Review

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Emerging Needs, Expanding Applications, and Recent Technological Advances of Biosensors, Especially in Fish Aquaculture

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Review

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Biswaranjan Paital [1,*], Sk Abdul Rashid [2,3], Prajnyani Dikshit [4], Dipak Kumar Sahoo [5], Tejasweta Bhuyan [1,4], Ashutosh Panigrahi [4], Tapaswini Subudhi [4,6], Akshama Noorenazar [4], Samarjeet Pradhan [4], Barsha Sarangi [4,7] and Prasana Kumar Rath [1,8]

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Abstract

Issues pertaining to malnutrition are largely addressed by the consumption of fish meat, as it is both affordable and accessible to economically weaker sections of the population. Therefore, challenges observed in the aquaculture and fishery sectors, such as the detection of environmental changes, disease outbreaks, hindered growth, and poor fish health management, need to be addressed to increase production. Employment of modern technologies, such as (bio)sensors, is helpful for enhanced production in artisanal and large aquaculture systems. Because these can timely detect challenges, including climate change factors, sea-level rise-induced salinity load, changes in inland temperatures, ocean acidification, changes in precipitation patterns, ammonia toxicity, infectious diseases, and stress factors in water bodies or among their inhabitants, as a result, appropriate and timely measures can be taken at various stages of fish culture to address common problems. Using major scientific electronic databases, we comprehensively reviewed the topic of emerging needs, expanding applications, and recent technological advances in biosensors, with a particular focus on pisciculture. We highlight the biosensor technology used in the fisheries industry, which represents a pivotal step towards addressing its various aspects.

Keywords: AI-based biosensing in aquaculture; aquaculture challenges; aquaculture water pathogen; biosensors; electrochemical detection; monitoring in fisheries; modern biosensing technology

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1. Introduction

Population growth-induced food security and nutritional challenges are among the significant problems in many countries [1]. Under such a scenario, the supply of nutritious food has been considered a major global issue, especially for the economically weaker section of people [2]. In 2023, approximately 713 to 757 million people, or one in eleven, experienced hunger globally. As per the World Health Organization (WHO), about 2.5 billion adults and 149 million children under the age of 5 years in 2022 have been suffering from malnutrition [3]. It marks the beginning of the blue revolution in aquaculture worldwide, as fish meat is considered an accessible and affordable source of food for economically weaker sections of the population. Therefore, the use of modern technology, such as bio(sensors), to meet the challenges observed in the aquaculture sectors to increase production is required [3].

The use of modern technology in aquaculture, including biosensors, over the last few decades could be a reason for the enhanced production [4,5]. The State of World Fisheries and Aquaculture (SOFIA) in the UN's latest edition, published in 2024, states a 4.4% global expansion of fisheries and aquaculture, accounting for 223.3 million tonnes, from 2022 to 2024 [3]. The recent production of aquatic animals amounts to an astonishing value of 185.4 million tonnes, compared to 37.8 million tonnes of algal species [6]. This was predicted to meet the demand for digestible fish protein, addressing global food scarcity among economically weaker sections [7]. Global aquaculture production has increased threefold in response to current demands over the last twenty-five years. It has surpassed any other food industry and has successfully established itself as a massive international industry, constantly growing with leaps and bounds [8,9]. Asia became the leading player in the aquaculture industry, accounting for more than 91% of total production in 2017, with an annual growth rate of 5.89%. The second position was occupied by the American continent with a yearly increase in rate of 5.45% per annum in this industry, followed by Europe, accounting for 2.7% of global production at 2.7% per annum, and lastly the African continent, although producing 2% of the worldwide output but a higher rate of 9.81% per year since 2000 [10]. Click or tap here to enter text.The most significant factors contributing to the massive expansion of the aquaculture industry are the rise in global demand for fish consumption and the adoption of modern technologies, including biosensors [11]. For example, various problems, including toxicity such as aminophenol in *Labeo rohita* fingerlings [12] and meloxicam in *Cyprinus carpio* [13], have already been proven to decrease fish farming production limits as a result of early detection and adoption of appropriate measures against infection, disease, pollution, toxicity using modern technology added to fish farming for its double expansion in the last 50 years, exceeding meat and pork consumption by a significant margin [3,14,15]. The fish food industry is dominated by inland freshwater fish farming, which accounted for approximately 62% of the global live weight volume and three-fourths of the global edible weight volume in 2020 [3,9]. Although the most significant contributors to this industry are fish, it also includes other aquatic products, ranging from the tiny unicellular Chlorella algae [16] to Atlantic salmon (*Salmo salar*) [3]. Although the above data explain the ever-evolving and flourishing aquaculture industry, which has thrived for centuries, it faces numerous challenges in detecting and managing problems at various levels, including environmental issues, seed production, supply chain management, pollution, disease outbreaks, and mismanagement of coastal areas [17,18]. Aquatic flora and fauna face alarming threats from human interventions, including oil spills, ocean warming, overexploitation, eutrophication, and the introduction of invasive species [19]. Advances in modern technology have introduced biosensors as promising tools for the early detection and timely management of crises detected in aquatic systems. Biosensors are analytical devices that detect chemical reactions between analytes and bioreceptors, with a transducer converting the bio-recognition signal into a measurable value [20]. Recent developments include point-of-care biosensors, which enable the immediate application of remedial measures at the site to minimize contamination following human intervention [21,22]. Biosensors offer early, continuous, and real-time monitoring of environmental parameters, facilitating the detection of stress or disease in aquatic organisms [23]. Conventional methods often fail to provide timely data acquisition, which is essential for effective fish farm management. Although most biosensors in biomedical sciences are primarily developed for clinical applications, such as in cancer and organ disorder detection [24,25], their use in fish farms has been limited to areas like disease detection and quality control [26,27]. Therefore, it was hypothesized that a comprehensive, updated review focusing specifically on biosensors used in fish aquaculture could help clarify their significance in the sector. This article examines advancements in the application of biosensor technologies in aquaculture, focusing on pathogen detection, informed decision-making, optimized feeding strategies, enhanced animal welfare, and sustainable aquaculture practices. It also critically examines existing limitations, emphasizing the potential of biosensor adoption to revolutionize the aquaculture industry.

2. Search Strategy

To review the topic of biosensors in fish aquaculture, a literature survey was conducted primarily in electronic databases. Major scientific electronic databases, including PubMed, ScienceDirect, Web of Science, Agricola, Google Scholar, and Scopus, were searched using relevant keywords. The keywords were mainly focused on fish and fisheries, with an addendum of words such as “challenges,” “disease,” “sensor,” “biosensor,” “marine water,” and “fresh water.” The published articles in the search results were only included in the study. Articles that merely contain any of the relevant terms but are out of the scope of the topic were excluded. Similarly, articles published in local languages were also excluded from the review. Articles that fall under the scope of the current review were included in the review, irrespective of the journal, book, chapter, religion, author, region, race, or country of publication. Authentic websites, such as those of the FAO and WHO, were also considered for the current review to collect information, facts, and figures about biosensors in fish aquaculture.

3. Current Status in Aquaculture

In 1987, 10 million tonnes of farmed fish and shellfish were cultivated, a figure that increased threefold to 29 million tonnes by 1997, alongside approximately 300 farmed species. It further increased to 80 million tonnes in 2017, which includes 425 farmed species [3,10]. About 31.8 million tonnes of aquatic plants, 17.4 million tonnes of mollusks, and 8.4 million tonnes of crustaceans are produced, accounting for 28.4%, 15.4%, and 7.5% of the total aquaculture production, respectively. About 422,124 tonnes of the smaller marine and freshwater invertebrates were also produced [10]. Aquaculture provides 43% of the world’s aquatic fauna for human food consumption. It is expected that it will grow to quench the future demand of the expanding population. Over the past 50 years, global aquaculture has experienced tremendous growth, increasing from approximately 52.5 million tonnes in 2008. The production was highest in Asia, accounting for 89% by volume and 79% by value [28] (Figure 1). The major product of the aquaculture industry is animal protein, which plays a crucial role in combating nutritional deficiencies and disorders. Edible products from the fisheries industry not only supply high-quality proteins but also essential vitamins, micronutrients, and minerals. For approximately 950 million people, fish remain the primary source of protein [29]. In Asia, aquaculture generates significant economic returns annually, being $471.66 billion USD by China alone in 2024. Japan alone imports an estimated 5,400–10,000 tonnes of jellyfish products each year. At the same time, aquaculture practices have expanded to countries such as Namibia, Australia, the USA, and the UK to meet the rising demand [30].

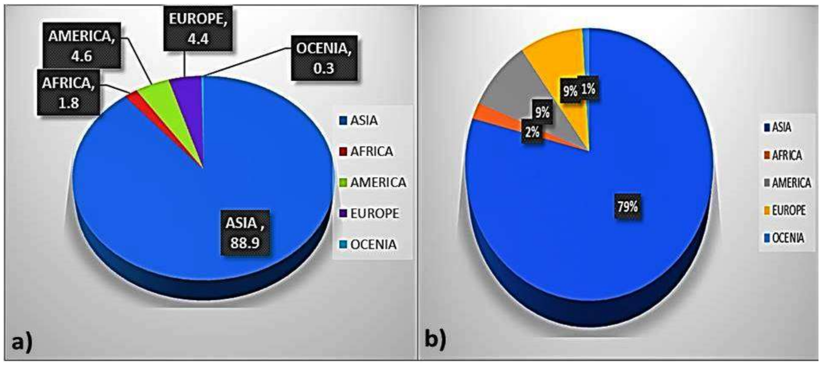

Figure 1. Aquaculture across continents. Figure (a) Global aquaculture quality by 2008 (except aquatic plants). Figure (b) Global aquaculture quality by 2008. Data are collected from the Bostock et al. [28].

In India, aquaculture exhibits an annual growth rate of approximately 7%, with catfish species accounting for 90% of total aquaculture production [31]. Globally, aquaculture production reached 214 million tonnes in 2020, reflecting a 0.2% increase from 2019 but a 0.6% decrease compared to 2018, primarily due to the COVID-19 pandemic [32]. Of this, aquatic animals for human consumption accounted for approximately 157 million tonnes. The total production from aquaculture comprised 87.5 million tonnes of aquatic animals intended for food. Other products include 35.1 million tonnes of seaweed and algae used for both food and non-food purposes, as well as 700 tonnes of shells and pearls designated for ornamental purposes. The rapid expansion of aquaculture, while addressing global nutritional demands, has also exposed the sector to emerging environmental and biological vulnerabilities [1]. These challenges underscore the critical need for adaptive strategies and resilience-building measures within aquaculture systems [4,5,11].

4. Challenges Associated with Aquaculture

The rapidly expanding aquaculture industry, with its rising demand for fishery products, poses numerous challenges, therefore requiring attention to sustain production. Among the major threats, climate change is particularly significant [33,34]. Finfish and shellfish are directly impacted through unpredictable alterations in their physiological traits, while shifts in primary and secondary productivity indirectly affect their health and ecosystem structure [33–35]. Rising sea levels and inland temperature fluctuations disrupt critical coastal ecosystems such as mangroves and salt marshes, leading to declines in fish abundance and seed stock availability [36].

The effects of climate change on aquaculture are attributed to geography, climate zone, economics, farming methods, and the species cultivated [35,37–43]. Elevated temperatures impair the growth and development of aquatic animals, with prolonged thermal stress affecting their endocrine and osmoregulatory systems [44]. Changes observed in sea surface temperature trigger algal blooms that deplete dissolved O_2 and reduce reef fishery productivity through coral bleaching [36]. Early detection of temperature patterns may mitigate such threats, at least in artisanal aquatic sectors, when fish are cultured in open seas. Additionally, an increase in atmospheric CO_2 levels leads to ocean acidification, resulting in a reduction in carbonate availability that is crucial for the skeletal development of shell-forming organisms. As a result, it increases their vulnerability to predation and reduces their productivity [41,45–49].

Ocean acidification also increases production costs, forcing large producers to rely on hatcheries more frequently [44]. Furthermore, global warming alters precipitation patterns, and excessive rainfall causes floods that introduce invasive species into aquaculture systems. It degrades water quality on one hand and increases predation risks on the other hand [44]. Conversely, drought intensifies stress on aquatic organisms, leading to stock losses, elevated maintenance costs, and reduced overall production capacity [36]. Rising sea levels, along with natural phenomena such as storms and cyclones, can exacerbate salinity intrusion, posing a significant threat to aquaculture [50]. Human activities, including coastal aquaculture operations such as shrimp farming, also contribute to salinity intrusion, which has an adverse effect on aquatic flora and fauna [50,51]. Ammonia toxicity, with LC50 concentrations ranging from 0.3 to 0.9 mg/L for cold-water fish, 0.7 to 3.0 mg/L for warm-water fish, 0.6 to 1.7 mg/L for marine fish, and 0.7 to 3.0 mg/L for marine shrimp, raises significant concerns in aquaculture [52]. Ammonia levels are inversely related to dissolved O_2, and their imbalance can lead to water eutrophication [52]. Parasitic, bacterial, viral, and fungal infections also heavily impact aquaculture, leading to severe fish health conditions such as pancreatic necrosis in salmonids [53] and fin rot, which can cause severe tissue damage in Atlantic salmon and rainbow trout [54].

Another critical but less attended issue is the need for sex control to stabilize mating systems, maintain fish quality, and prevent precocious maturation, which, altogether or alone, can reduce feeding rates and hinder growth [55]. In species such as Nile tilapia, producing mono-sex populations is desirable as males exhibit faster growth and better feed conversion efficiency compared to females [56]. Stress is a significant factor that affects aquaculture, particularly in farmed fish, and induces adverse effects on growth, reproduction, immune function, and disease susceptibility [57,58]. Diet plays a crucial role in modulating stress sensitivity [59], while feed quality, feeding rate, reproductive frequency, and male-to-female ratio are important for optimal growth and development [60]. The use of advanced technology to address the above issues is believed to be essential for enhancing productivity in the aquaculture sector [4,5,11]. Additionally, handling and transport are major stressors that indicate the need for stress-minimizing water quality management and oxygen maintenance during these processes [61]. Many aquaculturists who lack resources and knowledge on pond preparation under climate change and above conditions bear huge losses [36]. In such cases, the importance of early prediction of environmental or disease challenges and educating farmers on the use of modern technologies, including (bio)sensors, is crucial. Various obstacles to aquaculture are listed in Table 1 and illustrated in Figure 2. Given these operational challenges, the need for real-time monitoring and quality assessment technologies has become increasingly crucial in aquaculture systems.

Table 1. Challenges to aquaculture and their effects.

Challenges	Effects	References
Climate Change	Alters physical and physiological aspects of finfish and shellfish; changes in primary and secondary productivity; ecosystem structure alterations.	[33–35]
Sea-Level Rise and Inland Temperature Changes	Damages coastal ecosystems, mangroves, and salt marshes; reduces fish abundance and distribution.	[36]
Geographical and Climatic Variations	Varying impacts on aquaculture based on location, climate zones, economy, production systems, and species.	[35,37–43]
Rising Temperatures	Affects growth and development of aquatic animals; impacts endocrine and osmoregulatory systems; leads to algal blooms reducing dissolved oxygen; coral bleaching affecting reef fisheries.	[36,44]
Ocean Acidification	Decline in pH affecting shell-forming organisms like shrimps, mussels, oysters, and corals; increased vulnerability to predation; higher production costs due to reliance on hatcheries.	[41,44–49]
Changes in Precipitation Patterns	Increased rainfall causing floods introducing invasive species; droughts leading to water stress, stock loss, and higher maintenance costs.	[36,44]
Sea-Level Rise and Natural Phenomena	Salinity intrusions threatening aquaculture; anthropogenic activities like shrimp farming exacerbating salinity intrusion affecting aquatic flora and fauna.	[50,51,62]

Ammonia Toxicity	Harmful effects on aquatic life; inverse relationship with dissolved oxygen; eutrophication due to imbalance in ammonia and nitrate levels.	[52,63,64]
Disease Outbreaks	Parasitic, bacterial, viral, and fungal diseases causing significant harm; examples include pancreatic necrosis in salmonids and fin rot in Atlantic salmon and rainbow trout.	[65–68]
Need for Sex Control	Ensures stability of mating systems; prevents precocious maturation; desire for mono-sex populations for better growth rates, e.g., male Nile tilapia grow faster.	[55,56]
Stress Factors	Negatively impacts growth, reproduction, immune function; influenced by diet, handling, and transport; poor water quality and oxygen levels exacerbate stress.	[60,69,70]
Lack of Education and Awareness	Aqua culturists often being poor are inadequately prepared to adapt to changes, making them vulnerable to impacts on fish resources.	[36]

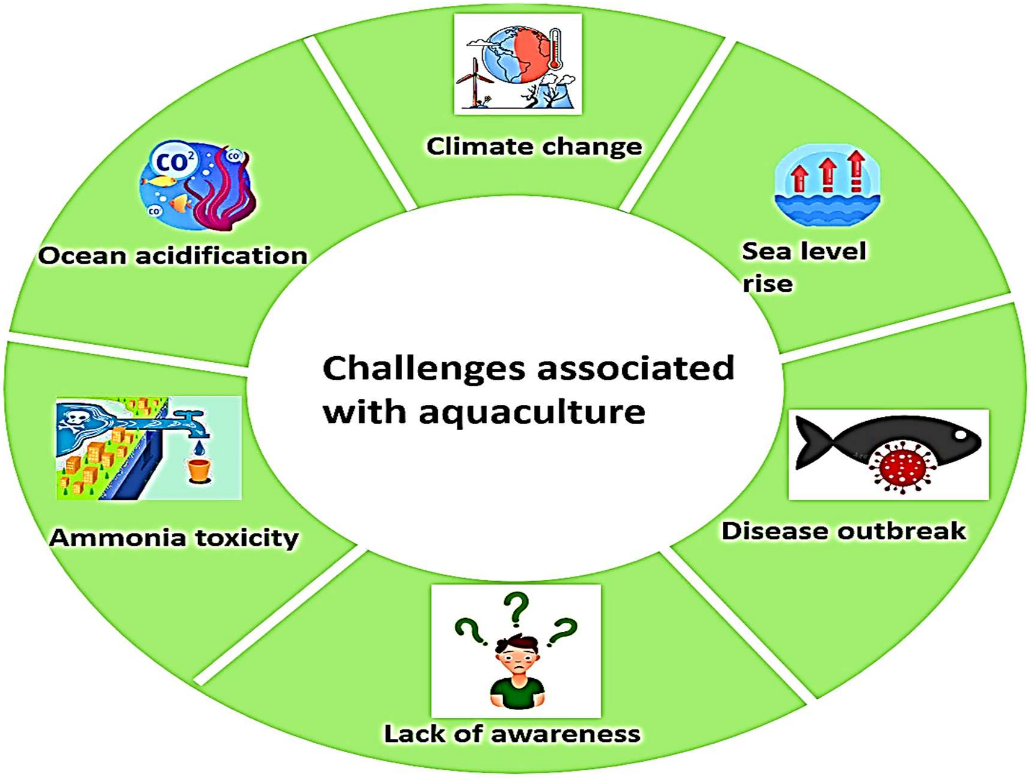

Figure 2. Challenges associated with aquaculture (modified after Sarkar et al. [71]).

5. Biosensors

Since ancient times, humans have conducted bioanalysis using their senses, and the evolution of biosensors has advanced as an integrative tool for quality control, food safety, environmental impact assessment, and applications in medicine, agriculture, and industry [72]. A biosensor typically integrates biological recognition components (bio-receptors) with a transducer system to efficiently detect specific compounds or conditions, offering rapid, low-cost, on-site detection compared to conventional, time-consuming methods [72]. A standard biosensor comprises an analyte of interest, bioreceptors such as enzymes, cells, aptamers, DNA, or antibodies that generate signals upon recognition, and a transducer that translates these signals in proportion to the analyte–bioreceptor interactions [20]. Electrical components then convert the signal into a digital output, which is displayed on devices such as Liquid Crystal Display (LCD) screens, computers, or printers in various forms, including numeric, graphic, tabular, or image formats [20] (Figure 3).

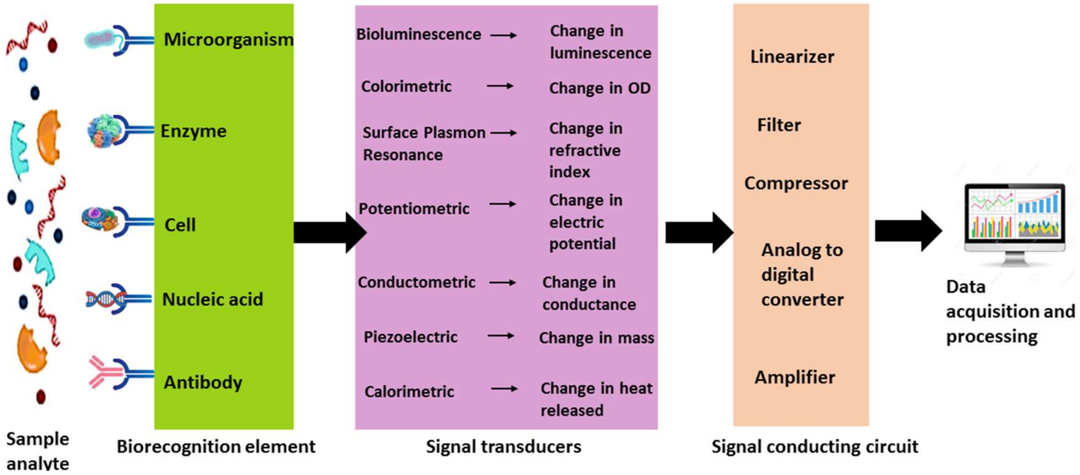

Figure 3. Schematic representation of the basic mechanism of biosensors.

5.1. Types of Biosensors Used in Pisciculture

The performance and application of biosensors are highly influenced by the design and functionality of their transducer modules. Accordingly, biosensors are classified into various types based on the nature of the transducer used (Table 2). Recent advancements in sensor technology have significantly enhanced detection accuracy, sensitivity, and operational stability, driving broader adoption across multiple domains, including aquaculture.

Table 2. Types of biosensors and their applications in aquaculture.

Transducer type	Biosensor type	Working principle	Application	Reference
Optical	Bioluminescent	Luminescence variation	Detection of heavy metals, food toxicants, and pathogens	[73]
	Fluorescence	Interaction with fluorescence-labeled biomolecules	BOD measurement, water availability assessment in plants, pathogen detection	[74]
	Colorimetric	Changes in optical density	Identification of waterborne and foodborne pathogens	[75]

	Surface Plasmon Resonance	Variation in refractive index due to bio analyte binding	Disease diagnosis, drug residue analysis, livestock monitoring, toxic gas detection	[76]
Electrochemical	Potentiometric	Measures electric potential	Detection of urea, CO_2, pesticides, sugars, and pH levels	[77]
	Conductometric	Variation in electrical conductance	Monitoring environmental contamination, pesticide, and heavy metal detection	[78]
	Amperometric	Electron transfer due to redox reactions	Identification of organophosphate pesticides and pathogens	[79]
	Impedimetric	Measures electrochemical cell impedance	Detection of peptides, small proteins, milk toxins, and foodborne pathogens	[80]
Piezoelectric	Quartz Crystal Microbalance	Mass variations in biological components	Used as a humidity sensor, food safety tool, and for detecting organophosphate and carbamate pesticides, as well as glucose measurement	[81]
Thermal	Calorimetric	Heat absorption and release	Detection of organophosphate pesticides and food and waterborne pathogens	[82]

5.2. Mode of Detection

Various modules of operation of specific types of biosensors are employed in aquaculture to address several challenges. Integrating specialized biosensor systems has enabled real-time monitoring of critical aquatic parameters, contributing to the sustainable management of aquaculture practices.

5.2.1. Wireless Sensor Network

Wireless Sensor Networks (WSNs) have emerged as an alternative to conventional cable networks in aquaculture. These address challenges such as complexity, maintenance, and limitations on expansion [83]. In 2011, researchers at Jiangsu University developed a WSN system capable of real-time measurement of six to seven water quality parameters, including dissolved oxygen, pH, and temperature [84]. The WSN operates according to the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard, comprising sensor nodes, routing nodes, and a gateway node [85]. A simplified model consists of three components: the WSN Unit (with sensor, routing, and gateway nodes placed in the fish pond), a monitoring unit (data and web servers), and a client network [83]. Sensor nodes gather environmental data, routing nodes that optimize the transmission path to the gateway, and the collected information is processed by servers and relayed via the internet to authorized clients [83] (Figure 4). Recent advancements in nanotechnology have further enhanced the sensitivity and functionality of biosensing systems integrated into such networks, particularly through the application of nanoparticles. These developments introduce a new dimension to real-time aquatic monitoring, enabling the early detection of biological and chemical changes. In aquaculture, both environmental changes and changes induced by these changes make fish vulnerable to infection and death. For example, cold susceptibility of Nile tilapia (*Oreochromis niloticus*) or high temperature-induced infection of reovirus in grass carp (*Ctenopharyngodon idella*) [86,87]. Therefore, real-time monitoring of water parameters using WSN biosensors in aquaculture, combined with a client information alert system, is beneficial.

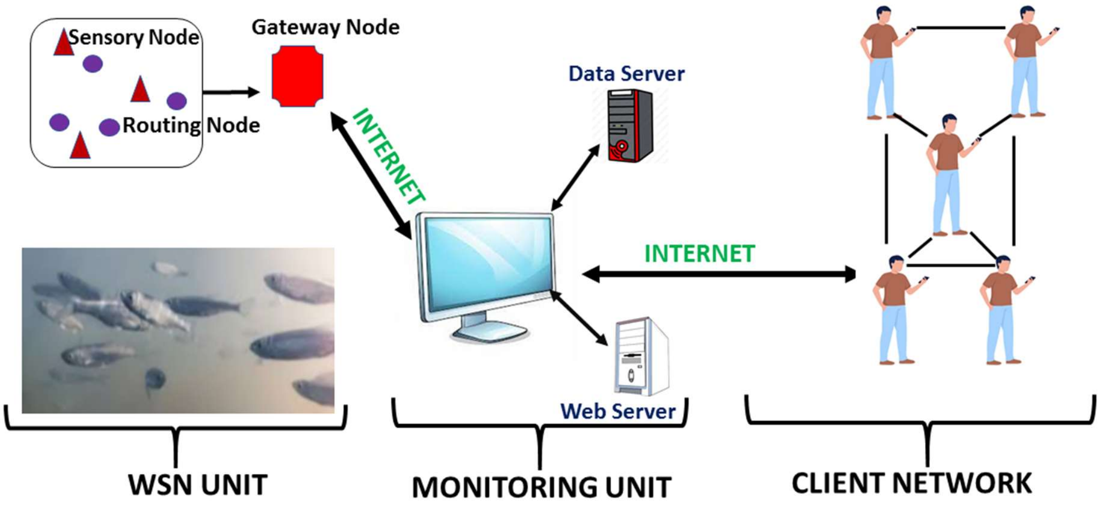

Figure 4. Wireless Sensor Network (working mechanism) for determining water quality in the fishpond (modified after Shi et al. [83]).

5.2.2. Nanoparticle Biosensor

Nanoparticles ranging in size from 10 to 500 nm possess a spherical, polymeric structure, offering a high surface area-to-volume ratio. It enables their applications across fields such as aquaculture [88]. They aid in disease detection, drug delivery, and the management of water quality. Designed nano-sensors/particles (diaminonaphthalene/Remazol Blue R-capped zinc oxide and carbon nanotubes) can help detect hormones such as epinephrine in biological fluids [89,90]. Metal nanoparticles such as gold, silver, and platinum serve as ideal core materials due to their excellent conductivity and catalytic properties [91,92]. Interestingly, gold nanoparticles (AuNPs) appear ruby red rather than gold, and their size inversely influences enzyme stability and biosensor sensitivity [93]. Un-aggregated particles are ruby red, and their color varies with aggregation, whereas aggregated particles exhibit blue to black hues, depending on the degree of aggregation [94–96]. AuNPs efficiently adsorb biomolecules to form recognition complexes, which is essential in aquaculture applications for water quality monitoring and disease detection [97]. These nanoparticles are coated with bio-recognition materials, such as DNA, RNA, enzymes, or antibodies, which interact with target analytes, enabling detection through fluorescence, colorimetric, or electrochemical methods (Figure 5).

AuNPs have shown promising results in disease diagnostics [22,98]. For example, a fiber-optic SPR biosensor was developed to detect nervous necrosis virus (NNV) early in infection by targeting viral coat proteins with AuNPs [22]. In shrimp sensitive to the pathogen white spot syndrome virus (WSSV) , characterized by calcium deposition and lethargy, was identified using AuNPs functionalized with anti-WSSV antibodies via self-assembled alkanethiol monolayers [99].

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Integrating AuNPs with optical sensing platforms such as SPR biosensors has significantly enhanced the sensitivity and specificity of aquatic disease diagnostics. These advances underline the critical role of SPR-based approaches in real-time monitoring of aquatic pathogens. Since the above methods provide quick results, extreme conditions such as viral disease outbreaks can be detected in fish quickly, allowing for timely and appropriate measures [100,101].

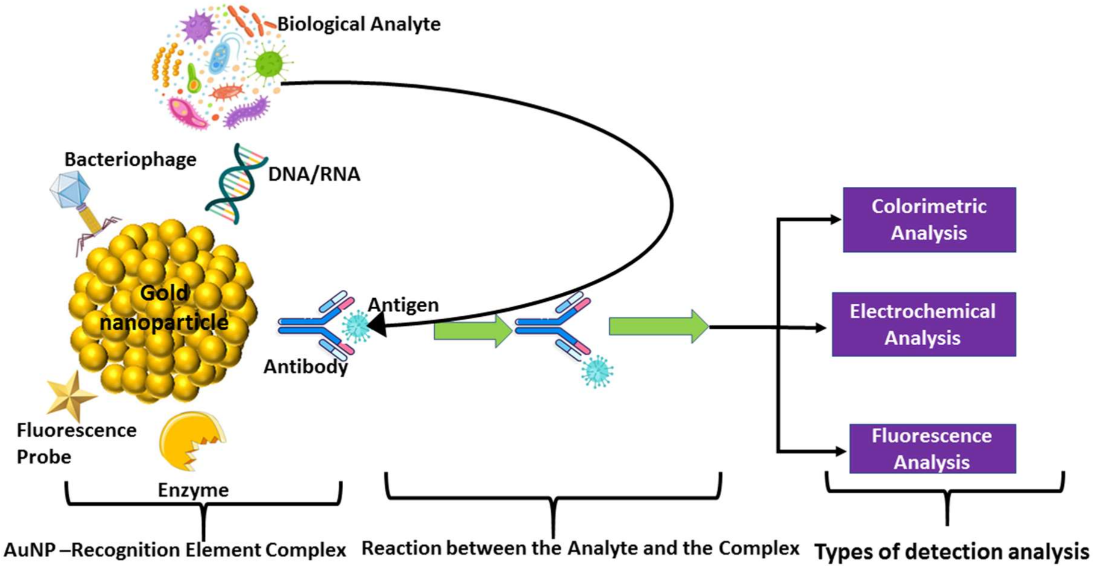

Figure 5. Mechanism of working of the Nanoparticle Biosensor (modified after Hegde et al., [102]).

5.2.3. Surface Plasmon Resonance (SPR)

The SPR biosensors are optical instruments that detect changes in refractive angles during specific analyte binding events [103]. These sensors play a crucial role in aquaculture by detecting pathogens and toxins that are harmful to aquatic life. The Kretschmann configuration is the most widely used model that includes a dielectric-metal interface with a prism attached to a metal layer in an inverted position [104]. When plane-polarized light exceeds the critical incident angle, total internal reflection occurs, and it transfers energy to excite surface electrons (typically on gold). It produces surface plasmon waves. Noble metals such as gold, silver, platinum, and palladium enhance optical absorption properties [105]. The plasmonic band, detected in the visible to near-infrared regions [106], shifts with analyte binding and is monitored by changes in resonance angles. Finally, it provides a highly sensitive method for analyte detection [107] (Figure 6).

SPR technology is increasingly applied in aquaculture for water quality monitoring. Excess nitrogenous compounds from uneaten feed, fertilizer leaching, and fish waste pose toxicity risks, particularly due to ammonia load [108]. An SPR biosensor using nitrate reductase from *Aspergillus niger* and glutamine synthetase from *Escherichia coli* on gold nanoparticles was developed to measure nitrate (NO_3^-) and ammonium (NH_4^+) concentrations. It offers an effective tool for water analysis [109]. Aquaculture intensification often degrades water quality, leading to stress-related health issues in fish, and is influenced by factors such as pH, water flow, and temperature [110]. Prolonged exposure to poor water conditions elevates cortisol, urea, and creatinine levels beyond normal physiological ranges [111]. Addressing such issues, a polymer optical fiber coated with gold/platinum nanoparticles and anti-cortisol antibodies has been developed for direct cortisol monitoring in water bodies [112] which can enhance fish health surveillance. Therefore, the use of SPR-based technology for detecting toxins, such as tetrodotoxin, in water bodies or for detecting diseases by measuring pathogen products, is recommended in aquaculture [113]. In addition to water quality monitoring, biosensor innovations have expanded into pathogen detection, enabling early disease diagnosis in aquaculture systems. One such advancement involves cantilever-based biosensors, which offer remarkable sensitivity for detecting biological targets.

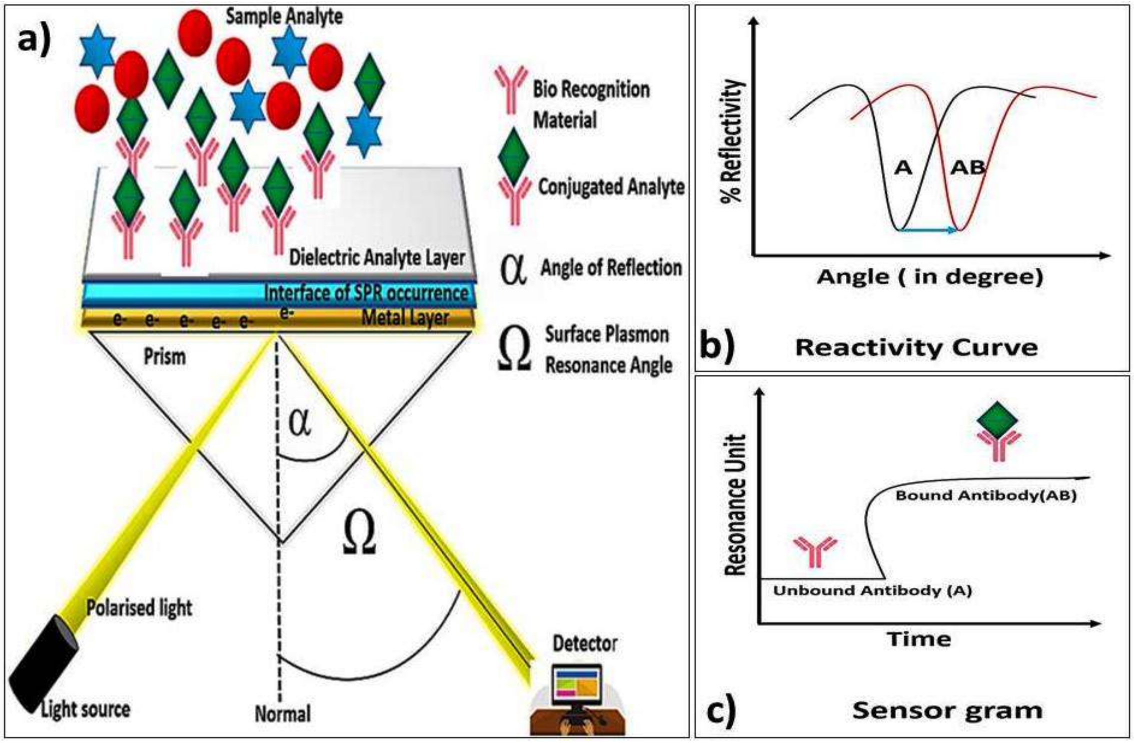

Figure 6. Surface Plasmon Resonance biosensor. Figure (a) A schematic diagram representing the mechanism of the Surface Plasmon Resonance. Figure (b) The figure represents the shift in Reactivity Curve: A represents the unbound antibody, and AB represents the bound antibody. Figure (c) The figure represents a Sensogram. Two cases are represented: unbound antibody and bound antibody (modified after Lifeasible (https://www.lifeasible.com/custom-solutions/plant/analytical-services/gene-function-analysis/surface-plasmon-resonance-spr/; accessed on Dec 8th, 2025) [114]).

5.2.4. Microcantilever Biosensor

A cantilever, by definition, is a structure fixed at one end and free at the other, similar to a diving board [115]. Micro-cantilevers are a relatively recent innovation in aquaculture and have been utilized for disease detection in fish. It offers exceptional sensitivity and low detection limits, making it a valuable tool in aquaculture [116]. These biosensors integrate microcantilevers with dynamic force microscopy (DFM) within an atomic force microscope (AFM), which detects shifts in resonance frequency upon binding of the target analyte [117]. The piezoelectric actuator detects mass loading, resulting in a decrease in the resonance frequency [118]. A study from Thailand demonstrated the first cantilever-based cholera detection, where a gold-coated microcantilever functionalized with antibodies specific to *Vibrio cholerae* O1 showed a decrease in resonance frequency proportional to the bacterial concentration [119].

Resonance frequency changes are measured via the optical beam deflection method, where a photodetector monitors a laser reflected from the cantilever, and the resulting photocurrents are processed through a data acquisition system [120]. The differential displacement between a reference and measurement cantilever determines the presence and concentration of analytes, as evidenced by a bending signal that is lower than the base signal (Figure 7). Overall, cantilever-based biosensors offer a promising approach for the early detection of waterborne pathogens, which helps prevent disease outbreaks in aquaculture farms and artisanal fish farming. Despite their advantages, cantilever sensors can be limited by environmental disturbances, highlighting the need for alternative high-sensitivity detection platforms. Consequently, other biosensing technologies have been explored to further enhance diagnostic accuracy. Undoubtedly, ultrasensitive and rapid detection systems in microcantilever biosensors expand their diverse application fields, including aquaculture, to reduce the risk of contamination, particularly during disease outbreaks. Detection of *Vibrio cholerae* in water samples using DFM is a notable example in the aquaculture industry [119]. Detection of the bacterium *Escherichia coli* using a V-shaped microcantilever sensor from water samples is another example [121]. Similarly, the detection of a 1 pg/mL level of okadaic acid is also achieved using an aptamer-based microcantilever-array biosensor. Measurement of glucose level in bio-samples using integration of glucose aptamer, glucose oxidase, and horseradish peroxidase enzymes with the substrate 2,2′-biazobis(3-ethylbenzothiazoline-6-sulfonic acid is also noted at a sensitivity level of 0.013 mM [122].

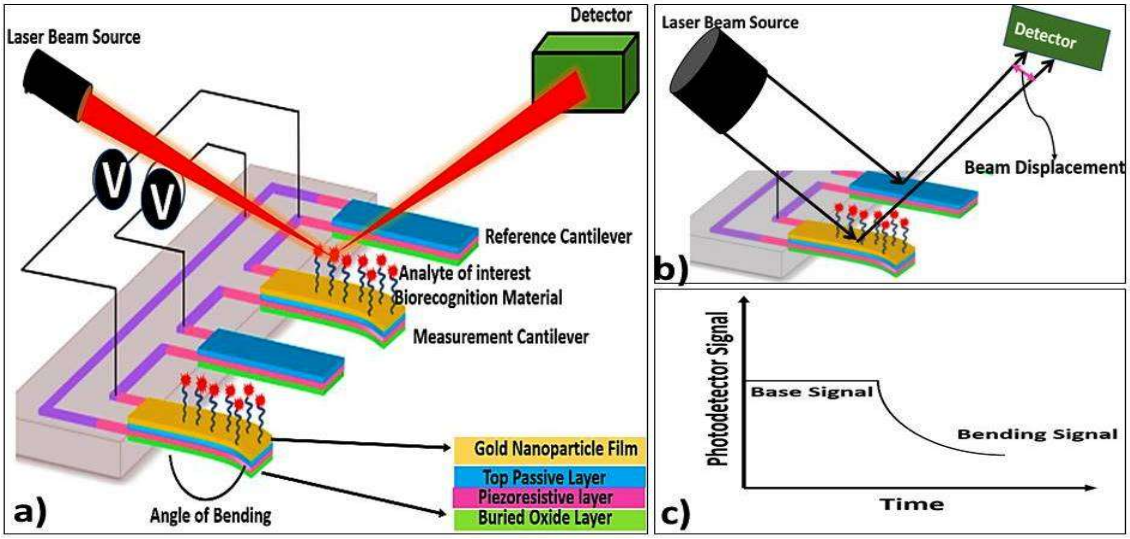

Figure 7. Working of a Micro-cantilever Biosensor. Figure (a) A schematic diagram representing the mechanism of the SPR. Figure (b) Ray diagram of the displacement beam measuring the analyte concentration. Figure (c) Photodetector vs Time graph (modified after Liu et al. [122]).

5.2.5. Quartz Crystal Microbalance Biosensor

Traditional detection methods, such as microscopy, ELISA, and PCR, are often tedious, time-consuming, and prone to yielding false positive results in samples. Consequently, the development of biosensors has provided a more sensitive, efficient, and point-of-care alternative for analyte detection [123]. Quartz Crystal Microbalance (QCM) biosensors offer a low detection limit and high specificity, which minimizes false positive results on one hand and limits the risk of biosensor damage on the other [124,125]. The QCM operates on the principle of piezoelectricity. It utilizes gold-coated quartz electrodes to detect changes in mass through shifts in resonance frequency, which facilitates analyte recognition [126]. The QCM with Dissipation Monitoring (QCM-D) system is an advancement of this technology. It measures both frequency changes and energy dissipation during analyte binding and removal, thereby enhancing analytical capabilities [127].

In QCM-D, a specific recognition material is immobilized on the quartz surface to selectively bind target analytes. It causes a mass increase coupled with a decrease in frequency. To further enhance the detection limit, nanoparticles can be attached to secondary antibodies without modification [128] or used directly to increase the detectable mass [129,130]. This multi-phase detection mechanism comprises initial antibody immobilization (highest frequency), analyte binding (reduced frequency), secondary antibody-nanoparticle conjugation (further decrease in frequency), and regeneration upon removal of bound entities (Figure 8). However, coatings of antibodies and nucleic acids are prone to denaturation when exposed to environmental fluctuations, which limits their stability. To overcome this issue, molecularly-imprinted polymers (MIPs) have been introduced as synthetic alternatives to biological recognition elements. MIPs provide enhanced stability against pH, temperature, and ionic changes, which help maintain the integrity of the QCM-D biosensing system [131]. While QCM-D leverages mechanical responses to detect biomolecular interactions, electrochemical biosensors translate biochemical events into electrical signals, which offer complementary approaches for sensitive detection. These platforms continue to evolve, incorporating innovative materials and transduction strategies that broaden their applications in diagnostics and environmental monitoring. Detection of *Vibrio harveyi* viral pathogens in shrimp farms [132] and *Aeromonas hydrophila* bacterial pathogens in fish farms using QCM has already been documented.

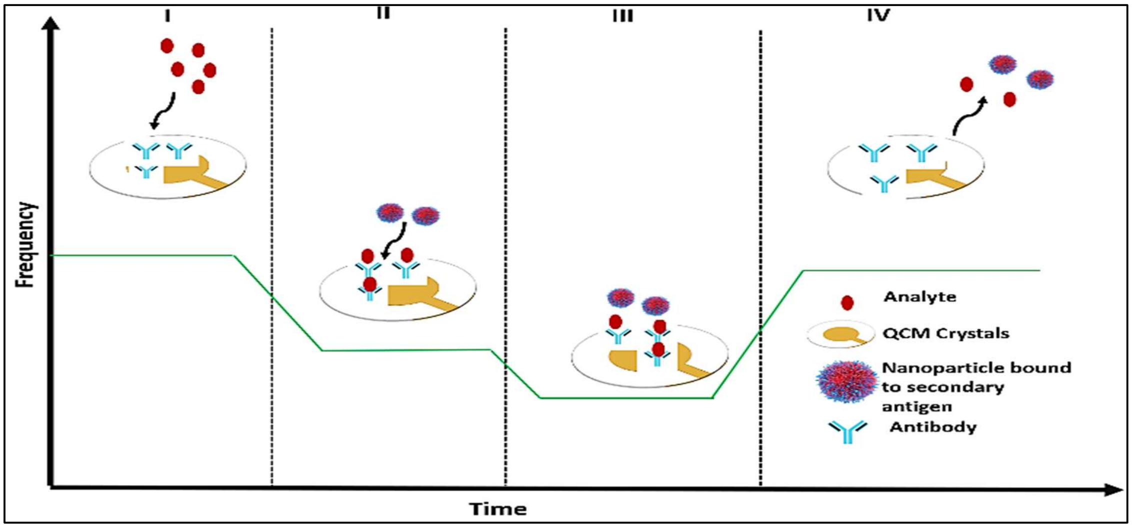

Figure 8. The frequency versus time graph represents the four phases of the Quartz Crystal Microbalance Method (modified after Lim et al. [133]).

5.2.6. Electrochemical Biosensor

Electrochemical biosensors represent a significant class of biosensing devices that transduce biological responses into electrochemical signals. These sensors incorporate biological compounds such as nucleic acids, antibodies, and enzymes, coupled with various types of transducers that define the specific biosensor category. They offer key advantages, including high specificity, robustness, ultra-high sensitivity, low detection limits, and suitability for point-of-care diagnostics [134]. Among electrochemical biosensors, potentiometric biosensors function by measuring the potential difference between a working and a reference electrode. The biorecognition material coated on the working electrode facilitates the selective detection of the analyte compared to the reference [135]. Amperometric biosensors are another prominent type of electrode that operates by detecting current changes in response to an applied potential. The sensor surface is coated with a redox-active analyte that undergoes oxidation or reduction, and the resulting electric current is directly proportional to the concentration of the analyte [136]. Additionally, conductometric biosensors monitor variations in electrical conductivity arising from the interaction between the biorecognition element and the target analyte [137]. Together, these approaches demonstrate the versatility and effectiveness of electrochemical reactions in biosensing applications [138]. For example, applications of such electrochemical biosensors for the detection of NH^{4+} at 0.65 μM concentration using nanoparticle/Polymethylene [139] and measurement of xanthine with 97% accuracy at 47.96 nM concentration as an indicator of spoilage in stored fish, even for 30 days [140] are noted. Therefore, the application of biosensors in aquaculture, specifically in fish farms, can enhance productivity by mitigating the associated on-field problems.

In summary, biosensors have the potential to mitigate several risks in the aquaculture sector, ranging from early, rapid, and real-time detection to auto-predicting solutions when integrated with AI or IoT-based tools. They can be used for routine analysis at a cost-effective rate. Optical sensors can also be used for early, quick, and real-time monitoring of aquaculture systems with high precision in a non-invasive mode. While QCM biosensors offer superior mass sensitivity for detecting pathogen loads at the molecular level, they can be costly. Therefore, the choice to use specific biosensors can depend on the requirements (Table 3).

Table 3. Comparative analysis of the electrochemical, optical, and QCM biosensors used in aquaculture systems.

Parameter	Electrochemical Sensors	Optical Sensors	QCM Sensors
Principle	Electrical changes in the form of current, voltage, impedance from biochemical reactions is measured	Changes in light signals in the form of absorbance, fluorescence, Raman, colorimetry is measured	Mass change on crystal surface via shift in resonance frequency is detcted
Typical Targets	Water parameters such as NH_3, NO_2^-, pH, dissolved O_2, metabolites, stress biomarkers are measured	Biological molecules such as proteins, enzymes, hormones, pathogens, dissolved O_2, turbidity, toxins, physiological stress indicators can be measured.	Titer and level of infection of pathogens, proteins, toxins, mucus biomarkers, immune molecules can be measured
Sensitivity	High sensitivity as low analyte levels can be measured with modified electrodes	Very high because it uses fluorescence/Raman spectral signal and allows multiplexing	Extremely high because uses mass measurement and sensitive up to ng–pg level
Selectivity	Moderate but can be enhanced with integration of additives such as nanomaterials	Optical probes provide highly selective molecules	Antibodies, aptamers provide high selectivity
Real-time Monitoring	Excellent and can be used routinely	Water transparency can hinder the signal and needs stable signal for real time monitoring	Usually limited for real tie assays
Environmental Interference	Can be affected by fouling and electrode change such as degradation	Turbidity, scattering, ambient light can influence the signal	Physical parameters such as temperature, viscosity, and water flow may affect
Cost	Usually low	Usually moderate	Usually high

Ease of use in fish farms	Easy	Moderately easy	Little difficult
Major Advantages	Low cost, fast response, portable, easy automation	Highly sensitive, non-invasive, supports remote sensing	Ultra-sensitive, label-free, ideal for pathogen detection
Major Limitations	Electrode fouling, routine calibration is required	Usually costly and can be affected by water transparency	Environmental changes may affect the signaling
Example	Ammonia (NH_3/NH_4^+) Electrochemical Sensor, Cortisol Electrochemical Immunosensor, Dissolved Oxygen Electrochemical Sensor (Clark-type electrode), Heavy Metal Detection Sensor (Pb^{2+}, Cd^{2+}, Hg^{2+}) sensors	Fluorescent DO Sensor, Raman Spectroscopy for Fish Pathogens, Colorimetric Ammonia Sensor Strip, Fiber-Optic pH Sensor, Fluorescence-based Cortisol Detection	QCM Immunosensor for Fish Pathogens, QCM Biosensor for Fish Mucus Proteins, QCM for Toxin Detection (e.g., microcystins), Aptamer-functionalized QCM for Antibiotic Residues

6. Application of Biosensors in Aquaculture

6.1. Biosensors for Fish Health Management

The physiological status and overall health of aquatic organisms can be assessed through the detection of various hormones, such as adrenaline [89] and epinephrine [90], as well as enzymes and chemicals present in aquatic animals, including fish [141]. Key indicators, such as blood glucose levels, cortisol, and lactic acid concentrations, serve as important biomarkers for evaluating fish health [110,142–145]. For example, glucose oxidase is monitored by entrapping it in nano $TiO_{2,}$ which is discussed as a potential use for glucose biosensors. The device, known as ENFET, is designed to function as a field-effect transistor and utilize enzymes, such as glucose oxidase, as bioreceptors to indicate the sample glucose level with a sensitivity of 1.5 μA/0.0001 mM [146]. Traditional detection techniques, including liquid chromatography, fluorescence detection, as well as more recent developments like polymerase chain reaction (PCR) and flow cytometry, are often labor-intensive, time-consuming, and can induce significant stress during sample collection [147–150]. Advances in biotechnology have enabled the development of highly sensitive biosensors for use in aquaculture. They are preferable for measuring error-free results due to their target specificity, rapid detection, and ability to quantify minute analyte concentrations. These are considered promising tools for the future of the aquaculture industry, specifically in fish farming [151–153]. Various types of biosensors used for detecting fish diseases are listed in Table 3. Beyond disease detection, biosensors have also been utilized to address critical challenges in aquaculture breeding and reproductive management. Recent developments emphasize their role in enhancing the precision and efficiency of fish ovulation monitoring (Table 4).

Table 4. Studies on biosensors and the detection of fish health parameters.

Name of biosensor	**Detected substance**	**Mechanism**	**References**
Cortisol Biosensor	Cortisol levels in fish plasma	Electrochemical immunoassay using glucose oxidase (Gox) as a signal amplifier	[154–158]
Glucose Biosensor	Blood glucose levels	Needle-type optical enzyme sensor system	[159–161]
Wireless Glucose Biosensor	Real-time glucose monitoring in fish	Microelectrode with enzyme reaction, wireless transmission	[159,160,162]
Ovulation Prediction Biosensor (DHP Sensor)	17,20β-Dihydroxy-4-pregnen-3-one (DHP) for predicting spawning time	Label-free immunosensor, carbon nanotube-enhanced electrochemical detection	[163,164]
Pathogen Detection Biosensor (HGIMS-FCM & HGIMS-PCR)	Detection of *Flavobacterium psychrophilum* in fish	High Gradient Immunomagnetic Separation (HGIMS) with Flow Cytometry (FCM) or Polymerase Chain Reaction (PCR)	[165–170]
Total Cholesterol Biosensor	Whole cholesterol concentration in fish	Wireless CNT-enhanced mediator-type sensor	[171,172]
L-Lactic Acid Biosensor	Blood L-lactic acid levels	Enzyme-based FIA biosensor	[159,165,173]
Visual Stress Monitoring Biosensor (LED Biosensor)	Fish stress response (glucose-based detection)	Color-switching biosensor using LED indicators	[174]

In aquaculture, the production and preservation of high-quality eggs are critical for successful breeding [175]. Ovulation timing varies with the environmental and physiological conditions of fish, making it difficult to predict accurately [110]. Biosensors have been developed to monitor dihydroprogesterone (DHP) levels, which rise sharply during egg maturation, and are used as a marker to enable more precise prediction of reproductive state [110]. The biosensor is operated by detecting changes in electric current caused by the interaction between DHP and immobilized anti-DHP antibodies on a gold nanoparticle-modified electrode surface [110]. To enhance sensitivity, Single-Walled Carbon Nanotubes (SWCNTs) are incorporated to improve conductivity [110] (Figure 9). Compared with the conventional ELISA method, which is invasive and labor-intensive, the biosensor demonstrated a strong correlation with ELISA results [110]. Such advancements in biomonitoring are crucial, as precise reproductive control has a direct impact on the efficiency of aquaculture and stock management.

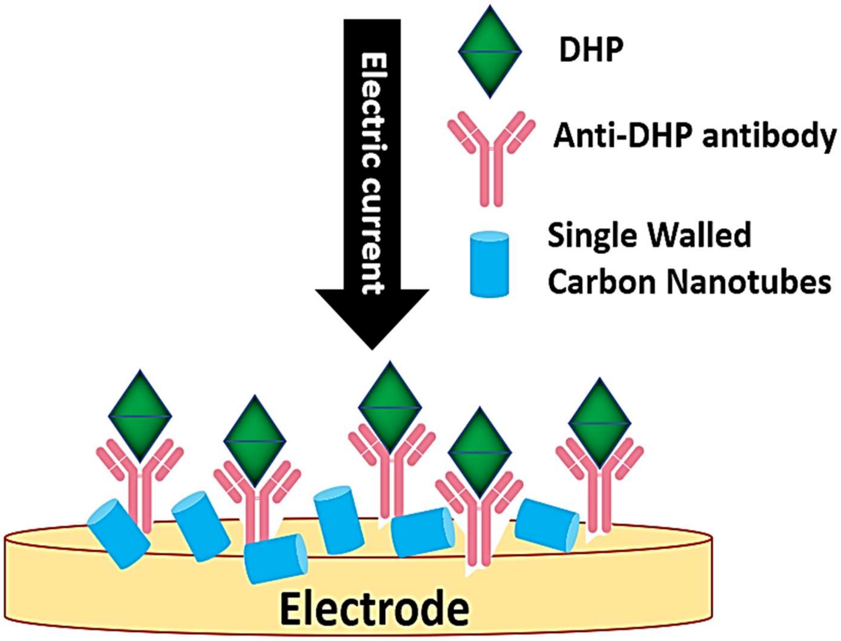

Figure 9. Schematic representation of DHP biosensor (modified after Endo and Wu [110]).

6.2. Biosensors in Monitoring Stress Response

Current aquaculture practices aim to enhance fish development and growth by improving environmental conditions [176]. Besides reproduction, continuous physiological monitoring has become essential for optimizing overall fish health and farm productivity. Monitoring the physiological status of cultured fish, particularly stress levels, is crucial for boosting productivity and reducing mortality [177]. Stress responses serve as an essential survival strategy, but can have a negative impact on metabolism, reproduction, growth, and the nervous and immune systems [177]. Stressors in aquaculture commonly arise from routine practices such as collection, handling, sorting, holding, and transportation. Also, fluctuations in key water quality parameters, including temperature, pH, hardness, salinity, dissolved oxygen, carbon dioxide, nitrate, nitrite, ammonia, and alkalinity, influence fish health [69]. Additionally, competition within and between species further impairs fish growth [70,178]. Therefore, monitoring stress levels in fish is found to enhance their productivity.

Blood analysis is a prevalent method for assessing fish health. Blood glucose and cortisol levels serve as primary indicators of stress [179]. The glucose level is strongly correlated with stress intensity and secondary stress responses, where the cortisol titer reflects the primary stress response [176]. Therefore, blood samples are a reliable source for detecting and managing fish stress levels. However, conventional blood sampling methods are labor-intensive and may induce additional stress that limits accurate physiological assessment. To overcome these challenges, a wireless biosensor integrating an enzyme sensor with a communication device has been developed [159]. This system measures glucose in the scleral interstitial fluid beneath the fish's eyeball, enabling continuous, real-time monitoring with rapid response, improved linearity, and enhanced reliability [180]. The scleral fluid around the fish's eyeball is the most suitable site for glucose sampling due to its lower contamination and confirmed glucose detection [180]. A setup was designed to measure the stress level in fish using LED lights placed on a communication board attached to the glucose biosensor, with the fish's eyeball [174,181] (Figure 10). Various types of biosensors and their stress-detection mechanisms are mentioned in Table 5. Besides monitoring stress, biosensors have emerged as valuable tools in pathogen detection, offering rapid and sensitive alternatives to conventional diagnostic methods. Early disease detection is critical for minimizing economic losses and ensuring sustainable aquaculture practices.

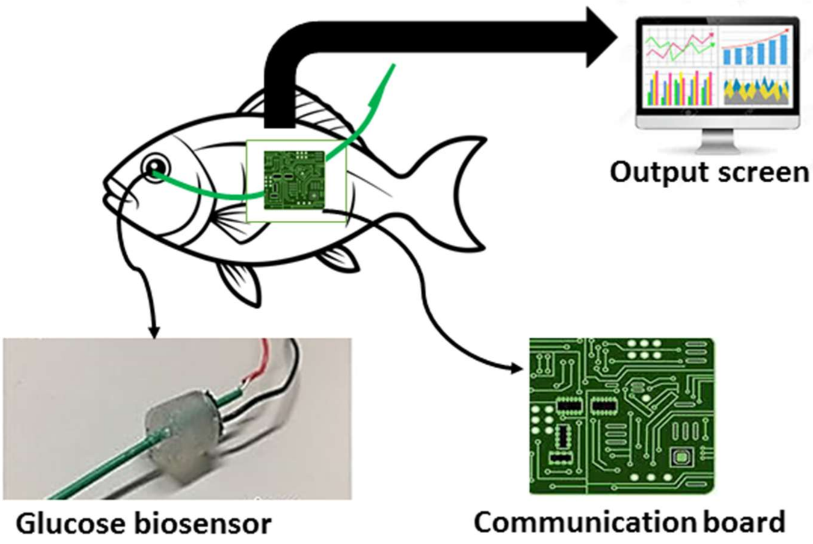

Figure 10. Schematic representation of a Glucose biosensor in aquaculture (modified after Wu et al. [176]).

Table 5. Studies on biosensor and their stress detection mechanism in aquaculture.

Name of biosensor	Stress detection	Mechanism	References
Silver nanoparticle-coated zeolite filter	Fungal infections in rainbow trout culture	Water filtration using silver nanoparticle-coated zeolite to reduce fungal infections	[182]
Gold-PDMS (Polydimethylsiloxane) filter	Removal of contaminants (thiophenol, thioanisole, toluene, sodium sulfide) from wastewater	Gold-PDMS-based filtration system for contaminant removal	[183]
Electrochemically synthesized conducting polymer-polyaniline sensor	Detection of heavy metal contamination (Cr VI) in water	Conducting polymer-based electrochemical sensor for chromium detection at low pH	[184]
Fluorescence-based biosensor	Detection of White Spot Syndrome Virus in shrimp and ammonia-oxidizing bacteria in aquaculture soil and biofilms	Fluorescence-based sensitive method for pathogen detection	[185]

6.3. Biosensors in the Detection of Harmful Pathogens in Aquaculture

A significant risk in the aquaculture industry is disease caused by pathogen infections. This results in a loss of approximately $6 billion per year globally [186]. Different types of pathogenic diseases related to aquaculture include hepatopancreatic necrosis disease, tilapia lake virus, white spot syndrome virus (WSSV), Infectious Salmon Anemia (ISA), etc [3]. Pathogens are detected using techniques such as biochemical methods, 16S rRNA typing, diagnostic PCR, serological tests, and associated protein detection methods [10]. These methods provide good results but are expensive. Recent innovative advanced techniques incorporated in the developed biosensors can detect pathogens in aquaculture. These biosensors are helpful to diagnose a wide range of bacterial (Table 6) and viral (Table 7) pathogens. In turn, it is noted that enhancing productivity in aquatic farms is beneficial.

Table 6. Studies on biosensors developed for detecting bacteria.

Name of biosensor	Target pathogen	Mechanism	References
Electrochemical Biosensor	*Escherichia coli* O157	Uses anti-E. coli O157 antibody on carbon screen-printed electrodes (SPEs) with gold nanoparticle modification for stability and sensitivity.	[187]
Photo-electrochemical Biosensor	*Vibrio parahaemolyticus*	Aptamer-based detection utilizing a layered assembly method for photocurrent response.	[188]
Chemiresistor Biosensor	*Escherichia coli* strains	M13 phage used to modify sensor material for F-pili selective detection via reduced graphene oxide.	[189]
Electrochemical Impedance Spectroscopy	*Staphylococcus aureus*	Uses vancomycin for bacterial binding.	[190]
Fluorescence Biosensor	*Staphylococcus aureus*, *Streptococcus pyogenes*, *Escherichia coli*, *Pseudomonas aeruginosa*	Uses fluorescence emission under UV light with gold and copper nanoclusters.	[191]
Fluorescence DNAzyme Sensor	*Aeromonas hydrophila*	DNAzyme-based fluorescence emission mechanism	[192]
Colorimetric CRISPR-Cas12a Sensor	*Salmonella*	Uses CRISPR-Cas12a technology for detection.	[193]

Table 7. Studies on biosensors developed for detecting viruses.

Name of biosensor	Target virus	Mechanism	References
Electrochemical Biosensor	HIV (Human Immunodeficiency Virus)	Uses graphene quantum dots to amplify electrochemical signal and immobilize p24-HIV aptamer for	[194]

		detection of p24 protein.	
Toehold Switch Sensor	Respiratory Syncytial Virus (RSV) (Subgroups A & B)	Detects RSV RNA trigger sequences via a toehold switch mechanism producing a colorimetric output.	[195]
Fluorescence DNA Walker Sensor	H5N1 (Avian Influenza Virus)	Uses DNA walker mechanism for fluorescence-based viral DNA detection	[196]
Electrochemical Immunosensor	Hepatitis B and C Viruses	Hepatitis B and C Viruses Uses anti-HBV and anti-HCV antibodies to detect respective surface/core antigens.	[197]
SERS-Based Biosensor	Influenza A H1N1 & Human Adenovirus (HAdV)	Uses monoclonal antibodies with surface-enhanced Raman spectroscopy for detection.	[198]
Electrochemiluminescence Biosensor	HIV (HIV-1 Protein)	Uses metal-organic framework (ZIF-8) for sensitive HIV detection.	(Wang et al., 2021)

6.4. Biosensors in the Detection of Adulterations in Fish

In addition to biological threats, post-harvest handling practices pose significant risks to the quality and safety of seafood. Due to the risk of protease activities and bacterial spoilage, fish are perishable after the post-harvest stage and should therefore be consumed in their fresh state [199]. To increase the profit margin, fishermen add hazardous and harmful chemicals, such as sodium benzoate, formaldehyde, and ammonia, to extend the storage life of fish and other seafood [200]. Various methods, including liquid chromatography, ultraviolet detection, mass spectrometry, fluorescence techniques, gravimetric methods, Eegriwe's method, and Deniges' method of colorimetric analysis, are used to detect adulteration in fish [30]. Various conventional techniques have been developed to detect these adulterated foods, but they have certain limitations. To overcome such constraints, biosensors are used to prevent post-harvest issues (Table 8).

Table 8. Studies on biosensors and their mechanism for detecting fish freshness.

Name of biosensor	Freshness indicator	Mechanism	References
Enzymatic Biosensor	Hypoxanthine (ATP degradation product)	Xanthine oxidase (XOD) immobilized on electrodes detects hypoxanthine oxidation to xanthine and uric acid, producing H_2O_2. Colorimetric or	[201–206]

		electrochemical detection is used.	
Colorimetric Sensor	Xanthine (byproduct of hypoxanthine oxidation)	Uses oxidation of 3,3′,5,5′-tetramethylbenzidine (TMB) dye enhanced by copper nanoclusters in the presence of H_2O_2 (produced from xanthine oxidation).	[207]
Gold Nanorods (GNRs)-Based Sensor	Hypoxanthine	Hypoxanthine oxidized by XOD produces H_2O_2, which undergoes a Fenton reaction in the presence of Fe^{2+}, leading to a visible color change. Different hypoxanthine concentrations generate different colors.	[207]
Organic Semiconductor Gas Sensor	Total Volatile Bases (TVB) - Ammonia, Dimethylamine (DMA), Trimethylamine (TMA)	Uses a porous top metal electrode with a nanostructured surface to enhance gas adsorption, detecting volatile compounds linked to fish spoilage.	[208]
Electronic Nose (E-nose) with MOS-FET Gas Sensor	Volatile Compounds from Fish Spoilage	Uses metal oxide semiconductor (MOS-FET) sensors to detect volatile amines and microbial spoilage markers in fish.	[209]

6.5. Biosensors for the Detection of Fresh Aquaculture Products

Given the challenges associated with chemical adulteration and the need for rapid freshness evaluation, biochemical markers have gained significant attention. Hypoxanthine, generated through ATP degradation, exists either independently or alongside other ATP metabolites and serves as a key indicator to evaluate fresh fish [201,202]. Various enzymatic biosensors employing colorimetric and electrochemical methods have been developed to detect hypoxanthine levels [204]. Xanthine oxidase (XOD) is widely used for the detection of hypoxanthine and xanthine, often immobilized on electrodes through cross-linking with glutaraldehyde and bovine serum albumin (BSA) [205]. These biosensors exhibit a color change corresponding to hypoxanthine concentrations ranging from 0 to 1.13 mM, allowing for semi-quantitative freshness assessment by visual inspection.

An alternative freshness assessment approach involves colorimetric analysis of histamine produced by the post-mortem decarboxylation of histidine, particularly in Scombridae species such as mackerel and tuna [210,211]. According to FDA guidelines to avoid histamine poisoning, the permissible histamine limit is accepted as 200 ppm [212]. Recent studies have demonstrated the use of Magnetic Graphene Oxide (MGO) combined with Diamine Oxidase (DO) for histamine detection via a colorimetric assay [213]. Diamines, indicative of nitrogen metabolism, serve as biorecognition elements [214] while MGO provides a high surface area and magnetic separation capabilities [215]. In this method, histamine reacts enzymatically to produce hydrogen peroxide (H_2O_2). In the presence of gold nanorods (AuNRs) and iodide ions, a visible color change occurs, ranging from dark green to colorless, as the histamine concentration increases [130]. The etching reaction on AuNRs produces a multicolour readout according to histamine concentration (Figure 11). Different colors correspond to the variation in the freshness of the fish according to the concentration of histamine (Figure 11).

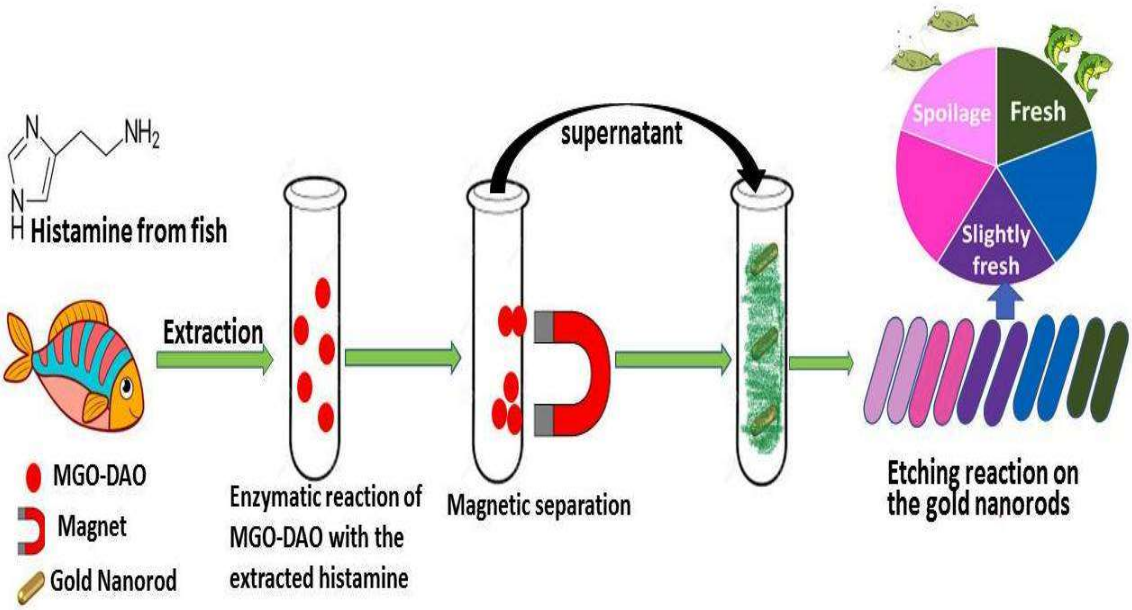

Figure 11. Colorimetric method of detection of the freshness of fish. A schematic representation of the Colorimetric biosensor method. The colour-coded pie chart represents the colour of etching on the AuNRs (modified after Xu et al. [213]).

6.6. Physiological Factors for Fish Health Management

Aquaculture has been expanding rapidly due to the increased demand for fish products. It necessitates intensive farming practices that are often reliant on antibiotics and growth factors, which pose risks to human health. As a result, non-pharmacological methods for monitoring fish health are in demand. Hemodiagnosis, which involves analyzing blood component concentrations, is a valuable tool for assessing the physiological status of fish (Maita et al., 1998b, 1998a). Indicators such as plasma total cholesterol and blood glucose levels reflect fish health, where elevated glucose levels signify stress, and reduced cholesterol is correlated with lowered bacterial resistance [216]. Changes in cholesterol concentration can be used to evaluate immunity [217], the effects of toxins [218], metabolism [219], and sperm function [220]. Studies by Maita et al. in 1998 demonstrated that reductions in plasma lipid components are associated with a decrease in disease resistance . Conventional colorimetric methods for hemodiagnosis were complex and costly, prompting the development of biosensor technologies that offer more straightforward and efficient health monitoring approaches in fish farming.

Yoneyama et al. (2009) [221] and Takase et al. (2014) [171] introduced a flow injection analysis (FIA)-based needle-type biosensor for the detection of total cholesterol. They have utilized a Teflon-coated Platinum-Iridium (PT-IR) electrode and a silver/silver chloride (Ag/AgCl) reference electrode with an enzyme-immobilized membrane at the tip. The sensor is inserted into the interstitial fluid (ISF) of the fish's eye to measure cholesterol through a series of sequential enzymatic reactions that culminate in the electrocatalytic oxidation of H_2O_2. This generates a current proportional to cholesterol concentration but is sensitive to dissolved O_2 levels (Figure 12). In contrast, mediator-based biosensors, which employ artificial electron mediators, minimize their dependency on oxygen [222,223]. Similar biosensors have been developed for glucose [174,221] and L-lactic acid [165] monitoring in the ISF, which facilitates stress assessment. Wireless systems enable continuous monitoring of total cholesterol for 24 h and glucose and L-lactic acid levels for up to 60 h. With existing biosensor methods, the integration of Artificial Intelligence (AI) has unlocked various pathways to monitor the aquaculture ecosystem and production successfully.

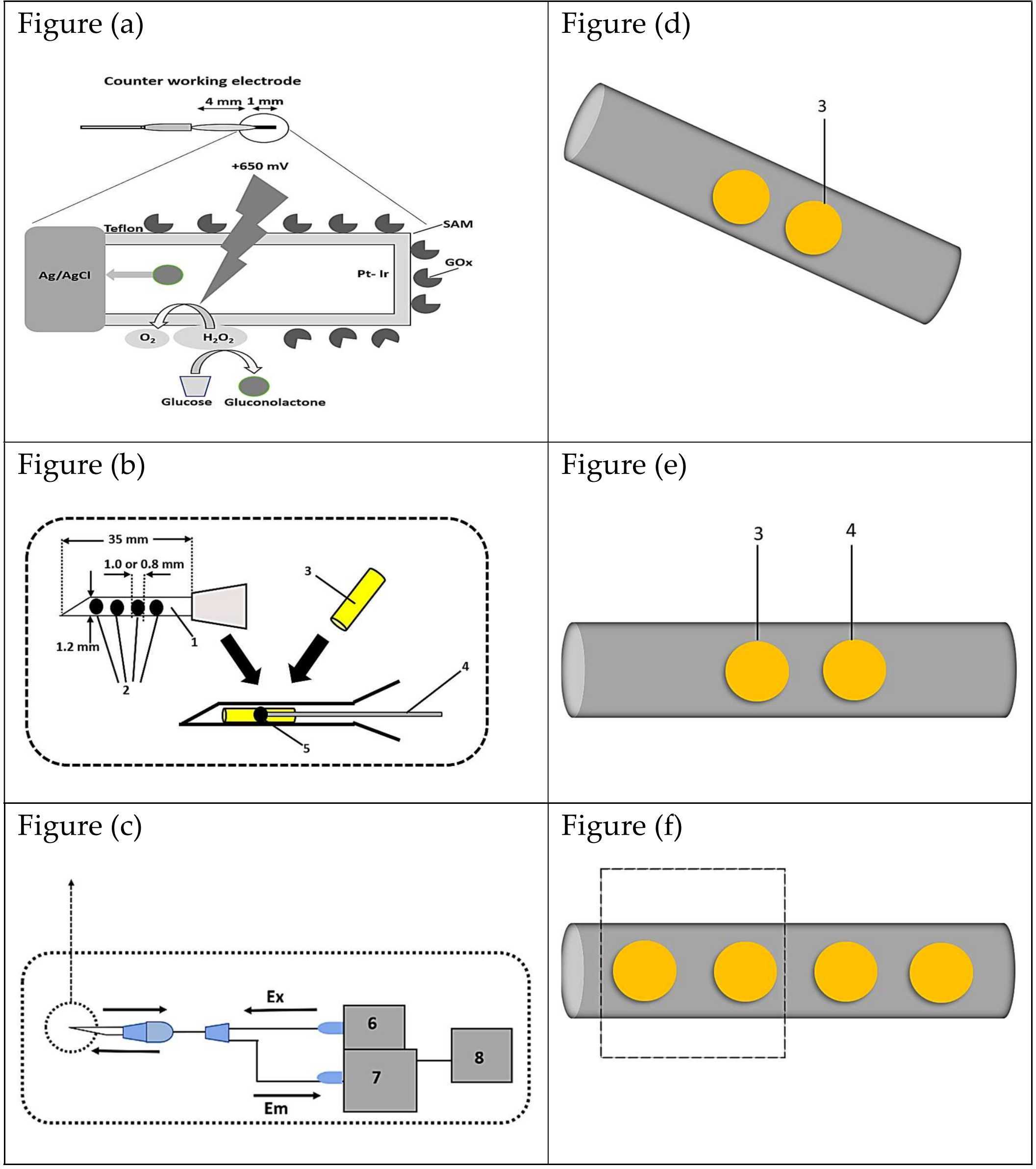
Figure (a)
Figure (d)
Figure (b)
Figure (e)
Figure (c)
Figure (f)

Figure 12. Figure (a) A schematic diagram of a glucose biosensor. Figure (b-f) Schematic diagram of the needle-type enzyme sensor system (b,c) and images of the detector region (d-f). 1 Needle-type hollow container, 2 round holes, 3 immobilized enzyme membrane, 4 optical fiber probe, 5 ruthenium complex, 6 excitation light source, 7 spectrometer, 8 personal computer (modified from Endo et al. [161], Endo and Wu [110] and Wu et al. [181]).

6.7. Integration of Biosensors and AI

The integration of biosensors and AI is transforming aquaculture by enhancing real-time monitoring, operational efficiency, and sustainability. Recent advancements demonstrate the use of sensing technologies coupled with machine learning for real-time data acquisition and automated decision-making [224]. A recent study tested a wireless biosensor network integrated with AI that yielded promising results. The system combined four core components: Random Forests (RF) predicted and maintained key environmental parameters such as temperature, pH, and dissolved oxygen; Support Vector Systems (SVS) enabled early pathogen detection to mitigate disease outbreaks; and Gradient Boosting Machines (GBM) optimized feeding schedules based on real-time conditions, thereby reducing food waste, and improved efficiency [225]. AI-driven systems thus offer smart monitoring, predictive analytics, and automated control mechanisms for aquaculture operations.

The performance and application of biosensors are highly influenced by the design and functionality of their transducer modules. Accordingly, biosensors are classified into various types based on the nature of the transducer used (Table 2). Recent advancements in sensor technology have significantly enhanced detection accuracy, sensitivity, and operational stability, driving broader adoption across multiple domains in aquaculture.

Several AI-based implementations have shown success at scale. The Japanese Kura Sushi chain, through its Kura Osakana production site, utilizes Umitron's AI-powered feeding system. It significantly enhanced mackerel tuna production. Cermaq's iFarm project utilizes AI for the early detection of sea lice and other pathogens, supporting sustainable fish farming practices. Bosch's AI feeding system analyses feeding sounds and environmental factors to minimize overfeeding and optimize feeding intervals. Despite these advancements, the deployment of AI in aquaculture necessitates robust regulatory frameworks to address data privacy, ownership, and ethical considerations. Ensuring animal welfare and maintaining environmental integrity must remain central to the responsible integration of AI technologies, especially sensors, in the aquaculture sector. Therefore, enhanced production is expected when sectors such as fish farming are free from diseases and associated issues, and biosensors are believed to be a major contributor to addressing such matters (Figure 13).

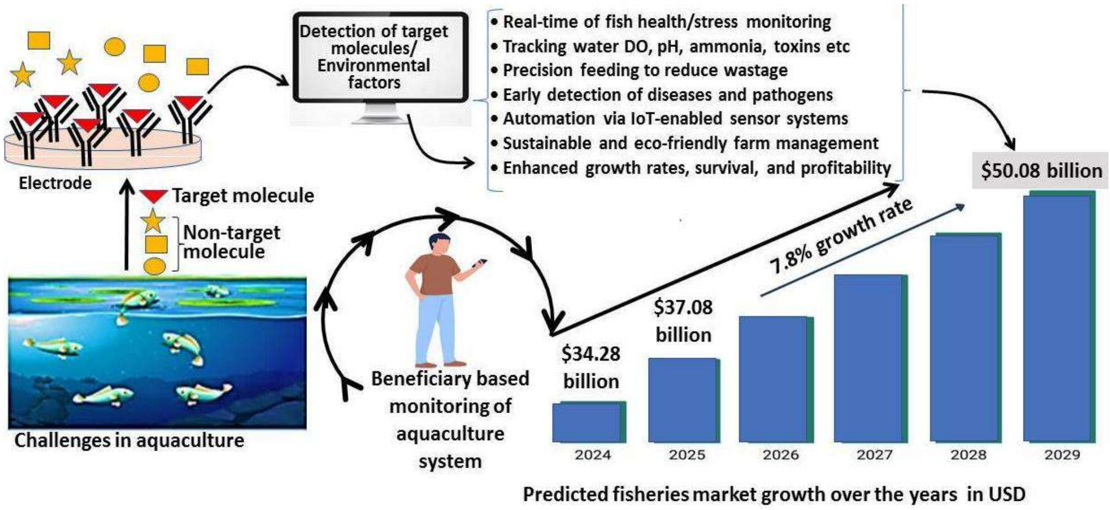

Figure 13. Enhanced production is expected in sectors such as fish farms when disease and related issues are eliminated, and biosensors are believed to play a significant role in addressing these challenges.

7. Conclusion and Prospective

The pressing global challenges of food security and malnutrition necessitate a significant increase in fish farming, surpassing the currently observed rate. Detection and management of the difficulties observed in fish farms would be beneficial in achieving the above goal sustainably. Sensor-based technology is used to detect such challenges, including environmental changes, disease detection and outbreak, growth assessment, production efficiency, and reproductive success. The application of contemporary technology, including biosensors, throughout various phases of fish culture has proven beneficial in addressing numerous prevalent challenges in the field. The potential to revolutionize the fishery industry by implementing biosensor technology represents a crucial advancement in addressing its various challenges. Despite the advancement of biosensor technology in aquaculture farms, the commercialization of multiple techniques and tools is still under investigation. Commercialization and production of miniatures of such techniques at a micro-level, such as for brood stock management, need to be achieved. Most portable devices require integration with automated AI-based algorithms to provide a need-based farmers' interface control system. Remote management of aquaculture challenges, using biosensors, is still to be resolved with AI and IoT-based tools. A broad focus needs to be given to the development of such biosensors for both artisanal and large-scale fish farming sectors.

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Abbreviations

The following abbreviations are used in this manuscript:

AFM: Atomic Force Microscope
AuNP: gold nanoparticles
BOD: Biological Oxygen Demand
BSA: Bovine Serum Albumin
COVID-19: Coronavirus Disease 2019
CRISPR-Cas: Clustered Regularly Interspaced Short Palindromic Repeats
DFM: Dynamic Force Microscopy
DHP: Dihydroprogesterone
DMA: Dimethylamine
DO: Diamine Oxidase
ELISA: Enzyme-Linked Immunosorbent Assay
FAO: Food and Agriculture Organization of the United Nations
FCM: Flow Cytometry
GBM: Gradient Boosting Machines
HIV: Human Immunodeficiency Virus
IEEE: Institute of Electrical and Electronics Engineers
LC50: Lethal Concentration 50
LCD: Liquid Crystal Display
MGO: Magnetic Graphene Oxide
MIPs: Molecularly-Imprinted Polymers
MOS-FET: Metal Oxide Semiconductor
NNV: Nervous Necrosis Virus

PCR: Polymerase Chain Reaction
PDMS: Polydimethylsiloxane
QCM: Quartz Crystal Microbalance
QCM-D: QCM with Dissipation Monitoring
RSV: Respiratory Syncytial Virus
SOFIA: State of World Fisheries and Aquaculture
SPR: Surface Plasmon Resonance
SVS: Support Vector Systems
SWCNT: Single-Walled Carbon Nanotubes
TMA: Trimethylamine
TVB: Total Volatile Bases
WHO: World Health Organization
WSN: Wireless Sensor Networks
WSSV: White Spot Syndrome Virus
XOD: Xanthine Oxidase

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