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Review Article

Biosensors and Nano-Detection Systems for Monitoring Animal Health and Environmental Safety

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Abstract: Monitoring environmental safety and animal health has been transformed by the fast developments in biosensor technology and nanotechnology. Integrated with nano-sensing systems, biosensors provide real-time, very sensitive, specialized diagnostic instruments for early illness diagnosis, metabolic health monitoring, and environmental assessment in cattle and aquaculture systems. By offering creative techniques for identifying pollutants, medication residues, and infections, these technologies help to improve food safety and sustainable animal production. The concepts, varieties, and uses of biosensors in veterinary and environmental sciences are investigated in this review together with their benefits, difficulties, and future directions. Notwithstanding their great promise, several obstacles like high manufacturing costs, legal restrictions, and integration difficulties prevent their broad acceptance of these technologies. To improve biosensor efficiency, lower costs, and guarantee more general applicability in the cattle and aquaculture sectors, more study and technology developments are required.

Keywords: Biosensors; Nanotechnology; Animal Health; Environmental Safety; Livestock

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Introduction

Biosensing technologies have advanced greatly in response to the growing need for environmental safety and sustainable livestock farming. Rising worries about zoonotic illnesses, food security, and ecological integrity have made biosensors and nano-detection systems more important instruments for tracking animal health and environmental safety [1,2]. These systems are sensitive and specifically detect pathogens, poisons, and physiological indicators by combining bio-recognition elements with sophisticated nano-materials. The combination of biotechnology and nanotechnology has produced very effective diagnostic tools competent of real-time, on-site monitoring, so transforming disease diagnosis, environmental hazard assessment, and precision livestock husbandry [3,4]. Biosensors are analytical tools made of a transducer turning the biological interaction into a measurable signal and a biological recognition element (such as enzymes, antibodies, nucleic acids, or microorganisms) [5,6]. In the context of animal health, biosensors enable early diagnosis of infectious diseases, monitoring of metabolic problems, and identification of stress biomarkers, so enhancing animal welfare and production. In environmental monitoring, biosensors also help to quickly identify pollutants, heavy metals, pesticides, and microbiological contaminants so guaranteeing ecosystem balance and public health [7,8].Through improved detection sensitivity, stability, and miniaturization, nanotechnology has greatly raised biosensor performance[9]. Widely used in biosensors to magnify signals and offer quick responses are nano-materials like gold nanoparticles, carbon nanotubes, graphene, and quantum dots [10,11]. Applied in precision agriculture, veterinary diagnostics, and environmental surveillance, these nano-detection technologies show promise in reducing the hazards related to disease outbreaks and ecological damage [12,13].

The Importance of Biosensors in Animal Health Monitoring

Maintaining food safety, productivity, and stopping the spread of zoonotic illnesses all depend on the state of animal health. Many times time-consuming and requiring laboratory equipment are traditional diagnostic approaches include polymerase chain reaction (PCR) and culture-based techniques [14,15]. As quick, reasonably priced, field-deployable methods for disease surveillance, biosensors present an option. Recent developments have produced piezoelectric, optical, and electrochemical biosensors catered for veterinary uses [16]. High sensitivity and portability of electrochemical biosensors—which track electrical changes following interaction with a target analyte—have helped them to become somewhat well-known. Amperometric biosensors have been effectively employed, for instance, to identify bacterial diseases including bovine mastitis, brought on by Escherichia coli and Staphylococcus aureus [17,18]. Analogous fluorescence, colorimetric, and surface plasmon resonance (SPR) methods are used by optical biosensors to identify viral infections like avian influenza virus (AIV) and foot-and- mouth disease virus (FMDV). Rapid on-farm diagnostics made possible by point-of- care (POC) biosensors for veterinary use have greatly enhanced disease control. Early intervention made possible by these devices helps to lower the demand for broad-spectrum antibiotics and hence minimize economic losses [19,20]. Wearable biosensors buried in collars or skin patches also continually monitor physiological indicators including body temperature, heart rate, and stress levels in cattle, so offering insightful analysis of animal well-being and productivity [21,22].

Nano-Detection Systems in Environmental Safety

Human and animal health suffers great hazards from environmental degradation. Effective monitoring methods are required in water, soil, and air as well as in other pollutants including heavy metals, pesticides, bacteria, and other toxins. Environmental safety evaluations have benefited much from nano-detection systems, which use nano-materials to improve detection capacities [23]. Monitoring water quality is among the most obvious uses for nano-detection devices. Developed to detect heavy metals including lead (Pb), mercury (Hg), and arsenic (As) at very low concentrations, nanostructured sensors—including graphene-based biosensors—have been perfect for ongoing environmental observation, these sensors provide great precision, fast response, and long-term stability[24]. Agricultural runoff's pesticide leftovers can harm ecosystems and animal health. With great precision, organophosphate insecticides in water and soil samples have been found using nano-biosensors fitted with molecularly imprinted polymers (MIPs). Similarly, real-time monitoring of antibiotic residues in cattle wastewater using gold nanoparticle-based colorimetric biosensors has addressed issues regarding antimicrobial resistance (AMR)[25].

Table 1. Nano-Detection Systems in Environmental Safety

Nano-Detection System	Principle of Detection	Applications in Environmental Safety	Advantages	Challenges & Limitations
Nanoparticle-Based Sensors	Uses metal nanoparticles (e.g., gold, silver) for colorimetric or fluorescence-based detection of contaminants.	Detection of heavy metals (lead, mercury, arsenic) in water and soil, pesticide residues in food.	High sensitivity, rapid detection, easy visualization.	Stability issues, potential toxicity of nanoparticles, expensive synthesis.
Carbon Nanotube (CNT) Sensors	CNTs enhance electrical conductivity upon binding with target molecules for electrochemical sensing.	Monitoring air pollutants (volatile organic compounds, CO, NO2), detecting bacterial contamination in water.	Ultra-sensitive detection, real-time monitoring, reusable sensor surfaces.	Complex fabrication, potential biotoxicity, high production cost.
Graphene-Based Sensors	Uses graphene sheets for high surface area adsorption and electrochemical signal amplification.	Detection of pesticide residues, heavy metals, and waterborne pathogens.	High selectivity, flexible and miniaturized sensor designs, fast response time.	Limited large-scale production, surface contamination issues.
Quantum Dot-Based Sensors	Fluorescent semiconductor nanocrystals that emit light upon target binding, enabling optical sensing.	Detection of toxins, heavy metals, and organic pollutants in water and food samples.	High photostability, tunable fluorescence properties, multiplex detection.	Cytotoxicity concerns, expensive synthesis, environmental persistence issues.

Molecularly Imprinted Polymer (MIP) Nanosensors	Synthetic receptors mimic biological molecules for highly selective contaminant detection.	Detection of endocrine-disrupting chemicals, antibiotics, and microplastics in water.	Highly selective, cost-effective compared to biological receptors.	Long synthesis time, difficulty in scaling up production.
Nano-Biosensors	Combines biological recognition elements (enzymes, antibodies, DNA) with nanomaterials for detecting environmental hazards.	Real-time detection of pathogens, antibiotic residues, and toxins in air, soil, and water.	High specificity, integration with portable devices, rapid field testing.	Sensitivity to environmental conditions, expensive biorecognition elements.
Surface-Enhanced Raman Spectroscopy (SERS) Nanosensors	Uses nanostructured surfaces to amplify Raman signals for ultra-sensitive molecular detection.	Identification of trace pollutants, pesticides, and industrial chemicals in environmental samples.	Ultra-low detection limits, rapid analysis, label-free sensing.	Complex sample preparation, interference from environmental matrices.
Nano-Optical Sensors	Uses plasmonic or fluorescent nanomaterials for detecting environmental pollutants.	Real-time air and water quality monitoring, identification of toxic gases.	High resolution, remote sensing capability, minimal sample preparation.	Sensitivity to environmental fluctuations, potential false signals.
Magnetic Nanoparticle Sensors	Magnetic nanoparticles capture target contaminants and are separated using a magnetic field for detection.	Removal and detection of heavy metals, oil spills, and pathogens from water bodies.	Rapid sample processing, reusable nanoparticles, high efficiency.	Nanoparticle aggregation, cost of functionalization, environmental impact concerns.
Nanoscale Field-Effect Transistors (FETs)	Uses nanomaterials to modulate electrical signals upon pollutant binding.	Detection of chemical toxins, biological pathogens, and greenhouse gases.	Low power consumption, ultra-sensitive real-time detection.	Fabrication complexity, need for calibration, susceptibility to environmental noise.
Nanostructured Membranes	Nanoporous membranes selectively filter and detect contaminants in water.	Desalination, removal of pharmaceuticals and heavy metals from water sources.	High filtration efficiency, energy-efficient, integration with existing purification systems.	Potential fouling, membrane degradation over time, high initial cost.

Integration of Biosensors with IoT and AI for Smart Monitoring

The combination of artificial intelligence (AI) and biosensors with the Internet of Things (IoT) has improved their use in environmental safety and animal health especially. Remote monitoring and predictive analytics are made possible by IoT-enabled biosensors, which send continuous data to cloud-based platforms [26]. By means of data pattern analysis, artificial intelligence systems identify anomalies and provide early warnings for environmental threats or disease epidemics. For example, smart agricultural systems now feature AI-driven biosensors tracking cattle health in real time. Using machine learning algorithms, these systems highly accurately identify ailments including heat stress, respiratory disorders, and nutritional deficits from sensor data [27]. Using nano-sensors, AI-integrated nano-detection systems have been applied in environmental applications for real-time air pollution monitoring, particulate matter (PM) and volatile organic compound (VOC) analysis [28,29].

Applications of Biosensors in Animal Health Monitoring

Disease Diagnosis and Pathogen Detection

By offering quick, reasonably priced, very sensitive detection techniques, biosensors have transformed the field of disease diagnosis and pathogen detection in veterinary medicine. Time-consuming and requiring specific laboratory environments are conventional diagnostic methods like polymerase chain reaction (PCR) and culture-based diagnostics. Conversely, biosensors are quite appropriate for on-site and point-of- care (POC) uses since they provide real-time detection capabilities[30]. Particularly electrochemical biosensors have shown considerable potential in identifying bacterial, viral, and fungal infections influencing animals. Amperometric biosensors have been effectively employed, for example, to identify Escherichia coli and Staphylococcus aureus, both of which are main causal agents of bovine mastitis [31]. Highly infectious viral diseases including foot-and- mouth disease virus (FMDV) and avian influenza virus (AIV) have been detected using optical biosensors comprising fluorescence-based sensors and surface plasmon resonance (SPR). Lab-on- a-chip (LOC) devices, which combine microfluidics with biosensing techniques to enable multiplexed pathogen detection, have also result from recent developments in biosensor technology. By enabling veterinarians and cattle growers to concurrently identify several infections, these small-scale diagnostic systems help to improve disease surveillance and epidemic avoidance [14].

Monitoring Livestock Metabolic and Nutritional Condition

The metabolic and nutritional condition of animals determines much of their health and output. Common in high-yielding dairy cows, metabolic diseases include ketosis, hypocalcaemia, and acidosis can cause significant financial losses if not controlled quickly. Emerging as indispensable instruments for real-time monitoring important metabolic parameters, biosensors guarantee faster intervention and better herd management [32,33]. Important markers of energy balance and ketosis in dairy cattle, non-esterified fatty acids (NEFA) and β-hydroxybutyrate (BHB) have been targets of development for electrochemical biosensors. Rapid and accurate data from these biosensors enable early metabolic illness identification and prevention [34]. Likewise, biosensors used to track blood calcium levels are absolutely essential in preventing hypocalcaemia in dairy cows, which can cause postpartum problems and lower milk production. Tracking physiological factors including body temperature, heart rate, and rumination habits has helped wearable biosensors further improve the capacity to continually monitor cattle health. By means of wireless communication technology, these biosensors send real-time data to cloud-based platforms, therefore empowering farmers to make educated decisions on feed formulation, illness prevention, and general herd health [35].

Detection of Veterinary Drug Residues

Food safety and antimicrobial resistance (AMR) have major questions about the indiscriminate use of veterinary medications including antibiotics, hormones, and anti-inflammatory compounds. Drug residues found in milk, meat, and other items generated from animals seriously jeopardize consumer health and might cause trade restrictions[36]. Emerging as useful instruments for identifying veterinary drug residues, biosensors guarantee compliance with food safety rules and support responsible drug use in animal farming. Antibacterial residue including tetracyclines, sulfonamides, and beta-lactams in dairy products and meat has been detected using electrochemical and optical biosensors rather extensively. For example, gold nanoparticle-based colorimetric biosensors have shown great sensitivity in identifying β-lactam antibiotics in milk, therefore offering a quick and simple substitute for conventional chromatographic methods [18]. Veterinary drug residue selective detection in complicated food matrices has also been using molecularly imprinted polymer (MIP)-based biosensors. Highly selective and sensitive detection is made possible by these biosensors' imitation of target molecule natural binding sites[37]. By combining biosensors with portable POC equipment, on-site food product screening has been further enabled, therefore saving time and money related to laboratory-based testing [38].

Table 2. Applications of Biosensors in Animal Health Monitoring

Biosensor Type	Principle of Detection	Target Analyte	Applications in Animal Health	Advantages	Challenges & Limitations
Electrochemical Biosensors	Measures electrical signals generated by biochemical reactions.	Pathogens, metabolites, stress biomarkers.	Early diagnosis of infectious diseases (e.g., Foot-and-Mouth Disease, Mastitis, Brucellosis).	High sensitivity, rapid response, portable devices.	Sensitivity to environmental conditions, need for calibration.

Optical Biosensors	Uses fluorescence, surface plasmon resonance (SPR), or colorimetric detection for analyte recognition.	Bacterial/viral antigens, hormones, toxins.	Detection of Avian Influenza, Bovine Tuberculosis, and stress indicators in livestock.	High specificity, real-time monitoring, label-free detection.	Expensive equipment, potential interference from complex biological samples.
Piezoelectric Biosensors	Detects mass changes through frequency shifts in a quartz crystal.	Viruses, bacteria, toxins.	Identification of zoonotic diseases (Rabies, Leptospirosis), foodborne pathogens.	No need for labeling, high specificity.	Affected by temperature and humidity, expensive fabrication.
Wearable Biosensors	Non-invasive monitoring using smart sensors embedded in collars, ear tags, or skin patches.	Body temperature, heart rate, stress biomarkers.	Continuous health monitoring of dairy cows, horses, and poultry for stress and disease detection.	Real-time, non-invasive, remote monitoring.	Data management issues, need for battery power.
Nanobiosensors	Uses nanomaterials (gold nanoparticles, graphene, and carbon nanotubes) to enhance sensitivity.	Microbial toxins, antibiotic residues, heavy metals.	Detection of drug residues in milk, meat, and feed to prevent antibiotic resistance.	Ultra-sensitive detection, miniaturized devices.	High production cost, regulatory hurdles.
Lab-on-a-Chip (LOC) Biosensors	Miniaturized devices integrating multiple biochemical tests into a single chip.	DNA/RNA of pathogens, cytokines, hormones.	On-site veterinary diagnostics for rapid disease screening in farms.	Portable, fast, requires minimal sample volume.	Requires expertise, integration with mobile data networks for real-time results.
Microfluidic Biosensors	Utilizes small fluid channels to detect biochemical reactions at micro/nanoscale.	Blood biomarkers, pathogens, metabolic markers.	Early detection of metabolic disorders like ketosis in dairy cows, pregnancy monitoring.	High-throughput analysis, minimal reagent consumption.	Fabrication challenges, requires precision engineering.
Enzymatic Biosensors	Uses enzyme-substrate reactions to generate measurable signals.	Glucose, urea, lactate.	Monitoring metabolic health in livestock, diagnosing ketosis and diabetes in pets.	High specificity, quick response time.	Enzyme degradation over time, need for storage under controlled conditions.
DNA-Based Biosensors	Hybridization of DNA probes with target genetic material for pathogen detection.	Bacterial/viral genetic material.	Identification of genetic diseases in livestock, detection of antibiotic resistance genes.	Highly specific, applicable for zoonotic disease monitoring.	Complex data interpretation, requires trained personnel.

Environmental Applications of Nano-Detection Systems

Monitoring Water Quality in Aquaculture

The health and output of aquatic life in aquaculture systems directly depend on the water quality. Emerging as extremely effective methods for monitoring important water quality indicators like dissolved oxygen, pH, ammonia, nitrites, heavy metals, and microbiological pollutants are nano-detection systems. Conventional water quality control techniques depend on laboratory-based chemical tests, sometimes time-consuming processes requiring specific tools. By means of quick, real-time, in situ monitoring, nano-based sensors, on the other hand, help to early identification of hazardous compounds and timely corrective action [39]. Developing very sensitive and selective biosensors for pollution detection in aquaculture systems has made extensive use of nano-materials like graphene, carbon nanotubes, and quantum dots. At trace levels, for example, gold nanoparticle-based sensors have shown extraordinary sensitivity in identifying heavy metals including lead (Pb), mercury (Hg), and arsenic (As). Furthermore used for the quick detection of ammonia and nitrate are nano-composite-based electrochemical sensors, which help to prevent harmful build-up causing fish mortality [40]. Furthermore linked with Internet of Things (IoT) devices are nano-enabled biosensors to provide ongoing water quality remote monitoring. These smart monitoring systems assess data patterns using artificial intelligence (AI) algorithms and cloud-based analytics, therefore provide farmers with useful information for preserving ideal water conditions [41]. Nano-detection systems applied in aquaculture have greatly raised general productivity, lowered disease outbreaks, and greatly improved sustainability [42].

Detection of Airborne Pathogens in Farm Animals

Animal farms are seriously threatened by airborne illnesses, which cause lower production and financial losses as well as respiratory problems. Preventing disease spread and applying biosecurity policies depend on the identification and tracking of airborne bacteria in agricultural settings. With high specificity and sensitivity, nano-detection systems have attracted more and more interest for their capacity to identify infections like Escherichia coli, Salmonella, Mycoplasma, and avian influenza virus (AIV). Real-time airborne bacterial and virus identification is possible with nanotechnology-enhanced biosensors including nano-plasmonic and nano-photonic sensors. Even at low pathogen concentrations, these sensors achieve ultra-sensitive detection by means of surface-enhanced Raman spectroscopy (SERS) and localized surface plasmon resonance (LSPR). For monitoring endotoxins and volatile organic compounds (VOCs) emitted by pathogenic bacteria, also created are electrochemical and fluorescence-based nano-biosensors. Further improving the capacity to regulate airborne pollutants in animal housing facilities is the combination of nano-detection systems with air filtration devices and smart ventilation technologies. IoT-connected nano-sensors continuously track air quality parameters and provide real-time alerts when pathogen levels exceed safe thresholds. In intense farming operations, this proactive method has shown success in reducing disease outbreaks and raising animal welfare [43].

Waste and Soil Management

Maintaining environmental sustainability and avoiding damage of natural resources depends on efficient soil and waste management in cattle raising. Advanced options for soil health monitoring, pollution detection, and waste treatment process optimization abound from nano-detection devices. Traditional soil testing methods require extensive laboratory analyses, whereas nano-based sensors enable rapid and on-site assessments of soil composition and contamination levels [44]. Designed to find heavy metals, pesticide residues, and antibiotic pollutants in agricultural soils, nanomaterial-based biosensors For example, graphene oxide-functionalized biosensors have shown high sensitivity in identifying lead and cadmium contamination, which can pose serious risks to plant and animal health. Similarly, enzyme-based nano-biosensors have been utilized to monitor nitrogen and phosphorus levels, facilitating precision fertilization and reducing environmental pollution. Microbial activity, methane emissions, and nutrient recycling efficiency in livestock waste management are much enhanced by nano-detection devices. To maximize waste breakdown and biogas generation, nanostructured sensors have been combined with bio-digesters and composting facilities. Furthermore, portable nano-biosensors let farmers find pathogens including Salmonella and Clostridium in manure, so guaranteeing better waste disposal methods [45]. The use of nano-detection systems in soil and waste management not only enhances agricultural sustainability but also mitigates environmental pollution, safeguarding both animal and human health. Future advancements in nanotechnology will further improve sensor accuracy, affordability, and integration with digital farming platforms, making precision agriculture more accessible to livestock producers worldwide [46].

Table 3. Environmental Applications of Nano-Detection Systems

Nano-Detection System	Principle of Detection	Target Analyte	Environmental Applications	Advantages	Challenges & Limitations
Nanoparticle-Based Sensors	Uses metal nanoparticles (gold, silver) for colorimetric, fluorescence, or electrochemical detection.	Heavy metals (lead, mercury, arsenic), pesticides, toxins.	Monitoring water pollution, soil contamination, and food safety.	High sensitivity, rapid detection, portable.	Costly synthesis, stability issues, potential toxicity.
Carbon Nanotube (CNT) Sensors	Conductivity changes upon interaction with pollutants.	Air pollutants (CO, NO_2, VOCs), bacterial toxins.	Air quality monitoring, detection of airborne pathogens in farms.	Ultra-sensitive, fast response, reusable.	Complex fabrication, potential biotoxicity.
Graphene-Based Sensors	High surface area adsorption with electrochemical or optical signal transduction.	Heavy metals, pesticide residues, bacterial contaminants.	Water quality analysis, soil contamination assessment.	High selectivity, flexible sensor designs, real-time monitoring.	Limited large-scale production, interference from other substances.
Quantum Dot-Based Sensors	Fluorescent semiconductor nanocrystals emitting light upon target binding.	Heavy metals, toxins, organic pollutants.	Detection of toxins in water, food safety monitoring.	High photostability, multiplex detection, rapid analysis.	Cytotoxicity concerns, environmental persistence, expensive.
Molecularly Imprinted Polymer (MIP) Nanosensors	Synthetic receptors mimic biological molecules for selective detection.	Pesticides, antibiotics, endocrine disruptors.	Detection of contaminants in water, soil, and animal feed.	Highly selective, cost-effective.	Long synthesis time, complex scalability.
Nano-Biosensors	Integrates biological recognition (enzymes, antibodies) with nanomaterials for contaminant detection.	Pathogens, antibiotic residues, toxins.	Real-time pathogen detection in water and food production facilities.	High specificity, fast, field-deployable.	Sensitive to environmental fluctuations, expensive.
Surface-Enhanced Raman Spectroscopy (SERS) Nanosensors	Uses nanostructured surfaces to amplify Raman signals for ultra-sensitive molecular detection.	Trace pollutants, pesticides, heavy metals.	Detection of industrial chemicals in environmental samples.	Ultra-low detection limits, rapid analysis.	Complex sample preparation, environmental noise interference.
Nano-Optical Sensors	Uses plasmonic or fluorescent nanomaterials for contaminant detection.	Airborne toxins, volatile organic compounds (VOCs).	Real-time air quality and gas pollution monitoring.	High resolution, remote sensing capability.	Environmental fluctuations can affect sensitivity.

Magnetic Nanoparticle Sensors	Uses magnetic nanoparticles to capture and isolate contaminants.	Heavy metals, pathogens, oil spills.	Removal and detection of toxins from water sources.	Rapid sample processing, reusable, high efficiency.	Nanoparticle aggregation, environmental impact concerns.
Nanoscale Field-Effect Transistors (FETs)	Conductivity modulation upon binding with target analytes.	Chemical pollutants, greenhouse gases, biological toxins.	Real-time sensing of toxic gases and industrial waste.	Low power consumption, ultra-sensitive.	Susceptibility to interference, complex calibration.
Nanostructured Membranes	Nanoporous membranes selectively filter and detect contaminants.	Microplastics, heavy metals, pharmaceuticals.	Water purification, filtration of industrial waste.	High efficiency, energy-efficient, sustainable.	Potential fouling, high initial cost.

Advantages and Challenges of Biosensors in Veterinary and Environmental Sciences

Advantages of Biosensors and Nano-Detection Systems

Biosensors and nano-detection systems have revolutionized veterinary and environmental sciences by providing rapid, accurate, and cost-effective monitoring solutions. Traditional diagnostic methods, such as culture-based techniques and polymerase chain reaction (PCR), require extensive laboratory infrastructure and lengthy processing times. In contrast, biosensors offer real-time detection capabilities, allowing for immediate decision-making in disease management and environmental assessment [47]. One of the primary advantages of biosensors is their high sensitivity and specificity. By incorporating nano-materials such as gold nanoparticles, graphene, and quantum dots, biosensors can detect pathogens, toxins, and pollutants at extremely low concentrations. This enhanced sensitivity is crucial in veterinary diagnostics, where early disease detection can prevent outbreaks and improve animal health outcomes. Similarly, in environmental applications, nano-detection systems facilitate the monitoring of contaminants such as heavy metals, pesticides, and antibiotic residues, ensuring ecosystem balance and public health. Another key advantage is the portability and ease of use of biosensors. Unlike traditional analytical instruments, biosensors can be miniaturized into handheld or wearable devices, enabling on-site monitoring. This feature is particularly beneficial in remote or resource-limited settings, where access to centralized laboratories is restricted. Point-of-care (POC) biosensors have gained widespread adoption in veterinary medicine for rapid disease diagnosis, while wearable biosensors integrated with IoT platforms provide continuous physiological monitoring in livestock. Moreover, the integration of biosensors with artificial intelligence (AI) and the Internet of Things (IoT) has enhanced their functionality. AI-driven data analytics can process sensor outputs to identify patterns, predict disease outbreaks, and optimize environmental management strategies. Smart farming systems utilizing biosensor technology have significantly improved livestock welfare, disease surveillance, and feed optimization, contributing to the sustainability of the agricultural industry [48].

Challenges and Limitations

Despite their numerous advantages, biosensors and nano-detection systems face several challenges that hinder their widespread adoption. One of the main limitations is the high production cost associated with advanced nano-materials and bio-recognition elements. The fabrication of biosensors requires specialized techniques, and mass production remains a challenge, making these devices less accessible for small-scale farmers and low-income region. Another significant challenge is the stability and durability of biosensors. Many biosensors rely on biological components such as enzymes and antibodies, which can degrade over time, reducing their operational lifespan. Environmental factors, including temperature fluctuations and humidity, can further affect sensor performance, necessitating regular calibration and maintenance. Developing robust and long-lasting biosensors remains a priority for researchers. The accuracy and reliability of biosensors can also be influenced by interference from complex biological and environmental matrices. In veterinary diagnostics, bodily fluids such as blood, saliva, and milk contain multiple biomolecules that can cause non-specific binding, leading to false-positive or false-negative results. Similarly, environmental samples, including soil and water, may contain various contaminants that interfere with sensor readings, necessitating additional sample preparation steps. Furthermore, regulatory and standardization challenges pose barriers to biosensor commercialization. Unlike conventional diagnostic tools, biosensors must undergo rigorous validation to ensure their accuracy, reproducibility, and compliance with regulatory frameworks. The lack of standardized protocols for biosensor testing and certification delays their acceptance in mainstream veterinary and environmental applications. Addressing these regulatory hurdles is crucial for the broader adoption of biosensor technologies [49].

Future Perspectives

The future of biosensors in veterinary and environmental sciences is promising, with ongoing research focused on improving their sensitivity, affordability, and integration with digital platforms. Advances in nanotechnology are expected to lead to the development of more stable and cost-effective biosensors. For instance, synthetic nano-materials and molecularly imprinted polymers (MIPs) are being explored as alternatives to biological recognition elements, offering greater stability and reusability [17]. The convergence of biosensors with AI and blockchain technology holds great potential for real-time data sharing and secure disease tracking. AI algorithms can enhance sensor accuracy by filtering out background noise and compensating for environmental variations. Blockchain-based biosensor networks can facilitate transparent and tamper-proof disease reporting, improving disease management and regulatory compliance in animal health. Another exciting area of development is the use of wearable biosensors for continuous health monitoring in animals. Smart collars, implantable microchips, and biosensor patches are being designed to track vital signs, stress levels, and metabolic changes in livestock. These innovations will enable farmers to implement precision farming techniques, reducing the reliance on antibiotics and improving overall herd health. Furthermore, miniaturized and cost-effective biosensors are expected to play a crucial role in environmental conservation. Emerging nano-biosensors capable of detecting microplastics, emerging contaminants, and greenhouse gases will aid in monitoring climate change impacts and mitigating environmental risks. The development of eco-friendly and biodegradable biosensors will further enhance sustainability efforts [16].

Conclusion

Biosensors and nano-detection systems have transformed veterinary diagnostics and environmental monitoring by offering rapid, sensitive, and real-time detection capabilities. While these technologies present numerous advantages, including portability, specificity, and AI integration, challenges such as high costs, stability issues, and regulatory hurdles must be addressed for their widespread adoption. Future research should focus on enhancing biosensor durability, affordability, and interoperability with digital platforms. With continued advancements, biosensors will play an integral role in sustainable livestock farming, disease prevention, and environmental protection, ensuring a healthier future for both animals and humans.

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