Nanobiosensors in Veterinary Medicine: A Systematic Review of Emerging Applications and Future Prospects for Disease Diagnosis

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ABSTRACT

Background/Objective- Veterinary medicine is on the verge of a fundamental transformation with the integration of nanotechnology and biosensors. Nanobiosensors, as diagnostic tools with unparalleled sensitivity and specificity, have great potential to change the conventional paradigms in disease diagnosis, animal health monitoring, and food chain safety assurance. This systematic review aims to provide a comprehensive analysis of the fundamental principles, a wide range of emerging applications, and future prospects of nanobiosensors in the veterinary field.

Method- This study was conducted as a systematic review by searching reputable scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar. The keywords used were “veterinary nanobiosensor”, “animal disease diagnosis”, “nanoparticle sensors”, “animal health monitoring”, and “foodborne pathogen detection”. Articles published between January 2015 and December 2024 were screened and evaluated based on predefined criteria, including direct relevance to the application of nanobiosensors in veterinary medicine, technological innovation, and scientific validity.

Results- Nanobiosensors based on nanoparticles (gold, silver, and magnetic), carbon nanotubes, and graphene, with optical, electrochemical, and piezoelectric detection mechanisms, have achieved detection levels at very low (femtomolar) concentrations. An important advantage of nanobiosensors is their ability to detect critical veterinary pathogens, such as viruses, bacteria, and parasites, with accuracy equal to or higher than traditional methods (e.g., ELISA and PCR), but in a significantly shorter time and without the need for complex equipment.

Conclusion- Nanobiosensors, as a leading technology, hold promise for accurate, rapid, and cost-effective veterinary medicine. However, significant challenges such as standardizing production, assessing nanomaterial toxicity, and ensuring cost-effectiveness for on-farm use require serious attention. Overcoming these challenges and investing in interdisciplinary research will pave the way for the widespread commercialization of this promising technology, revolutionizing animal health, public health, and food safety.

Keywords: Nanobiosensors, veterinary medicine, disease diagnosis, health monitoring

INTRODUCTION

The veterinary industry and livestock production have consistently faced numerous challenges in diagnosing infections [1]. These two industries are key foundations of food security and public health worldwide. Traditional diagnostic methods, such as microbial culture, serological tests (e.g., ELISA), and molecular techniques (e.g., polymerase chain reaction, PCR), although accurate and sensitive, are often time-consuming, expensive, and require specialized laboratory equipment and operators with advanced knowledge [2-4]. In the context of epidemics of infectious diseases such as foot-and-mouth disease or avian influenza, which require swift action in the field and on the farm, these constraints may lead to the spread of disease and substantial economic losses [5, 6]. This is particularly true in the scenario of epidemics of infectious diseases. Conventional techniques make it very difficult to continuously monitor the health of individual animals in large herds and ensure the quality control of livestock products for pollutants such as antibiotics and toxins [7, 8]. Such monitoring and control are both essential for ensuring the safety of livestock. Because of this, there is an immediate need in this area for the development of diagnostic instruments that are quick, sensitive, specific, portable, and affordable.

In this sense, the revolution in nanotechnology and its convergence with the life sciences have paved the way for the emergence of nanobiosensors as a new generation of diagnostic instruments with unique capabilities [9, 10]. Nanobiosensors are analytical devices that combine a biological detecting element (such as an antibody, enzyme, nucleic acid, or cellular receptor) with a nanoscale transducer [11]. Nanobiosensors are endowed with outstanding physicochemical properties due to the use of nanomaterials, including gold and silver nanoparticles, carbon nanotubes,s and graphene [12, 13]. Nanobiosensors also include very high surface-to-volume ratios, distinctive optical and electrical properties, and increased biocompatibility. Due to these characteristics, nanobiosensors can detect biological interactions at the molecular level with an unparalleled level of sensitivity, thereby transforming these interactions into a measurable signal (either optically, electrochemically, or magnetically) [14] (Figure 1).

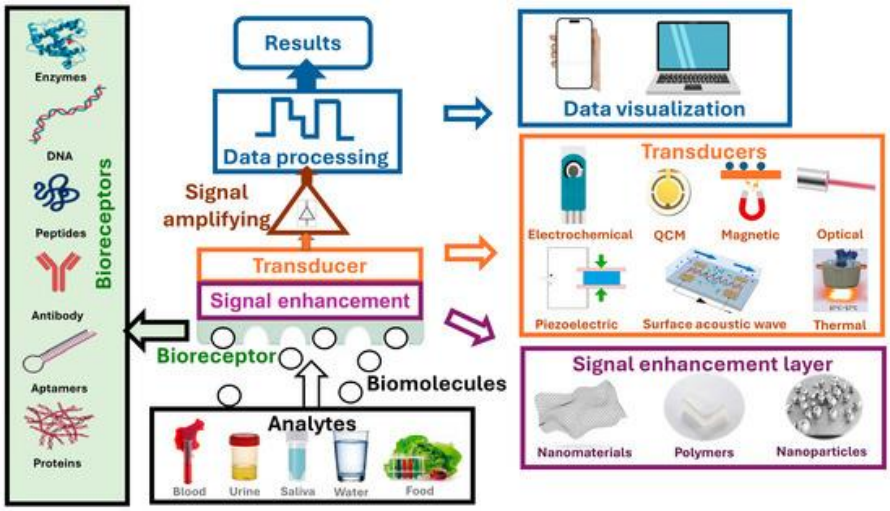


Figure 1. Common components of a biosensor and its working principles are used to detect various biomolecules from different analytes [15] (MDPI copyright).

Although the revolutionary potential of nanobiosensors in human health has been extensively established, nanobiosensor applications in veterinary care appear even more appealing and urgent in several ways. Nanobiosensors are a suitable solution due to the significant size of the livestock industry, the urgent need for point-of-care testing (POCT), and the inextricable relationship between animal health and human health [16-19]. On the farm or in the clinic, these sensors can identify specific infections, indicators of inflammation and stress, medication residues, and toxins in a variety of samples, including blood, milk, saliva, and even air [15, 20]. A skill of this kind would not only change the way illness is managed, but it would also pave the way for "Precision Veterinary Medicine," a method in which health and nutritional treatment are tailored to the specific needs of each animal.

The research conducted to systematically assemble, evaluate, and critique these advancements in the form of a comprehensive systematic review has been minimal, despite the rapid advancements made in this subject and the numerous publications published in this field. The majority of available studies focus on a specific type of nanomaterial or disease, and they do not provide a comprehensive picture of all aspects of the technology. This encompasses everything from the principles of design and manufacturing to practical applications in various veterinary professions, as well as the obstacles that hinder commercialization. Due to the absence of such an analysis, it is challenging for academics, veterinarians, and policymakers to gain a clear understanding of the current state of the technology, the gaps in research, and the approach that should be taken moving forward. Hence, the purpose of this systematic review is to give a complete and organized study of the most recent advancements in the use of nanobiosensors in the field of veterinary medicine.

1. METHODS AND MATERIALS

This study was designed and conducted as a systematic review following the PRISMA guidelines to ensure the comprehensiveness, transparency, and reproducibility of the search, screening, and selection process. The search protocol was carefully defined, and an initial search was conducted in international and authoritative databases, including Scopus, Web of Science (Core Collection), PubMed/MEDLINE, and Google

Scholar (to cover grey literature) between January 2015 and December 2024. To avoid publication bias, searches in trial registries and the reference lists of relevant review articles were also manually reviewed to identify potentially relevant studies that the initial search may have missed.

1.1. Search strategy

The search strategy was designed using a logical combination of keywords and key phrases in the title, abstract, and keywords sections of the articles. The main keywords were categorized into 3 conceptual groups and combined with the Boolean operators "AND" and "OR".

Group 1 (nanobiosensor concept): ("nanobiosensor" OR "nano-biosensor" OR "nanosensor" OR "nanomaterial-based sensor" OR "nanoparticle sensor" OR "gold nanoparticle biosensor" OR "graphene biosensor" OR "carbon nanotube biosensor").

Group 2 (diagnosis/analyte concept): ("detection" OR "diagnosis" OR "identification" OR "biosensing" OR "point-of-care" OR "pathogen" OR "virus" OR "bacteria" OR "biomarker" OR "antibiotic residue" OR "toxin").

Group 3 (Veterinary and animal concepts): ("veterinary" OR "veterinary medicine" OR "livestock" OR "cattle" OR "cow" OR "dog" OR "cat" OR "poultry" OR "chicken" OR "avian" OR "sheep" OR "goat" OR "pig" OR "swine" OR "animal health" OR "dairy").

The final search pattern was as follows: (Group 1) AND (Group 2) AND (Group 3).

1.2. Screening and selection process of articles

After retrieving all of the entries from the various databases, they were all sent to the EndNote reference management program, and any duplicates were immediately eliminated. In accordance with the predetermined criteria (PICOS), the screening procedure was conducted by two researchers in two separate phases, without any collaboration between them. During the first phase, a screening was carried out based on the titles and abstracts of the publications. Publications that were obviously not relevant to the subject matter were disregarded, such as research that concentrated entirely on human medicine or sensors that were not biological in nature. During the second step, the complete texts of articles that were pertinent to the study were obtained and thoroughly examined. Among the criteria for inclusion were the following: (1) the primary focus of the article was on the design, fabrication, or testing of a nanobiosensor for veterinary application; (2) the article provided experimental data that was relevant to the evaluation of the sensor (for example, sensitivity, specificity, and limit of detection); and (3) the article was written in English. Finally, to facilitate qualitative and structured analysis, key data from the final articles were extracted and tabulated in a standardized format. This data included the author, publication year, type of nanomaterial, detection mechanism, target analyte, biological sample, and sensor performance (detection limit, linear range, etc.).

2. RESULTS

In the context of rapid detection of important veterinary infectious diseases, the results indicated the successful development of nanobiosensors for a wide range of viral [21-32], bacterial [33-55], and parasitic pathogens [56-78]. Specifically, aptamer- or antibody-based sensors against essential viruses such as foot-and-mouth disease virus (FMDV) and avian influenza virus (AIV) have been designed, which can detect these viruses directly in oral swab or poultry feces samples, in a short time (less than 30 minutes) and without the need for a gene amplification step (such as PCR). Similarly, for bacterial diseases such as brucellosis and bovine tuberculosis, sensors have been developed that detect specific antigens or antibodies in milk or serum samples with accuracy and specificity comparable to ELISA, but with the significant advantage of much higher speed and the potential for point-of-care testing. This capability represents a fundamental revolution in epidemic management and disease surveillance programs.

One of the most remarkable accomplishments reported is the achievement of extremely high diagnostic sensitivity, which often falls within the femtomolar and even attomolar ranges. This technology represents a significant departure from conventional rapid detection kits (LFA) and even some more advanced laboratory methods. The unique properties of the nanomaterials used are largely responsible for this level of sensitivity. For instance, gold nanoparticles can amplify powerful optical signals due to the long-range surface plasmon resonance (LSPR) effect. Carbon nanotubes and graphene, on the other hand, provide an ideal foundation for electrochemical biosensors, offering very low detection limits due to their high electrical conductivity and large specific surface area. This essential characteristic enables the identification of pathogens or biomarkers even in the very early stages of infection or disease, when the concentration of the analyte in the sample is extremely low. This presents a wonderful opportunity for early intervention and disease prevention in the flock.

Nanobiosensors play a crucial role in enhancing food safety along the food chain [79-85]. In animal products, such as milk, meat, and honey, a significant amount of research has been dedicated to the development of highly sensitive and rapid sensors for the simultaneous detection of various antibiotic residues (including penicillin and tetracycline) and mycotoxins (such as aflatoxin M1 in milk). These sensors have been designed to detect several antibiotic residues simultaneously. Methods that are electrochemical or optical (like fluorescence) are often used in the construction of these sensors. In a short amount of time, they can identify very low amounts of these pollutants, which is particularly difficult for traditional approaches to do. This enables the continuous and efficient monitoring of production lines in food processing facilities, significantly reducing the likelihood of tainted goods entering the consumer market and posing a threat to human health. Additionally, sensors capable of rapidly detecting food pathogens in meat samples, such as Salmonella and E. coli, have also been reported. This evidence demonstrates the significance of this technology in maintaining the health of the general population.

3. DISCUSSION

Nanobiosensors hold great promise for transforming various aspects of veterinary medicine, including disease detection, monitoring health, and ensuring food safety [86-88]. This review clearly demonstrates the remarkable potential of their approach. They directly address long-standing problems in the veterinary field, specifically the need for rapid point-of-care tests and ongoing health monitoring of large herds. These sensors can quickly and accurately detect very small amounts of different analytes, a feat that has never been achieved previously. The successes in identifying important pathogens, such as the virus that causes foot-and-mouth disease and the influenza virus that spreads among birds, are only the beginning of what this technology can achieve. One of the most remarkable aspects of these results is the development of "multiplexing," which enables a single sensor to detect multiple illnesses or biomarkers in a sample simultaneously. This ability facilitates the identification of health issues in animals and enables faster differential diagnosis in the field, a crucial aspect of managing an epidemic.

Even with these promising achievements, there are still many problems that need to be solved before nanobiosensors can be sold to veterinarians. One of the most significant problems that needs to be addressed is ensuring that things are reliable and legitimate in real life. The efficiency of a nanobiosensor may be affected by the intricate matrix of real biological samples, which contrasts with the simpler conditions of a laboratory setting [89, 90]. Some examples of these types of samples include milk with different components or blood with proteins, which makes it challenging to analyze. Because of this, the livestock business must conduct thorough validation testing with large sample sizes and diverse animal populations before they can sell their products. Another problem that has to be solved is how to make things scalable and affordable for mass production [91, 92]. To make these sensors affordable enough for many cattle producers and veterinarians to utilize, significant technical challenges need to be addressed. Some of these challenges include producing high-quality, homogeneous nanomaterials on a large scale and ensuring that biological elements can be reliably incorporated into them.

There are problems with nanobiosensors, but there are also significant concerns about the safety and potential harm of the nanomaterials being employed. It is essential to consider the potential consequences of what happens to these nanomaterials after they are used, particularly when the sensor is in proximity to an animal or food, such as milk [93, 94]. Can nanoparticles go through the food chain of people and cause harm? A thorough risk assessment, along with the establishment of regulatory frameworks and safety standards by authorities such as the Food and Drug Administration, is crucial for the public to accept this technology and for it to succeed in the business sector. It is also a significant challenge for designers to make nanobiosensors user-friendly for agricultural workers who aren't experts in the field [95, 96]. An ideal nanobiosensor would be a device that is easy to "plug in and play with," doesn't need any sample preparation or user training, and shows the findings plainly (for example, on a mobile phone screen).

Despite these challenges, the future of nanobiosensors in veterinary medicine appears quite promising [97]. In the future, research will likely focus on developing smart sensors that work together. These sensors can be placed under the skin or directly on the animal. They would then send physiological data (such as temperature, pH, glucose levels, or inflammatory indicators) to a central platform wirelessly and continuously. Big Data, Artificial Intelligence (AI), and the Internet of Things (IoT) can collaborate to create intelligent early warning systems, predict disease outbreaks, and fully automate herd health management [98]. The combination of these three technologies will make all of these things conceivable. This idea involves the complete implementation of Precision Livestock Farming and One Health. In this approach, the health of each

animal is regularly assessed, and the information obtained from these checks is used to plan and implement effective therapies.

4. CONCLUSION

Nanobiosensors, which take advantage of the one-of-a-kind characteristics of nanomaterials, are on the verge of bringing about a revolution in the field of veterinary medicine. By delivering capabilities that have never been seen before in ultra-sensitive and quick detection of infections, monitoring of health biomarkers, and management of food pollutants, this technology offers a direct answer to diagnostic issues that have been present for a long time in both field and industrial settings. However, to successfully transition from research to broad commercial use, it is necessary to overcome substantial hurdles. These problems include standardizing manufacturing processes, validating them under real-world settings, conducting a comprehensive safety evaluation, and ensuring economic feasibility.

Declarations and statements

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No funding was received to conduct this study.

Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical approval

All applicable international, national, and/or institutional guidelines for writing a review paper were followed.

Author contribution

Conceptualization: [Sina Sadeghi Nezhad], …; Methodology: [All Authors], …; Formal analysis and investigation: [All Authors], …; Writing - original draft preparation: [All Authors]; Writing - review and editing: [Sina Sadeghi Nezhad], …; Funding acquisition: [Self-funding], …; Supervision: [Marzieh Saki].

Consent to participate

Not applicable

Consent for publication

Not applicable

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Declaration of the use of generative AI

This paper was composed without the use of any artificial intelligence tools for generating data.

REFERENCES

1. Orakpoghenor O. Problems in veterinary pathology: A focus on diagnosis. European Journal of Scientific Research and Reviews. 2024;1(2):103-.
2. Vainionpää R, Waris M, Leinikki P. Diagnostic techniques: serological and molecular approaches. Reference module in biomedical sciences. 2015:B978-0-12-801238-3.02558-7.
3. Liu Q, Jin X, Cheng J, Zhou H, Zhang Y, Dai Y. Advances in the application of molecular diagnostic techniques for the detection of infectious disease pathogens. Molecular Medicine Reports. 2023;27(5):104.
4. Yang S, Rothman RE. PCR-based diagnostics for infectious diseases: uses, limitations, and future applications in acute-care settings. The Lancet infectious diseases. 2004;4(6):337-48.
5. Yadav MP, Singh RK, Malik YS. Emerging and transboundary animal viral diseases: Perspectives and preparedness. Emerging and transboundary animal viruses: Springer; 2020. p. 1-25.
6. Arzt J, White W, Thomsen B, Brown C. Agricultural diseases on the move early in the third millennium. Veterinary pathology. 2010;47(1):15-27.
7. Ghimpețeanu OM, Pogurschi EN, Popa DC, Dragomir N, Drăgotoiu T, Mihai OD, et al. Antibiotic use in livestock and residues in food—A public health threat: A review. Foods. 2022;11(10):1430.
8. Neethirajan S, Tuteja SK, Huang S-T, Kelton D. Recent advancement in biosensors technology for animal and livestock health management. Biosensors and Bioelectronics. 2017;98:398-407.
9. Sadr S, Nazemian S, Dianaty S, Hajjafari A, Fazel B, Rezaei A, et al. Advancing gut microbiome insights: Graphene quantum dot nanobiosensors for microbial metabolite detection. Chemical Engineering Journal. 2025;513:162954.
10. Kulkarni MB, Ayachit NH, Aminabhavi TM. Recent advancements in nanobiosensors: current trends, challenges, applications, and future scope. Biosensors. 2022;12(10):892.
11. Shivakumar N. Recent advances in biological nanodevices and biosensors: insights into applications and technological innovations. Malaysian NANO-An International Journal. 2024;4(1):86-101.
12. Barbosa AI, Rebelo R, Reis RL, Bhattacharya M, Correlo VM. Current nanotechnology advances in diagnostic biosensors. Medical Devices & Sensors. 2021;4(1):e10156.
13. Orozco J. Nanoscience, nanotechnology, and disruptive technologies in the context of precision medicine. Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales. 2023;47(183):221-41.
14. Sadr S, Hajjafari A, Sazmand A, Santucciu C, Masala G, Soroushianfar M, et al. Nanobiosensors for revolutionizing parasitic infections diagnosis: a critical review to improve global health with an update on future challenges prospect. European Journal of Medical Research. 2025;30(1):484.
15. Nastasijevic I, Kundacina I, Jaric S, Pavlovic Z, Radovic M, Radonic V. Recent advances in biosensor technologies for meat production chain. Foods. 2025;14(5):744.
16. Amin N, Almasi A, Ozer T, Henry CS, Hosseinzadeh L, Keshavarzi Z. Recent advances of optical biosensors in veterinary medicine: Moving towards the point of care applications. Current topics in medicinal chemistry. 2023;23(23):2242-65.
17. Zhengtian L, Chen L, Yuan H, Ayub J. Biosensors and Nano-Detection Systems for Monitoring Animal Health and Environmental Safety. Animal BioSphere. 2025;1(1):1-11.
18. Manessis G, Gelasakis AI, Bossis I. Point-of-care diagnostics for farm animal diseases: from biosensors to integrated lab-on-chip devices. Biosensors. 2022;12(7):455.
19. Deka A, Mandal M. Conducting Polymer Nanocomposite-Based Sensors and Their Applications in Food Contaminant Detection: A Review. Sustainable Green Nanotechnology. 2024:72-96.
20. Younis S, Zia R, Tahir N, Bukhari SZ, Khan WS, Bajwa SZ. Nanosensors for animal health monitoring. Nanosensors for smart agriculture: Elsevier; 2022. p. 509-29.
21. de Lima LF, Barbosa PP, Simeoni CL, de Paula RFO, Proenca-Modena JL, de Araujo WR. Electrochemical Paper-Based Nanobiosensor for Rapid and Sensitive Detection of Monkeypox Virus. ACS Appl Mater Interfaces. 2023;15(50):58079-91.
22. Shin J, Kim HR, Bae PK, Yoo H, Kim J, Choi Y, et al. Reusable surface amplified nanobiosensor for the sub PFU/mL level detection of airborne virus. Sci Rep. 2021;11(1):16776.

23. Flores MSC, Alocilja EC, Amalin DM, Aguila MJB, Purificacion MV, Merca FE, et al. DNA-Based Nanobiosensor for the Colorimetric Detection of Dengue Virus Serotype 2 Synthetic Target Oligonucleotide. Biosensors (Basel). 2025;15(2).
24. Zhang Z, Wu Y, Xu J, Meng Z, Chen Q, Yin S. Quantitative Analysis of Hepatitis D Virus Using gRNA-Sensitive Semiconducting Polymer Dots. Anal Chem. 2025;97(3):1575-83.
25. Wasik D, Mulchandani A, Yates MV. Point-of-Use Nanobiosensor for Detection of Dengue Virus NS1 Antigen in Adult Aedes aegypti: A Potential Tool for Improved Dengue Surveillance. Anal Chem. 2018;90(1):679-84.
26. Shenagari M, Ebrahimi A, Bozorgzadeh E, Khosravi M, Hasan-Alizadeh E. Advanced multiplexed electrochemical nanobiosensors for simultaneous detection of BK polyomavirus miRNAs in renal transplants. Anal Methods. 2025;17(8):1804-12.
27. Manohara Reddy YV, Shin JH, Hwang J, Kweon DH, Choi CH, Park K, et al. Fine-tuning of MXene-nickel oxide-reduced graphene oxide nanocomposite bioelectrode: Sensor for the detection of influenza virus and viral protein. Biosens Bioelectron. 2022;214:114511.
28. Cheng MS, Ho JS, Tan CH, Wong JP, Ng LC, Toh CS. Development of an electrochemical membrane-based nanobiosensor for ultrasensitive detection of dengue virus. Anal Chim Acta. 2012;725:74-80.
29. Sabzehparvar F, Rahmani Cherati T, Mohsenifar A, Roodbar Shojaei T, Tabatabaei M. Immobilization of gold nanoparticles with rhodamine to enhance the fluorescence resonance energy transfer between quantum dots and rhodamine; new method for downstream sensing of infectious bursal disease virus. Spectrochim Acta A Mol Biomol Spectrosc. 2019;212:173-9.
30. Kim MW, Park HJ, Park CY, Kim JH, Cho CH, Phan LMT, et al. Fabrication of a paper strip for facile and rapid detection of bovine viral diarrhea virus via signal enhancement by copper polyhedral nanoshells. RSC Adv. 2020;10(50):29759-64.
31. Tripathy S, Krishna Vanjari SR, Singh V, Swaminathan S, Singh SG. Electrospun manganese (III) oxide nanofiber based electrochemical DNA-nanobiosensor for zeptomolar detection of dengue consensus primer. Biosens Bioelectron. 2017;90:378-87.
32. Takemura K, Adegoke O, Takahashi N, Kato T, Li TC, Kitamoto N, et al. Versatility of a localized surface plasmon resonance-based gold nanoparticle-alloyed quantum dot nanobiosensor for immunofluorescence detection of viruses. Biosens Bioelectron. 2017;89(Pt 2):998-1005.
33. Zare H, Meshkat Z, Hatamluyi B, Rezayi M, Ghazvini K, Derakhshan M, et al. The first diagnostic test for specific detection of Mycobacterium simiae using an electrochemical label-free DNA nanobiosensor. Talanta. 2022;238(Pt 2):123049.
34. Srivastava SK, Hamo HB, Kushmaro A, Marks RS, Grüner C, Rauschenbach B, et al. Highly sensitive and specific detection of E. coli by a SERS nanobiosensor chip utilizing metallic nanosculptured thin films. Analyst. 2015;140(9):3201-9.
35. Jonidi Shariatzadeh F, Logsetty S, Liu S. Ultrasensitive Nanofiber Biosensor: Rapid In Situ Chromatic Detection of Bacteria for Healthcare Innovation. ACS Appl Bio Mater. 2024;7(4):2378-88.
36. Imran M, Ehrhardt CJ, Bertino MF, Shah MR, Yadavalli VK. Chitosan Stabilized Silver Nanoparticles for the Electrochemical Detection of Lipopolysaccharide: A Facile Biosensing Approach for Gram-Negative Bacteria. Micromachines (Basel). 2020;11(4).
37. Mousavizadegan M, Hosseini M, Sheikholeslami MN, Ganjali MR. A fluorescent sensor array based on antibiotic-stabilized metal nanoclusters for the multiplex detection of bacteria. Mikrochim Acta. 2024;191(5):293.
38. Sen S, Sarkar P. Impedance nanobiosensor based on enzyme-conjugated biosynthesized gold nanoparticles for the detection of Gram-positive bacteria. Biotechnol Prog. 2024;40(2):e3421.
39. Karuppiah S, Mishra NC, Tsai WC, Liao WS, Chou CF. Ultrasensitive and Low-Cost Paper-Based Graphene Oxide Nanobiosensor for Monitoring Water-Borne Bacterial Contamination. ACS Sens. 2021;6(9):3214-23.
40. Maldonado J, González-Guerrero AB, Fernández-Gavela A, González-López JJ, Lechuga LM. Ultrasensitive Label-Free Detection of Unamplified Multidrug-Resistance Bacteria Genes with a Bimodal Waveguide Interferometric Biosensor. Diagnostics (Basel). 2020;10(10).
41. Song D, Xu W, Han X, Wang H, Zhuo Y, Liu J, et al. CRISPR/Cas12a-powered evanescent wave fluorescence nanobiosensing platform for nucleic acid amplification-free detection of Staphylococcus aureus with multiple signal enhancements. Biosens Bioelectron. 2023;225:115109.

42. Nadzirah S, Hashim U, Gopinath SCB, Parmin NA, Hamzah AA, Yu HW, et al. Titanium dioxide-mediated resistive nanobiosensor for E. coli O157:H7. Mikrochim Acta. 2020;187(4):235.
43. Gao X, Zhang H, Liu L, Jia M, Li X, Li J. Nano-biosensor based on manganese dioxide nanosheets and carbon dots for dual-mode determination of Staphylococcus aureus. Food Chem. 2024;432:137144.
44. Rebelo AR, Liu C, Schäfer KH, Saumer M, Yang G, Liu Y. Poly(4-vinylaniline)/Polyaniline Bilayer-Functionalized Bacterial Cellulose for Flexible Electrochemical Biosensors. Langmuir. 2019;35(32):10354-66.
45. Mostajabodavati S, Mousavizadegan M, Hosseini M, Mohammadimasoudi M, Mohammadi J. Machine learning-assisted liquid crystal-based aptasensor for the specific detection of whole-cell Escherichia coli in water and food. Food Chem. 2024;448:139113.
46. Gangwar R, Rao KT, Khatun S, Rengan AK, Subrahmanyam C, Krishna Vanjari SR. Label-free miniaturized electrochemical nanobiosensor triaging platform for swift identification of the bacterial type. Anal Chim Acta. 2022;1233:340482.
47. Wang Y, Schill KM, Fry HC, Duncan TV. A Quantum Dot Nanobiosensor for Rapid Detection of Botulinum Neurotoxin Serotype E. ACS Sens. 2020;5(7):2118-27.
48. Naghshgar N, Hosseinzadeh S, Derakhshandeh A, Shaali R, Doroodmand MM. Introducing a portable electrochemical biosensor for Mycobacterium avium subsp. paratuberculosis detection using graphene oxide and chitosan. Sci Rep. 2024;14(1):34.
49. Alvandi H, Rezayan AH, Hajghassem H, Rahimi F. Rapid and sensitive whole cell E. coli detection using deep eutectic solvents/graphene oxide/gold nanoparticles field-effect transistor. Talanta. 2025;283:127184.
50. Yang X, Wang Y, Mao S, Liu Y, Chen F, Huang J, et al. One-pot, uracil-DNA-glycosylase-aided, and multi-indicator nanobiosensor detection platform for identifying Brucella melitensis from the Brucella spp. BMC Microbiol. 2025;25(1):475.
51. Vaezi Z, Azizi M, Sadeghi Mohammadi S, Hashemi N, Naderi-Manesh H. A novel iron quantum cluster confined in hemoglobin as fluorescent sensor for rapid detection of Escherichia coli. Talanta. 2020;218:121137.
52. Mahfouz AR, Nada HG, Magar HS, ElBaghdady KZ, Hassan RYA. Nano-biosensors for rapid detection of antibiotic resistance genes blaCTX-M in Escherichia coli and blaKPC in Klebsiella pneumoniae. Int J Biol Macromol. 2025;310(Pt 2):143216.
53. Naderlou E, Salouti M, Amini B, Amini A, Narmani A, Jalilvand A, et al. Enhanced sensitivity and efficiency of detection of Staphylococcus aureus based on modified magnetic nanoparticles by photometric systems. Artif Cells Nanomed Biotechnol. 2020;48(1):810-7.
54. Elahi N, Kamali M, Baghersad MH, Amini B. A fluorescence Nano-biosensors immobilization on Iron (MNPs) and gold (AuNPs) nanoparticles for detection of Shigella spp. Mater Sci Eng C Mater Biol Appl. 2019;105:110113.
55. Amini B, Kamali M, Salouti M, Yaghmaei P. Spectrophotometric, colorimetric and visually detection of Pseudomonas aeruginosa ETA gene based gold nanoparticles DNA probe and endonuclease enzyme. Spectrochim Acta A Mol Biomol Spectrosc. 2018;199:421-9.
56. Safarpour H, Majdi H, Masjedi A, Pagheh AS, Pereira MdL, Rodrigues Oliveira SM, et al. Development of optical biosensor using protein a-conjugated chitosan–gold nanoparticles for diagnosis of cystic echinococcosis. Biosensors. 2021;11(5):134.
57. Arida H, Mersal GA, El-Badawy M. Development of a nanotechnology-based screen-printed biosensor for detection of schistosoma mansoni antibodies. International Journal of Electrochemical Science. 2016;11(2):1337-44.
58. Santos GS, Andrade CA, Bruscky IS, Wanderley LB, Melo FL, Oliveira MD. Impedimetric nanostructured genosensor for detection of schistosomiasis in cerebrospinal fluid and serum samples. Journal of Pharmaceutical and Biomedical Analysis. 2017;137:163-9.
59. Arcas AS, Jaramillo L, Costa NS, Allil RCS, Werneck MM. Localized surface plasmon resonance-based biosensor on gold nanoparticles for Taenia solium detection. Applied Optics. 2021;60(26):8137-44.
60. Deris S, Osanloo M, Ghasemian A, Ataei S, Kohansal M, Samsami S, et al. The efficacy of AuNP-probe conjugate nanobiosensor in non-amplification and amplification forms for the diagnosis of leishmaniasis. BMC Infectious Diseases. 2022;22(1):847.

61. Frias IA, Andrade CA, Balbino VQ, de Melo CP. Use of magnetically disentangled thiolated carbon nanotubes as a label-free impedimetric genosensor for detecting canine Leishmania spp. infection. Carbon. 2017;117:33-40.
62. Rivas L, de la Escosura-Muñiz A, Serrano L, Altet L, Francino O, Sánchez A, et al. Triple lines gold nanoparticle-based lateral flow assay for enhanced and simultaneous detection of Leishmania DNA and endogenous control. Nano Research. 2015;8:3704-14.
63. Welearegay TG, Diouani MF, Österlund L, Ionescu F, Belgacem K, Smadhi H, et al. Ligand-capped ultrapure metal nanoparticle sensors for the detection of cutaneous leishmaniasis disease in exhaled breath. ACS sensors. 2018;3(12):2532-40.
64. Moradi M, Sattarahmady N, Rahi A, Hatam G, Sorkhabadi SR, Heli H. A label-free, PCR-free and signal-on electrochemical DNA biosensor for Leishmania major based on gold nanoleaves. Talanta. 2016;161:48-53.
65. Ramos-Jesus J, Pontes-de-Carvalho LC, Melo SMB, Alcântara-Neves NM, Dutra RF. A gold nanoparticle piezoelectric immunosensor using a recombinant antigen for detecting Leishmania infantum antibodies in canine serum. Biochemical engineering journal. 2016;110:43-50.
66. Andreadou M, Liandris E, Gazouli M, Mataragka A, Tachtsidis I, Goutas N, et al. Detection of Leishmania-specific DNA and surface antigens using a combination of functionalized magnetic beads and cadmium selenite quantum dots. Journal of microbiological methods. 2016;123:62-7.
67. Adu DK, Nate Z, Alake J, Ike BW, Mahlalela MC, Mohite SB, et al. Rapid and label-free A2 peptide epitope decorated CoFe2O4-C60 nanocomposite-based electrochemical immunosensor for detecting Visceral Leishmaniasis. Bioelectrochemistry. 2024;157:108662.
68. Sattarahmady N, Movahedpour A, Heli H, Hatam G. Gold nanoparticles-based biosensing of Leishmania major kDNA genome: visual and spectrophotometric detections. Sensors and Actuators B: Chemical. 2016;235:723-31.
69. Toubanaki DK, Athanasiou E, Karagouni E. Gold nanoparticle-based lateral flow biosensor for rapid visual detection of Leishmania-specific DNA amplification products. Journal of microbiological methods. 2016;127:51-8.
70. Mohan S, Srivastava P, Maheshwari S, Sundar S, Prakash R. Nano-structured nickel oxide based DNA biosensor for detection of visceral leishmaniasis (Kala-azar). Analyst. 2011;136(13):2845-51.
71. Obisesan OR, Adekunle AS, Oyekunle JA, Sabu T, Nkambule TT, Mamba BB. Development of electrochemical nanosensor for the detection of malaria parasite in clinical samples. Frontiers in chemistry. 2019;7:89.
72. Kumar B, Bhalla V, Bhadoriya RPS, Suri CR, Varshney GC. Label-free electrochemical detection of malaria-infected red blood cells. RSC advances. 2016;6(79):75862-9.
73. Kumar V, Pal S, Singh V, Parajapati YK, Saini J. Design of a Highly Sensitive and Precise Long-Range Surface Plasmon Resonance Sensor for early Detection of Malaria. Physica B: Condensed Matter. 2024:416072.
74. Monisha S, Sain A, Jayaprakash N, Senthil Kumar A. Facile Antibody Immobilization on a Redox-Active Thionine-Functionalized Carbon Nanofiber Surface for Rapid Electrochemical Immunosensing of a Bioengineered Malaria Protein Biomarker. Langmuir. 2025.
75. Hemben A, Ashley J, Tothill IE. Development of an immunosensor for Pf HRP 2 as a biomarker for malaria detection. Biosensors. 2017;7(3):28.
76. Ma X, Chen J, Lei Y, Dey S, Zhao J, editors. Autofluorescent nanoparticles for the detection of malaria-infection indicator. 2016 IEEE SENSORS; 2016: IEEE.
77. Li T, Meng F, Fang Y, Luo Y, He Y, Dong Z, et al. Multienzymatic disintegration of DNA-scaffolded magnetic nanoparticle assembly for malarial mitochondrial DNA detection. Biosensors and Bioelectronics. 2024;246:115910.
78. Jeon W, Lee S, Manjunatha D, Ban C. A colorimetric aptasensor for the diagnosis of malaria based on cationic polymers and gold nanoparticles. Analytical biochemistry. 2013;439(1):11-6.
79. Das S, Agarwal DK, Mandal B, Rao VR, Kundu T. Detection of the Chilli Leaf Curl Virus Using an Attenuated Total Reflection-Mediated Localized Surface-Plasmon-Resonance-Based Optical Platform. ACS Omega. 2021;6(27):17413-23.
80. Tessaro L, Aquino A, Panzenhagen P, Ochioni AC, Mutz YS, Raymundo-Pereira PA, et al. Development and Application of an SPR Nanobiosensor Based on AuNPs for the Detection of SARS-CoV-2 on Food Surfaces. Biosensors (Basel). 2022;12(12).

81. Zhou C, Zhang Y, Yang X, Zhao Z, Xia M, Wei C, et al. A magnetic CRISPR/Cas12a-SERS nanobiosensor for amplification-free and ultrasensitive detection of norovirus in water and food samples. Anal Chim Acta. 2025;1363:344133.
82. Karimiravesh R, Mohabati Mobarez A, Behmanesh M, Nikkhah M, Talebi Bezmin Abadi A, Esmaeilli S. Design of an optical nanobiosensor for detection of Legionella pneumophila in water samples. Iran J Microbiol. 2022;14(6):802-12.
83. Rahman MA, Karthikeyan M, Johnson I, Raja K, Sekar C, Mary XA, et al. Ensuring food security through rapid and in-field detection of diseases in food crops using real time and portable sensors. Anal Biochem. 2025;705:115925.
84. Alvandi H, Rezayan AH, Hajghassem H, Rahimi F, Askari Moghadam R, Firoozbakhtian A. Aptasensor based on rGO-AuNPs Field-effect Transistor for selective detection of Escherichia coli in river water. Anal Biochem. 2025;700:115796.
85. Ding Y, Yang Q, Liu X, Wang Y, Wang J, Wang X. An ultrasensitive fluorescence nano-biosensor based on RBP 41-quantum dot microspheres for rapid detection of Salmonella in the food matrices. Food Chem. 2025;468:142504.
86. Davidescu MA, Panzaru C, Creanga S, Simeanu C, Simeanu D, Dolis M, et al. Exploring Nanobiotechnologies in the Food Industry: Applications, Benefits and Challenges. Scientific papers animal science and biotechnologies. 2024;57(1):63-.
87. Ulucan-Karnak F, Kuru Cİ, Türkcan C, Kulabhusan PK. Potential application of nanobiotechnology for creating various diagnostic approaches for diseases in livestock. Nanobiotechnology for the Livestock Industry: Elsevier; 2023. p. 157-74.
88. Boodhoo N, Shoja Doost J, Sharif S. Biosensors for Monitoring, Detecting, and Tracking Dissemination of Poultry-Borne Bacterial Pathogens Along the Poultry Value Chain: A Review. Animals. 2024;14(21):3138.
89. Hassan RY. Advances in electrochemical nano-biosensors for biomedical and environmental applications: from current work to future perspectives. Sensors. 2022;22(19):7539.
90. Chamorro-Garcia A, Merkoçi A. Nanobiosensors in diagnostics. Nanobiomedicine. 2016;3:1849543516663574.
91. Mahato K, Maurya PK, Chandra P. Fundamentals and commercial aspects of nanobiosensors in point-of-care clinical diagnostics. 3 Biotech. 2018;8(3):149.
92. Perdomo SA, Marmolejo-Tejada JM, Jaramillo-Botero A. Bio-nanosensors: Fundamentals and recent applications. Journal of The Electrochemical Society. 2021;168(10):107506.
93. Guruprasath N, Sankarganesh P, Adeyeye SAO, Babu AS, Parthasarathy V. Review on emerging applications of nanobiosensor in food safety. Journal of Food Science. 2024;89(7):3950-72.
94. Singh RP. Recent trends, prospects, and challenges of nanobiosensors in agriculture. Biosensors in agriculture: Recent trends and future perspectives. 2021:3-13.
95. Rafi Z, Khan H, Husain A, Khanam A, Alafnan A, Alobaida A, et al. Food contamination and the emerging application of nanobiosensors in food safety. Journal of Food Science. 2025;90(2):e70073.
96. Awlqadr FH, Altemimi AB, Qadir SA, Salih TAH, Alkanan ZT, AlKaisy QH, et al. Emerging trends in nano-sensors: A new frontier in food safety and quality assurance. Heliyon. 2025;11(1).
97. Sadr S, Lotfalizadeh N, Abbasi AM, Soleymani N, Hajjafari A, Roohbaksh Amooli Moghadam E, et al. Challenges and prospective of enhancing hydatid cyst chemotherapy by nanotechnology and the future of nanobiosensors for diagnosis. Tropical medicine and infectious disease. 2023;8(11):494.
98. Pandhi S, Kumari N, Jain A, Sharma V. Emerging technologies in food safety: AI-powered, nano-enabled, and biosensor-based strategies for rapid contaminant detection. Food Analytical Methods. 2025:1-15.