Nucleic acid functionalized cadmium sulfide quantum dots as fluorescence probes for Listeria detection. Biosens Bioelectron. 2003;19(1):59–66.

26. Wang Y, Xu H, Zhang J, Li G. Electrochemical sensors for clinic analysis. Sensors (Basel). 2008;8(4):2043–2081.