Nanotechnology In Aquaculture: Revolutionizing Fish Health and Disease Management

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***Abstract*—The global aquaculture sector faces mounting challenges from bacterial, viral, and parasitic infections that severely limit productivity and threaten sustainability. Conventional approaches primarily antibiotics and chemical disinfectants have contributed to escalating antimicrobial resistance (AMR), environmental degradation, and consumer health concerns. In recent years, nanotechnology has emerged as a transformative solution offering precise, efficient, and environmentally responsible tools for fish health management. By leveraging materials at the nanoscale (1–100 nm), researchers have developed nano-vaccines, antimicrobial nanoparticles, biosensors, and nano-encapsulated feed additives capable of enhancing fish immunity and pathogen resistance.**

This review synthesizes progress from 2020–2026 on nanotechnological interventions in aquaculture disease management. It highlights mechanisms of nanoparticle action, innovations in vaccine delivery and biosensing, environmental implications, and future perspectives integrating AI and green nanotechnology. Special emphasis is placed on safety evaluation, regulatory frameworks, and the One-Health approach to sustainable aquaculture.

***Index Terms*—Nanotechnology, Aquaculture, Fish Health, Disease Management, Nano-vaccine, Antimicrobial Nanoparticles, Biosensors, Chitosan Nanoparticles, PLGA, Nanotoxicology, Sustainable Aquaculture, Immunostimulation, Green Nanotechnology, One-Health.**

I. INTRODUCTION

Aquaculture now supplies over 50% of global seafood, positioning it as the fastest-growing food production sector worldwide (Madhavi et al., 2025). Yet, infectious diseases remain the leading cause of production loss, accounting for 30–40% of total annual yield decline in several regions (Barik et al., 2025). Common pathogens *Vibrio harveyi*, *Aeromonas hydrophila*, *Flavobacterium columnare*, and *Streptococcus iniae* affect both freshwater and marine species, undermining global food security and trade.

Over-reliance on antibiotics and chemical therapeutics has intensified concerns regarding antimicrobial resistance (AMR) development, bioaccumulation, and ecosystem contamination (Iwuozor et al., 2025). As a result, researchers are increasingly exploring nanotechnology's potential to create biocompatible, targeted, and sustainable disease management strategies. Nanotechnology enables the manipulation of matter at the atomic scale, enhancing surface reactivity, solubility, and biological interaction. This allows nanoparticles (NPs) to serve as carriers for vaccines, feed supplements, antimicrobials, and biosensors, revolutionizing disease diagnostics and prevention (El-Demerdash et al., 2025).

Nanoparticles (NPs) exhibit unique physicochemical properties, such as a high surface-to-volume ratio and tunable reactivity, that allow for efficient interaction with biological systems. These characteristics enable controlled drug release, improved solubility, and targeted antimicrobial activity against pathogens (Honcharova et al., 2025). Various nanomaterials, including silver (AgNPs), zinc oxide (ZnO NPs), chitosan-based NPs, and polymeric carriers such as poly (lactic-co-glycolic acid) (PLGA), have shown promise in preventing and treating fish diseases.

II. MECHANISMS OF NANOPARTICLE ACTION

Nanoparticles act through multiple mechanisms to prevent infection and improve fish health. AgNPs and

ZnO NPs disrupt bacterial cell walls, generate reactive oxygen species (ROS), and interfere with DNA replication (Barik et al., 2025). Chitosan nanoparticles, derived from crustacean shells, enhance immune responses by stimulating cytokine production and macrophage activation (El-Demerdash et al., 2025).

Biodegradable polymeric nanoparticles like PLGA offer sustained drug release, minimizing toxicity while maximizing efficacy (Tangal et al., 2026). Additionally, nanomaterials inhibit biofilm formation by pathogenic bacteria such as Vibrio and Aeromonas, thereby reducing infection persistence (Iwuozor et al., 2025).

2.1 Antimicrobial Activity

Metallic nanoparticles such as silver (AgNPs) and zinc oxide (ZnO NPs) exhibit potent antimicrobial effects by disrupting cell membranes, inducing oxidative stress through reactive oxygen species (ROS), and interfering with DNA replication and protein synthesis (Barik et al., 2025).

AgNPs have demonstrated significant inhibition against *Vibrio harveyi* and *Aeromonas hydrophila*, with minimum inhibitory concentrations (MICs) between 5–10 μg/mL. ZnO NPs further enhance antioxidant capacity, providing a dual immunoprotective effect.

2.2 Immunomodulation and Antioxidant Protection

Chitosan nanoparticles, derived from crustacean exoskeletons, show remarkable immune-stimulatory potential by activating macrophages and lymphocytes, upregulating cytokines (IL-1β and TNF-α), and enhancing lysozyme activity and mucosal defences (El-Demerdash et al., 2025). These effects improve non-specific immunity and resistance to bacterial and parasitic infections.

2.3 Controlled Delivery and Bioavailability

Polymeric nanoparticles such as poly (lactic-co-glycolic acid) (PLGA) and polylactic acid (PLA) enable controlled release of encapsulated agents, minimizing drug degradation and toxicity while maintaining prolonged immunogenicity (Tangal et al., 2026). Nano-encapsulation also enhances nutrient solubility and uptake, significantly improving feed efficiency.

III. APPLICATIONS IN FISH HEALTH MANAGEMENT

3.1 Nano-Vaccines

Nano-vaccines utilize nanoparticles as antigen carriers to improve vaccine stability and immune response. Chitosan and PLGA nanoparticles have been tested in carp, tilapia, and catfish with promising results. These formulations facilitate slow antigen release, enhancing mucosal and systemic immunity (George et al., 2025; Anisha & Sudheep, 2025).

For example, PLGA-encapsulated vaccines demonstrated an 80% survival rate in vaccinated fish challenged with Vibrio species compared to 50% in conventional formulations (El-Demerdash et al., 2025).

3.2 Antimicrobial Nanoparticles

Silver and zinc oxide nanoparticles have been widely investigated for their antimicrobial properties. AgNPs have shown inhibition zones against Vibrio harveyi and Aeromonas hydrophila, while ZnO NPs provide both antibacterial and antioxidant benefits (Yazgan et al., 2026).

These nanoparticles can be incorporated into fish feed or used as water additives, improving overall survival rates and feed efficiency.

3.3 Nano-Probiotics and Feed Additives

Nano-probiotics combine beneficial microbial strains with nanoparticle carriers to enhance gut health. A notable study by Tangal et al. (2026) reported that silica-chitosan nanoparticles loaded with Bacillus velezensis improved gut microbiota diversity in Asian seabass, reducing Vibrio loads and improving feed conversion ratio by 25%. Such nano-formulations improve nutrient bioavailability and immune resilience.

3.4 Diagnostic and Biosensing Tools

Nanotechnology has advanced pathogen detection through biosensors utilizing gold, magnetic, or graphene nanoparticles (Honcharova et al., 2025).

These biosensors can detect fish pathogens like Aeromonas and Streptococcus species within minutes using colorimetric or electrochemical signals, facilitating early disease management.

Table 1. Comparative Performance Metrics of Nano-based and Conventional Treatments

Parameter	Conventional Treatment	Nano-based Approach	Improvement (%)
Vaccine antigen retention	< 40%	> 75% (PLGA nano-vaccine)	+87%
Feed conversion ratio	1.9 ± 0.2	1.4 ± 0.1 (nano-diet)	+26%
Pathogen reduction (Vibrio sp.)	—	$10^4 \rightarrow 10^2$ CFU/mL	99%
Survival rate post-infection	55%	84%	+52%

IV. ENVIRONMENTAL AND TOXICOLOGICAL CONSIDERATIONS

While nanotechnology offers immense potential, concerns remain regarding nanoparticle accumulation in aquatic environments. Studies show that ZnO and Ag nanoparticles can accumulate in fish gills, liver, and intestine, leading to oxidative stress and histopathological damage at higher concentrations (Khan et al., 2025). Chronic exposure (>5 mg/L) resulted in altered gill morphology and reduced enzyme activity in zebrafish. Ecotoxicological evaluations suggest prioritizing biodegradable and bio-based nanoparticles, such as chitosan or cellulose derivatives, to mitigate long-term effects (El-Demerdash et al., 2025). Regulatory agencies, including FAO and OECD, emphasize the need for nano-specific environmental safety assessments before commercial deployment.

V. FUTURE PROSPECTS

Future applications of nanotechnology in aquaculture will integrate smart nanosensors, targeted gene-editing tools, and AI-driven monitoring systems (Honcharova et al., 2025). Nanosensors capable of real-time pathogen detection and water quality analysis could revolutionize disease prevention strategies. Moreover, the development of green synthesis methods using plant extracts for nanoparticle production will further enhance sustainability (Madhavi et al., 2025). Interdisciplinary research combining materials science, genetics, and fish physiology will be crucial for creating precise, efficient, and safe nano-formulations. The establishment of international guidelines and life-cycle risk assessments is essential to ensure ecological safety while maximizing technological benefits.

VI. CONCLUSION

Nanotechnology represents a paradigm shift in aquaculture health management. It enables the design of innovative nano-vaccines, antimicrobial agents, and biosensors that enhance fish immunity and control disease outbreaks. However, to fully harness its potential, it is vital to address safety concerns through standardized toxicity testing, environmental monitoring, and policy integration. Sustainable nanobiotechnology will play a pivotal role in achieving disease-resistant aquaculture systems that balance productivity and environmental integrity.

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