Nanobiosensors and Their Emerging Applications in Fisheries and Aquaculture

Shiv Kumar Yadav[1]* and Shawna Yadav[2]

[1]Department of Fish Genetics and Breeding, College of Fisheries, Lembucherra, Central Agricultural University (I), Tripura, India- 799210

[2]Department of Fisheries Biotechnology, Institute of Fisheries Post Graduate Studies-TNJFU, OMR Campus, Vaniyanchavadi, Chennai, India- 603103

*Corresponding author

Email address: shiv98kr@gmail.com

How to cite this article:

Yadav, S. K., & Yadav, S. (2026). Nanobiosensors and their emerging applications in fisheries and aquaculture. Agrolife Frontiers, 1(6), 26-33.

Abstract

Nanobiosensors are advanced nanoscale devices that integrate nanotechnology and biological sensing to enable rapid, sensitive detection of chemical and biological targets. They enable real-time monitoring of water quality, pathogens, fish health, and product safety in aquaculture systems. Their high sensitivity, portability, and specificity support precision farming and sustainable aquaculture management. With ongoing advancements in nanomaterials and biosensing technologies, nanobiosensors are expected to play a key role in improving productivity and environmental monitoring in fisheries and aquaculture.

Keywords: Nanobiosensors, Aquaculture, Fisheries, Water Quality Monitoring, Fish Health Management

1. Introduction

The development of nanobiosensors with incredibly focused microscopic sensors and high levels of miniaturization based on nanotechnology. It resulted from advances in science in the twenty-first century. Biosensors with remarkable sensing capabilities have recently been developed by researchers using an integrated approach that combines nanoscience, electronics, computing, and biology (Kerry et al., 2021). Nanobiosensors are actually nanosensors that have immobilized bioreceptor (Enzyme, Antibody, Protein molecule, DNA, Bacteria, or any cells, etc.) probes that are selective for the molecules of the target analyte. A nanobiosensor is often constructed at the nanoscale to collect, process, and analyze data at the atomic level (Sharma et al., 2021). Earlier bio-analytical processes were impractical, hitherto enabling actual applications and presenting new avenues for fundamental research. Its developments brought about nanoscale biosensors with exceptional sensitivity and adaptability. Its principle is based on identifying biochemical and biophysical signals associated with a particular disease at the molecular or cellular level. To make molecular diagnostics easier, it can be included in other technologies like lab-on-a-chip. Their applications include the detection of analytes like pathogens, microbes, prokaryotic cells, viral particles, urea, glucose, pesticides, etc., and the monitoring of metabolites.

2. Understanding the mechanism of Nano-biosensors

A nanobiosensor is an electroanalytical device in which a bioreceptor is incorporated into the transducer to generate measurable signals correlated with the concentration of a particular analyte in any type of sample (Bhattarai and Hameed, 2020). First, the analyte is recognized by the bioreceptor. After that, the biological material is immobilized, and a contact is then created between it and the transducer. The biological substance and the analyte combine to form a bound analyte, which results in a measurable response from an electronic system. The transducer then transforms the product (Kulkarni et al., 2022). Linked changes are converted into amplified, measurable electrical impulses, as illustrated in Figure 1. Furthermore, the transducer's output is processed and presented. At last, the signal can be interpreted as concentration.

Nanotechnology-based methods for rapid disease detection, enhanced fish absorption, vaccinations, hormone-like medicines, and vitamins could completely transform the fisheries and aquaculture industries. While there is a need for increased research and development in applying nanotechnology to aquaculture, several opportunities exist in areas such as fish health management, water treatment within aquaculture, animal breeding, and harvest and post-harvest technology

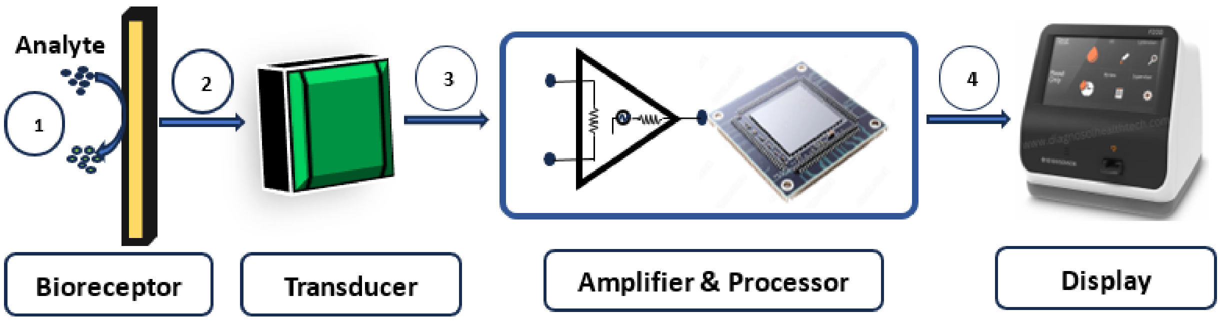

Fig. 1 Schematic diagram and Components of a Nanobiosensor: 1- Biochemical conversion (Bioreceptor, i.e., Antibody, Enzyme, DNA, Bacterial, Cell); 2- Biochemical signal detected by Transducer; 3- Signal sent to Amplifier connected with Processor to modulate and refine; 4- Signals are decoded by Processor and can be shown on Display.

3. Characteristics for an Ideal Nanobiosensor

An ideal nanobiosensor is designed to detect specific substances quickly and accurately while avoiding interference from other materials. It should be extremely small, safe for biological systems, and easy to carry and operate, even outside sophisticated laboratories. The device must be affordable, stable during storage, and capable of delivering reliable and consistent results (Ramesh et al., 2022). Additionally, its performance should remain unaffected by environmental conditions such as temperature, pH, or water quality, ensuring dependable detection with minimal signal disturbance.

4. Types of Nano-biosensors

Nanobiosensors can be categorized by their sensing mechanism and the transducer used to convert biological interactions into measurable signals. Different nanobiosensor platforms employ mechanical, optical, electrical, or nanomaterial-based approaches to detect specific analytes with high sensitivity and accuracy. Such classification helps in understanding their operational principles and selecting suitable sensors for applications including disease diagnosis, environmental monitoring, food safety, and aquaculture management. The major categories of nanobiosensors and their working concepts are illustrated in Figure 2**.**

The principles and major applications of different nanobiosensor systems are summarised in Table 1. The diversity of nanobiosensor platforms demonstrates the versatility of nanotechnology in modern biosensing applications. Variations in sensitivity, response time, portability, and detection mechanisms allow these sensors to be adapted for multiple fields, particularly healthcare diagnostics, environmental surveillance, and precision aquaculture monitoring (Bohara et al., 2024).

5. Application in Aquaculture

Aquaculture is rapidly adopting advanced technologies to improve productivity, fish health, and product quality. Among these innovations, nanobiosensors have emerged as smart monitoring tools capable of providing rapid, accurate, and real-time information throughout the aquaculture production cycle. From pond management to post-harvest processing, these sensors support precision farming and sustainable aquaculture practices.

Table 1 Different Nanobiosensors, principles, and their applications

Sl. No.	Nanobiosensors	Principle	Applications
1.	Mechanical Nanobiosensors	Cantilever bending or resonance change due to mass, stress, or temperature variation	Mass sensing, biomolecule detection, and environmental monitoring

2.	Optical Nanobiosensors	Light resonance or optical signal change upon analyte binding	Biomolecular interaction analysis, diagnostics, biochip sensing
3.	Nanowire Biosensors	Electrical signal modulation using DNA/CNT nanowire hybrids	High-throughput diagnostics, in vivo sensing, and environmental monitoring
4.	Ion Channel Switch Biosensor Technologies	Synthetic membrane generates an electrical signal upon molecular recognition	Detection of proteins, DNA, viruses, drugs, and pesticides
5.	Electronic Nanobiosensors	Electrical bridging between microelectrodes after target DNA binding	Genetic detection, pathogen identification
6.	Nanoshell Biosensors	Spectral change of antibody–nanoshell conjugates in the near-infrared region	Rapid immunoassays, chemical and biomedical sensing
7.	PEBBLE Nanobiosensors	Sensor molecules encapsulated in inert	Intracellular imaging, ion monitoring, and real-time cellular analysis

Smart Monitoring of Soil and Water Quality

Maintaining optimal pond soil and water conditions is essential for healthy fish growth. Nanobiosensors enable continuous monitoring of microbial activity, nutrient levels, pesticides, and toxic metals at extremely low concentrations. By detecting early environmental stress, farmers can take timely corrective measures and prevent disease outbreaks.

Case example: Gold nanoparticle–based aptamer sensors have been successfully used to detect mercury ions (Hg^{2+}) in aquatic environments, while nanowire field-effect transistor biosensors enable ultrasensitive detection of DNA changes associated with environmental stress, thereby supporting real-time water quality assessment (Tu et al., 2018).

Early Detection of Pathogens and Microbes

Disease outbreaks remain one of the biggest challenges in aquaculture. Nanobiosensors can rapidly identify bacteria, viruses, and parasites, even before visible symptoms appear, thereby reducing economic losses. Functionalized nanoparticles and carbon nanotube sensors provide high sensitivity for detecting pathogens directly from water or biological samples.

Case example: Electrical nanowire sensors demonstrated the capability to detect individual virus particles, highlighting their potential for early disease surveillance. Immuno-targeted gold nanoparticles have also been used for the specific detection of bacterial pathogens, such as *Staphylococcus aureus*, in aquatic systems (Rtimi, 2019).

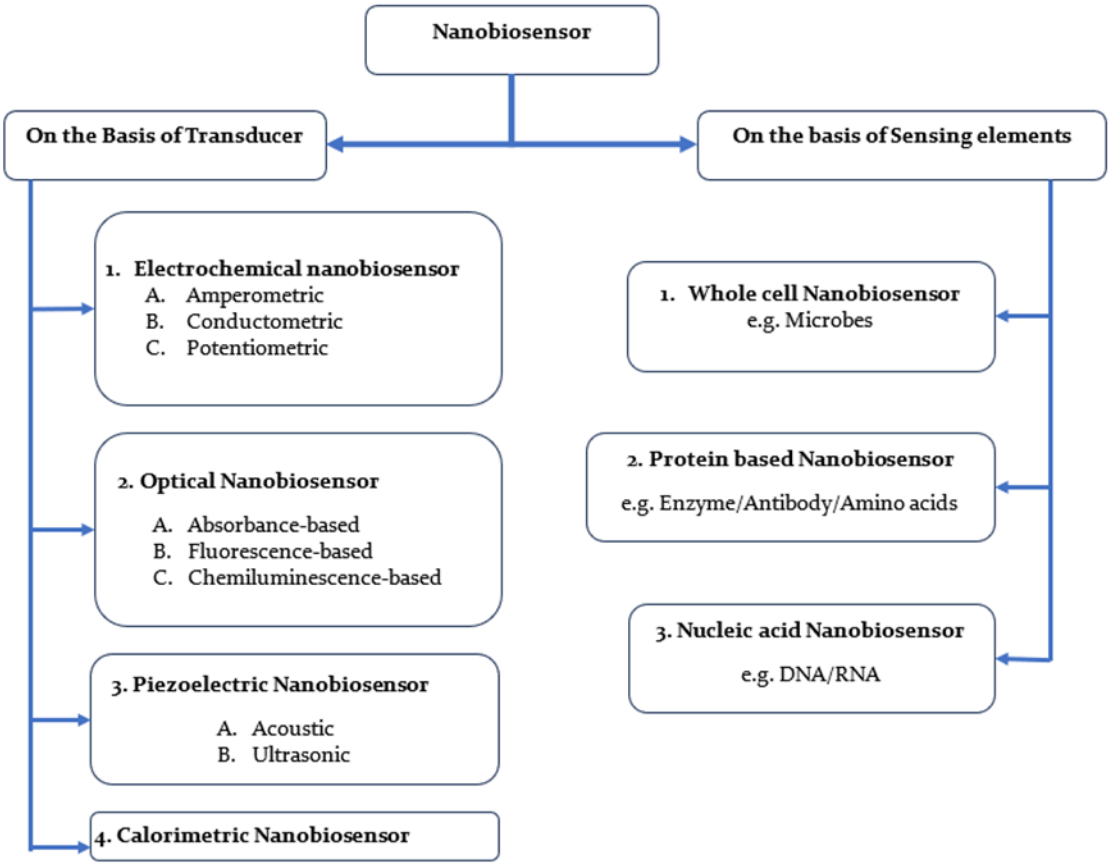

Fig. 2 Types of Nanobiosensor

Fish Tracking and Geolocalization

Modern aquaculture is moving toward intelligent farming systems where individual fish health and behavior can be monitored. Nano-enabled tags and nano-barcode devices, equipped with miniature circuits, enable remote identification and tracking of fish movement, feeding patterns, and physiological status.

Case example: Nano-barcode tagging technology enables automatic scanning and identification of individual fish from a distance, improving stock management, traceability, and smart cage farming operations (Ahuekwe et al., 2023).

Quality Detection in Processed Fish Products

Nanobiosensors also play an important role after harvesting by ensuring seafood safety during storage and transportation. Sensors integrated with DNA-tagged probes can monitor microbial contamination, temperature variations, and package leakage, helping maintain product freshness and consumer safety.

Case example: Nano-barcode systems, combined with color-coded DNA probes, have been used to simultaneously detect pathogens and monitor storage conditions, thereby improving quality control across the seafood supply chain (Rather et al., 2011).

Fish Gender Identification for Breeding Management

Selective breeding programs require accurate identification of fish sex, which is often difficult using external morphology alone. Nanobiosensors based on single-walled carbon nanotubes can detect the hormone 11-ketotestosterone (11-KT), a biomarker associated with male fish development.

Case example: A nanotube-based biosensor successfully measured 11-KT levels in Nile tilapia plasma, showing strong agreement with conventional ELISA analysis (Wu et al., 2022). This technique offers a rapid, non-invasive approach to gender determination and broodstock management.

6. Advantages of Nano-biosensors in Aquaculture

Nanobiosensors provide highly sensitive, rapid detection compared to conventional sensors due to their use of nanostructured materials. They enable real-time monitoring of water quality, environmental stress, and fish health, helping farmers take timely management decisions (Naresh and Lee, 2021). Their portability, accuracy, low cost, and minimal environmental impact improve disease prevention, enhance fish survival, and increase overall aquaculture productivity.

7. Future Prospects

Advancements in nanotechnology are driving the development of smarter, more efficient nanobiosensors. Novel nanomaterials such as gold nanoparticles, carbon nanotubes, magnetic nanoparticles, and quantum dots are improving biomolecule detection, pathogen diagnosis, and environmental monitoring (Bhuma, 2014). Emerging biosensor platforms, including acoustic and optical sensors, are expected to support automated monitoring and precision aquaculture in the future.

8. Conclusion

Nanobiosensors represent a significant technological advancement for fisheries and aquaculture. Their high sensitivity, rapid response, and portability enable efficient monitoring of environmental conditions, disease outbreaks, and fish health. With continued technological progress, nanobiosensors are expected to play a key role in the development of sustainable and intelligent aquaculture systems.

References

Ahuekwe, E. F., Isibor, P. O., Akinduti, P. A., Salami, A. O., Onuselogu, C. C., Oshamika, O. O., ... & Obembe, O. O. (2023). Application of nanochitosan in tagging and nano-barcoding of aquatic and animal meats. Next generation nanochitosan, 483-498.

Bhattarai, P., & Hameed, S. (2020). Basics of biosensors and nanobiosensors. Nanobiosensors: from design to applications, 1-22.

Bhuma, S. R. (2024). Innovative Nanomaterial-Based Analytical Techniques for Early Detection of Diseases: A Comprehensive Review. World Journal of Current Medical and Pharmaceutical Research, 76-81.

Bohara, K., Joshi, P., Acharya, K. P., & Ramena, G. (2024). Emerging technologies revolutionising disease diagnosis and monitoring in aquatic animal health. Reviews in Aquaculture, 16(2), 836-854.

Kerry, R. G., Ukhurebor, K. E., Kumari, S., Maurya, G. K., Patra, S., Panigrahi, B., ... & Patra, J. K. (2021). A comprehensive review on the applications of nano-biosensor-based approaches for non-communicable and communicable disease detection. *Biomaterials Science*, *9*(10), 3576-3602.

Kulkarni, M. B., Ayachit, N. H., & Aminabhavi, T. M. (2022). Recent advancements in nanobiosensors: current trends, challenges, applications, and future scope. Biosensors, 12(10), 892.

Naresh, V., & Lee, N. (2021). A review on biosensors and recent development of nanostructured materials-enabled biosensors. Sensors, 21(4), 1109.

Ramesh, M., Janani, R., Deepa, C., & Rajeshkumar, L. (2022). Nanotechnology-enabled biosensors: a review of fundamentals, design principles, materials, and applications. Biosensors, 13(1), 40.

Rather, M. A., Sharma, R., Aklakur, M., Ahmad, S., Kumar, N., Khan, M., & Ramya, V. L. (2011). Nanotechnology: a novel tool for aquaculture and fisheries development. A prospective mini-review. Fisheries and Aquaculture Journal, 16(1-5), 3.

Rtimi, S. (2019). Toxicity Analysis of Ag and Au Nanoparticles. In Toxicity of Nanomaterials (pp. 121-138). CRC Press.

Sharma, P., Pandey, V., Sharma, M. M. M., Patra, A., Singh, B., Mehta, S., & Husen, A. (2021). A review on biosensors and nanosensors application in agroecosystems. *Nanoscale Research Letters*, *16*(1), 136.

Tu, J., Gan, Y., Liang, T., Hu, Q., Wang, Q., Ren, T., ... & Wang, P. (2018). Graphene FET array biosensor based on ssDNA aptamer for ultrasensitive Hg2+ detection in environmental pollutants. Frontiers in Chemistry, 6, 333.

Wu, H., Saito, Y., Yoshizaki, G., Yoshiura, Y., Ohnuki, H., & Endo, H. (2022). Study on the development of carbon nanotube enhanced biosensor for gender determination of fish. Sensing and Bio-Sensing Research, 35, 100474.