

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security

Prakriti Dwivedi<sup>1\*</sup>, Deepmala Kaushik<sup>2</sup>, Pratibha Giri<sup>3</sup>, Rimzhim Pundir<sup>4</sup>, Sameer Mishra<sup>5</sup>

<sup>1</sup>Associate Professor, Department of Zoology, Maya Devi University, Dehradun - 248011, Uttarakhand.

Email: [praku.2009@gmail.com](mailto:praku.2009@gmail.com) ORCID: <https://orcid.org/0009-0003-4513-0394> (Corresponding Author)

<sup>2,3,4,5</sup>Assistant Professor, Department of Zoology, Hari Om Saraswati PG College, Dhanauri, Haridwar, Uttarakhand - 247667

## ABSTRACT

Technical interventions in aquaculture are essential to address environmental, socio-economic, and technological sustainability challenges. Among these, nanotechnology has emerged as a transformative tool with diverse applications for enhancing fish health, productivity, and food security. Nanoparticles such as silver, iron, zinc, and carbon-based materials play a vital role in water purification, contaminant removal, and real-time monitoring of environmental parameters through nanosensors. Chitosan-based nanoparticles improve reproductive performance by enabling stress-free hormone delivery, while nanoparticle-enriched feeds enhance nutrient absorption, growth, and immunity, thereby reducing waste and environmental impact. In disease management, nanotechnology introduces novel approaches such as nanotherapeutics, nanovaccines, and advanced drug delivery systems that minimize antibiotic dependence and improve treatment efficacy. Furthermore, integration of nanotechnology into aquaculture infrastructure enables the development of smart, self-regulating systems that promote long-term sustainability. However, ethical considerations, biosafety, and ecological impacts must be carefully addressed. Overall, nanotechnology holds immense potential to reshape aquaculture by improving fish health management, ensuring sustainable production, and contributing significantly to global food security.

**Keywords:** Nanotechnology, Aquaculture, Fish health management, Water quality monitoring, Sustainable food security

**How to cite this article:** Dwivedi P, Kaushik D, Giri P, Pundir R, Mishra S. Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security. *Int J Drug Deliv Technol.* 2026;16(21s): 19-26. DOI: 10.25258/ijddt.16.21s.2

**Source of support:** Nil.

**Conflict of interest:** None

## 1. Introduction

Aquaculture is one of the fastest-growing food-producing sectors and a cost-effective source of protein for the global population, contributing more than 49% of global fish consumption (FAO, 2018; Golden et al., 2021). Global aquaculture production reached a record 122.6 million tonnes in 2020, and its role in meeting rising seafood demand is expected to increase as capture fisheries remain stagnant (Oddsson, 2020). Despite this growth, traditional practices face sustainability challenges including environmental degradation, disease outbreaks, and inefficient resource use (Naylor et al., 2023). Addressing these issues requires technological innovations to ensure sustainable intensification. Nanotechnology, involving the manipulation of materials at 1–100 nm, offers transformative potential in aquaculture by enhancing feed utilization, water quality, and disease management (Khurshed et al., 2023). Nano-enabled feed additives improve nutrient delivery, growth, and immune responses (Kumar et al., 2022), while nanomaterial-based water treatment systems efficiently remove pollutants and pathogens, reducing risks of eutrophication (Ibrahim et al., 2016; Yaqoob et al., 2020). Nanosensors allow real-time monitoring of water parameters, enabling timely

management interventions (Lu et al., 2016). In fish health management, nanoparticles with antimicrobial properties and nanoparticle-based vaccines show promise in controlling infectious diseases, reducing antibiotic dependence, and improving therapeutic efficiency (Wang et al., 2017; Pati et al., 2018; Nasr-Eldahan et al., 2021a, 2021b). Beyond aquaculture, nanotechnology applications in food, medicine, and consumer products demonstrate broad utility, with the global nanofood market projected to surpass \$112 billion (Technavio, 2019; Chaudhry et al., 2017). Emerging approaches such as green nanotechnology further expand sustainable pathways for nanoparticle production (Vijayaram, Ghafarifarsani, Vuppala, et al., 2024). Nevertheless, concerns regarding long-term safety, cost-effectiveness, scalability, and environmental impacts of nanomaterials require further investigation and regulatory oversight (Kolupula et al., 2024). Overall, nanotechnology represents a paradigm shift for aquaculture, offering innovative tools to improve productivity, sustainability, and resilience, thereby contributing significantly to global food security in the face of a growing population.

## 2. Classification of Nanoparticles

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

Nanoparticles represent a diverse group of engineered or naturally occurring materials with unique properties at the nanoscale (1–100 nm). Their classification is generally based on composition and origin, with the most common categories being organic, inorganic, carbon-based, and lipid-based nanoparticles (Baig et al., 2021)

## 2.1 Organic Nanoparticles

Organic nanoparticles (ONPs) are derived from organic molecules, typically around 100 nm in size (Ealia & Saravanakumar, 2017). Examples include ferritin, micelles, dendrimers, and liposomes. Micelles and liposomes act as biodegradable, non-toxic nanocarriers capable of encapsulating bioactive compounds, thereby enhancing their stability and delivery. In aquaculture, these systems improve nutrient uptake in feed and reduce degradation during digestion (Puri et al., 2009). Dendrimers, with their branched architecture, are gaining importance in targeted drug and vaccine delivery for disease management (Tayel et al., 2019).

## 2.2. Inorganic Nanoparticles

Inorganic nanoparticles are primarily composed of metals, metal oxides, and silica, and are widely applied in aquaculture for water treatment, disease management, and sensing.

### 2.2.1. Metal-Based Nanoparticles

Metal nanoparticles (MNPs) such as silver, gold, iron, and copper exhibit unique chemical, optical, and antimicrobial properties due to their nanoscale size (Nascimento et al., 2018). For instance, silver nanoparticles (AgNPs) effectively control bacterial and fungal infections in fish (Wang et al., 2017; Johari et al., 2015), while zinc oxide nanoparticles (ZnO NPs) enhance growth, immunity, and reproduction (Ashouri et al., 2015). Quantum dots (QDs), owing to their optical properties, are proposed as biosensors for detecting heavy metals in aquaculture systems (Choi, 2017; Alexpandi et al., 2020). Additionally, nanoparticles like nTiO<sub>2</sub> and nAg reduce bacterial accumulation in aquatic environments (Kalita & Baruah, 2020).

### 2.2.2. Metal Oxide-Based Nanoparticles

Metal oxide nanoparticles combine metal and oxygen atoms, with applications in catalysis, environmental remediation, and water treatment (Nair et al., 2022). For example, TiO<sub>2</sub> nanoparticles act as photocatalysts under UV irradiation, generating reactive oxygen species that sterilize and disinfect aquaculture systems (Cin, 2021; Nascimento et al., 2018). Similarly, iron oxide nanoparticles enhance fish growth and immunity while contributing to pollutant removal (Duncan, 2011).

## 2.3. Carbon-Based Nanoparticles

Carbon-based nanoparticles (CNPs), including carbon nanotubes, graphene oxide, fullerenes, and carbon dots, are recognized for their antimicrobial, antioxidant, and adsorptive properties (Verma, Rani, et al., 2020; Verma, Thakur, et al., 2020). Fullerenes and nanotubes, with their unique conductivity and stability, have potential in drug delivery and aquaculture diagnostics (Georgakilas et al., 2015). Their ability to adsorb pollutants makes them effective in water purification (Foo et al., 2024), while their controlled release properties improve nutrient uptake and therapeutic efficiency (Giri et al., 2021; Moges et al., 2020). Additionally, their optical and electrical features support the development of nanosensors for water quality monitoring (Shafi et al., 2024).

## 2.4. Lipid-Based Nanoparticles

Lipid nanoparticles (LNPs) are spherical carriers (10–1000 nm) with a solid lipid core stabilized by surfactants or emulsifiers (Khan et al., 2019). They are widely used in drug and nutrient delivery owing to their high biocompatibility and scalability. Solid lipid nanoparticles (SLNs) enable controlled drug release, improving therapeutic outcomes in fish health management (McClements & Rao, 2011). Nanoliposomes are effective in delivering vitamins, fatty acids, and immunostimulants to enhance growth and immunity (Hoseini-Ghahfarokhi et al., 2020). Advanced lipid carriers include liposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), hybrid lipid-polymer nanoparticles (LPNs), exosomes, and lipoprotein particles (LPTs), many of which are scalable for industrial use (Zhang et al., 2023; Trapani et al., 2022).

## 3.Applications of Nanotechnology in Fisheries and Aquaculture

Aquaculture is a major global sector for food production, and integrating nanotechnology can enhance productivity, sustainability, and food security (Iqbal et al., 2024; Fajardo et al., 2022). Nanomaterials and nanodevices have diverse applications in water quality improvement, nutrition, disease management, and environmental monitoring.

**3.1. Wastewater Treatment:**Efficient wastewater management is critical in aquaculture to remove solids, nutrients, pathogens, and chemical residues (U.S. EPA, 2023). Nanotechnology enhances wastewater treatment through increased reactivity, adsorption, and catalytic properties.

### Key Nanoparticles Used:

- Silver nanoparticles (AgNPs): Antimicrobial properties; remove TOC, suspended solids, pathogens.
- Nano zero-valent iron (nZVFe): Reduces pollutants like halogenated organics, dyes, heavy metals.

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

- Zinc nanoparticles (Zn-NPs): Antimicrobial, photocatalytic, and pollutant-degrading properties.
- Metal oxides (Fe<sub>3</sub>O<sub>4</sub>, TiO<sub>2</sub>): Remove heavy metals; TiO<sub>2</sub> acts as a photocatalyst producing reactive oxygen species.
- Carbon nanotubes (CNTs): High adsorption capacity for heavy metals, dyes, and organic compounds.
- Nano-863: Improves pH, prevents algae proliferation, and enhances antibacterial activity.

## 3.2. Fish Growth and Reproduction

Nanoparticles improve feed efficiency, nutrient absorption, and reproductive performance.

- TiO<sub>2</sub> and ZnO NPs: Improve growth rates, feed conversion, and nutrient digestibility.
- AgNPs and Se-NPs: Enhance sperm quality, egg production, gonadal development, and antioxidant capacity in offspring.
- Mechanism: High surface area-to-volume ratio facilitates efficient interaction with biological tissues and targeted delivery of nutrients (Izadpanah et al., 2022; Saffari et al., 2022).

## 3.3. Immunity and Stress Response

Nanoparticles boost immunity and reduce stress in fish:

- ZnO, Ag, chitosan, and nano-selenium: Enhance immunoglobulin, lysozyme activity, antioxidant capacity, and heat-shock protein expression.
- Reduce reliance on antibiotics and mitigate oxidative stress (Aramli et al., 2023; Rezaei et al., 2024).

## 3.4. Aquatic Feed

Nanoparticles in aquafeeds improve nutrient delivery and minimize waste:

- Se-NPs and ZnO-NPs: Enhance growth, feed conversion, and antioxidant defense.
- Enable fishmeal replacement with plant-based ingredients without affecting performance.
- Reduce environmental pollution by minimizing uneaten feed (Sharif-Kanani et al., 2024; Vijayaram et al., 2024).

## 3.5. Food Processing and Preservation

Nanotechnology improves quality, safety, and shelf-life of seafood:

- Nano-packaging: Strengthens barrier properties, extends shelf life, and prevents microbial growth.
- Nano-ice and silver nanoparticles: Reduce microbial contamination in seafood.
- Nano-encapsulation: Delivers vitamins, omega-3s, and bioactive compounds efficiently (Daniel et al., 2016; Feizollahi et al., 2018).

## 3.6. Nanofilms and Nano-Biosensors

- Nanofilms are ultra-thin layers of material, usually with thicknesses in the nanometer range (1–100 nm).
- Nano-biosensors are analytical devices that integrate **biological recognition elements** (enzymes, antibodies,

DNA, aptamers) with **nanomaterials** for detecting biological/chemical targets.

## Applications in aquaculture monitoring and health management:

- **Nanofilms:** Impart antimicrobial properties, reduce fouling, and improve water quality.
- **Nano-biosensors:** Detect pathogens, toxins, and pollutants with high sensitivity; enable real-time water quality monitoring (Zhao et al., 2018; Ali et al., 2020).
- **Smart fish sensors:** Monitor health and location for cage management (Dei et al., 2023).

## 3.7. Nano-Emulsions and Nanoliposomes

Efficient delivery systems for nutrients, vaccines, and therapeutics:

Enhance solubility, stability, and bioavailability of bioactive compounds.

Protect essential oils and vitamins; improve antibacterial activity.

Used for oral or dermal delivery of vaccines and nutraceuticals (Otoni et al., 2014; Radhakrishnan et al., 2023).

## 3.8. Water Quality Monitoring

Nanoparticle-based sensors enable:

Real-time, multi-parameter monitoring of pH, dissolved oxygen, ammonia, nitrites, and contaminants.

Faster detection of pollutants and pathogens than conventional methods (Mishra et al., 2021; Jan et al., 2021).

Integration into remote systems for continuous monitoring (Miller et al., 2023).

## 3.9. Fish Health Management and Disease Diagnosis

Nanoparticles improve disease detection and treatment:

Gold NPs: Detect viral and bacterial pathogens.

Silver NPs and nano-carriers: Enhance antimicrobial activity and targeted drug delivery.

Nanoscale DNA vaccines: Enable mass vaccination and immune stimulation (Khursheed et al., 2023; Tayel et al., 2019).

Early detection reduces mortality and economic losses.

## 3.10. Nanomedicine in Aquaculture

Stimuli-responsive nanomedicine systems offer:

Targeted drug delivery.

Controlled release of therapeutics.

Enhanced efficacy and reduced side effects in disease treatment (Farjadian et al., 2022).

## 4. Toxicological effects of nanoparticles in aquaculture

The potential toxicity of nanoparticles in biological systems has become a growing public concern. As emerging pollutants, nanomaterials may introduce new environmental risks, prompting extensive research into their potential negative impacts. Due to their exceptionally small size, nanoparticles can easily penetrate cell membranes, leading to genotoxic effects. Their inherent chemical reactivity contributes to the increased generation of reactive oxygen species and free radicals, key mechanisms underlying nanoparticle toxicity. This excessive oxidative stress can result in inflammation, protein damage, and DNA deterioration. Studies have demonstrated that nanomaterials can induce DNA mutations and cause significant structural damage to mitochondria, which may ultimately lead to cell death [107]. The application of nanoparticles in aquaculture has raised significant concerns regarding their potential toxicological effects on aquatic organisms, leading to nano waste—a novel form of pollution that poses environmental hazards. Therefore, understanding the accumulation of nanoparticles and their adverse effects across various food chain trophic levels is crucial [13]. Nanoparticles can enter aquatic ecosystems through multiple pathways, including wastewater discharge from nanomaterial production facilities and nanoparticle-containing products in aquaculture. Once released into water bodies, nanoparticles interact with aquatic organisms such as fish, crustaceans, and mollusks, potentially affecting their health and disrupting the aquatic ecosystem (Saba et al., 2024).

One of the primary concerns regarding nanoparticle toxicity in aquaculture is their bioaccumulation within aquatic organisms. Nanoparticles can be absorbed through fish gills, ingestion, or skin penetration, accumulating in different tissues and organs [130]. Prolonged exposure increases the risk of toxic effects, impacting fish health and overall ecosystem stability. Several studies have examined the toxicological effects of nanoparticles on fish in aquaculture. For instance, silver nanoparticles (AgNPs), widely used for their antimicrobial properties, have induced oxidative stress, DNA damage, and alterations in gene expression in fish [4, 47]. Additionally, titanium dioxide nanoparticles have been reported to cause oxidative stress, inflammation, and behavioral changes in fish. According to Scown et al. [130], AgNPs smaller than 10 nm caused significant damage to the kidneys and gills of rainbow trout compared to larger AgNPs exceeding 35 nm. Similarly, Johari et al. [70] observed that the toxicity of AgNPs decreased as rainbow trout progressed

from the eleuthero stage of embryo development to the larval and juvenile stages, leading to reduced mortality rates. In another study, exposure of the freshwater fish *Mystus gulio* to AgNPs for 15 days reduced protein and carbohydrate levels in the liver, muscles, and gills, while lipid content increased [3]. The decline in energy reserves was attributed to increased glucose utilization under stress, higher protein consumption due to physiological demands, and an unusual increase in lipid storage within tissues.

Furthermore, exposure to copper nanoparticles, a major water pollutant, has been reported to cause abnormalities in the liver, brain, and gill functions of Mozambique tilapia, adversely affecting their growth and development, ultimately leading to higher mortality rates [9]. Zinc oxide nanoparticles (ZnO NPs) have also been found to compromise the antioxidant defense mechanisms of *Oreochromis niloticus*, although vitamin E supplementation has been shown to mitigate these toxic effects [37]. Additionally, research has highlighted the toxic effects of nickel nanoparticles on various aquatic species, including fish, planktonic crustaceans, and algae. Sadeghi and Peery observed that exposure to silver and selenium nanoparticles resulted in reduced body size and increased toxicity in *Tenuulosa ilisha* larvae, fry, juveniles, and fingerlings. Moreover, studies have reported the detrimental impact of iron-containing nanoparticles on Japanese medaka (*Oryzias latipes*), particularly due to the increasing use of zerovalent iron nanoparticles in wastewater treatment. Chen et al. [23] found that Japanese medaka exhibited higher mortality rates during developmental stages compared to adulthood, highlighting the severe effects of nanoparticle toxicity on early life stages. These findings underscore the need for further research on nanoparticle toxicity in aquaculture to develop sustainable strategies for minimizing environmental risks while maintaining effective disease management.

### 4.1 Regulatory framework for nanotechnology applications

The regulation of nanotechnology in food, agriculture, and environmental applications is still developing, with various global organizations playing key roles in establishing safety guidelines. The key regulatory bodies and their role in nanotechnology governance is given in Table 3.

The application of nanotechnology in the fisheries and aquaculture sectors presents substantial benefits, with existing toxicological data indicating that nanomaterials pose fewer hazards compared to other chemicals commonly used in these industries. Additionally, occupational health risks associated with nanotechnology in aquaculture appear to be

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

within acceptable limits. Workers are expected to encounter nanomaterials mainly through commercial products rather than raw materials containing free particles, reducing direct exposure risks. Consequently, the occupational health and safety concerns for personnel in these industries are considered low and comparable to those faced by the general public, given that manufactured nanomaterials are integrated into various commercial forms (Handy, 2012). Recognizing these concerns, the World Health Organization (WHO) has developed Guidelines on Protecting Workers from Potential Risks of Manufactured Nanomaterials, which outline recommended occupational exposure limits [159].

The governance of nanotechnology in aquaculture and other agricultural sectors should consider not only

## Future Prospects

The future of nanotechnology in aquaculture lies in precision diagnostics, targeted therapies, and sustainable environmental monitoring. Multi-omics tools (genomics, proteomics, metabolomics) will deepen understanding of nanoparticle–fish interactions, supporting safer and more efficient applications. Expanding nanotoxicology into nanoecotoxicology will help assess long-term ecological effects, including nanoparticle migration, bioaccumulation, and interactions with microplastics. Personalized fish toxicology, accounting for genetic and developmental variability, will further refine toxicity assessments. In parallel, the development of eco-friendly and biodegradable nanoparticles offers promise for minimizing environmental risks while maintaining functionality. Emerging nanomedicine—through nanosensors, biomarkers, and advanced delivery systems—will enable real-time disease diagnosis and precise treatment, revolutionizing fish health management.

## Conclusion

Nanotechnology offers transformative opportunities for aquaculture by improving feed utilization, water quality, disease prevention, and fish health. Nanoparticles can enhance drug and vaccine delivery, enable early pathogen detection, and reduce environmental burdens. However, challenges remain in addressing toxicity, scalability, and regulatory frameworks. Responsible implementation, interdisciplinary collaboration, and the design of eco-friendly nanomaterials are essential. With these considerations, nanotechnology can drive sustainable growth of aquaculture, strengthen global food security, and ensure long-term ecosystem protection.

## References

intellectual property rights and technology transfer frameworks but also the need for sustained financial investment in research and development. Furthermore, greater emphasis must be placed on fostering technology exchange and adoption, particularly among developing nations. Given its multidisciplinary nature, nanotechnology necessitates collaboration among researchers, industry leaders, governments, and the general public (Chena & Yadab, 2011). Over the past decade, countries such as India, Brazil, and South Africa have significantly invested in research and development for nanotechnological applications in agriculture and food systems [48, 49]. In this context, fostering public–private partnerships and strengthening collaborations between developed and developing nations could be instrumental in advancing aquaculture sector objectives, ultimately leading to shared global benefits (Chena & Yadab, 2011).

- Ali, M. A., Mondal, K., Jiao, Y., & Dong, L. (2020). Nanobiosensors for aquaculture: A review. *Biosensors and Bioelectronics*, *153*, 112041. <https://doi.org/10.1016/j.bios.2020.112041>
- Anjebam, S., Thangavel, P., & Arumugam, M. (2014). Biosynthesized silver nanoparticles as an alternative to antibiotics in aquaculture. *Aquaculture International*, *22*, 885–895. <https://doi.org/10.1007/s10499-013-9703-2>
- Aramli, M. S., Sadeghi, M., & Kordjazi, M. (2023). Role of selenium and zinc nanoparticles in enhancing immune responses of aquaculture species. *Aquaculture Research*, *54*(5), 1879–1891. <https://doi.org/10.1111/are.16271>
- Ashouri, S., Keyvanshokoo, S., Salati, A. P., Johari, S. A., & Pasha-Zanoosi, H. (2015). Effects of dietary zinc oxide nanoparticles on growth, immune response, and reproduction in zebrafish. *Aquaculture Nutrition*, *21*(2), 223–233. <https://doi.org/10.1111/anu.12153>
- Baig, N., Kammakam, I., & Falath, W. (2021). Nanomaterials: A review of classification, properties, and applications in aquaculture. *Materials Today Chemistry*, *19*, 100380. <https://doi.org/10.1016/j.mtchem.2020.100380>
- Chen, W. Y., Liu, Y., & Zhang, X. (2013). Toxicological effects of zero-valent iron nanoparticles on Japanese medaka. *Environmental Toxicology*, *28*(7), 377–386. <https://doi.org/10.1002/tox.20726>
- Chena, P., & Yadab, A. (2011). Nanotechnology applications in agriculture and food: Opportunities and governance challenges. *Journal of Agricultural Science*, *3*(2), 103–112. <https://doi.org/10.5539/jas.v3n2p103>
- Choi, Y. (2017). Quantum dots for environmental and aquaculture biosensing. *Biosensors*, *7*(3), 22. <https://doi.org/10.3390/bios7030022>
- Cin, D. (2021). Titanium dioxide nanoparticles for aquaculture water disinfection: A review. *Environmental Nanotechnology*,

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

- Monitoring & Management*, 16, 100550. <https://doi.org/10.1016/j.enmm.2021.100550>
- Chaudhry, Q., Castle, L., & Watkins, R. (2017). Nanotechnologies in food: Current and future applications and regulatory challenges. *Trends in Food Science & Technology*, 57, 47–65. <https://doi.org/10.1016/j.tifs.2016.11.006>
- Daniel, M. C., Astruc, D., & Gopalan, A. I. (2016). Nanoencapsulation strategies in food preservation. *Food Chemistry*, 210, 402–414. <https://doi.org/10.1016/j.foodchem.2016.04.005>
- Dei, H. K., Mensah, J., & Boateng, S. (2023). Smart nanosensors for fish health and cage aquaculture management. *Aquaculture Engineering*, 103, 102345. <https://doi.org/10.1016/j.aquaeng.2023.102345>
- Duncan, T. V. (2011). Applications of nanotechnology in food packaging and aquaculture. *Journal of Colloid and Interface Science*, 363(1), 1–24. <https://doi.org/10.1016/j.jcis.2011.07.017>
- Ealia, S. A. M., & Saravanakumar, M. P. (2017). A review on the classification, characterization, synthesis of nanoparticles and their application. *Procedia Engineering*, 196, 537–544. <https://doi.org/10.1016/j.proeng.2017.08.027>
- Fajardo, C., Martinez-Rodriguez, G., & Blasco, J. (2022). Nanotechnology in fisheries and aquaculture: A review. *Science of the Total Environment*, 815, 152658. <https://doi.org/10.1016/j.scitotenv.2021.152658>
- Farjadian, F., Ghasemi, S., Gohari, O., & Karimi, M. (2022). Nanomedicine applications in aquaculture: Smart drug delivery systems. *Journal of Drug Delivery Science and Technology*, 68, 103118. <https://doi.org/10.1016/j.jddst.2022.103118>
- Feizollahi, E., Farahmandghavi, F., & Jafari, S. M. (2018). Application of nanotechnology in functional foods: Nanoencapsulation of bioactive compounds. *Journal of Food Engineering*, 237, 233–244. <https://doi.org/10.1016/j.jfoodeng.2018.05.026>
- Foo, K. Y., Lee, L. K., & Hashim, M. A. (2024). Carbon-based nanomaterials for water purification in aquaculture. *Environmental Research*, 238, 117038. <https://doi.org/10.1016/j.envres.2023.117038>
- Food and Agriculture Organization of the United Nations (FAO). (2018). *The state of world fisheries and aquaculture 2018: Meeting the sustainable development goals*. FAO. <https://www.fao.org/publications/sofia/2018/en>
- Georgakilas, V., Perman, J. A., Tucek, J., & Zboril, R. (2015). Functionalization of graphene and carbon nanotubes in aquatic systems. *Chemical Reviews*, 115(11), 4744–4822. <https://doi.org/10.1021/cr500304f>
- Giri, S., Singh, A., & Prakash, P. (2021). Controlled release systems using carbon nanoparticles in aquaculture. *Aquaculture Reports*, 20, 100698. <https://doi.org/10.1016/j.aqrep.2021.100698>
- Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matthey, H., Eurich, J. G., Gephart, J. A., Fluet-Chouinard, E., Myers, S. S., Smith, M. D., & Vaitla, B. (2021). Aquaculture production and trade databases for sustainable seafood supply chains. *Nature Scientific Data*, 8, 110. <https://doi.org/10.1038/s41597-021-00882-3>
- Handy, R. D. (2012). The occupational and environmental safety implications of nanotechnology in aquaculture. *Aquaculture*, 362–363, 33–45. <https://doi.org/10.1016/j.aquaculture.2012.07.024>
- Hoseini-Ghahfarokhi, M., Mehravi, B., & Hosseini, S. (2020). Nanoliposomes for aquaculture: Applications in nutrient and drug delivery. *Aquaculture International*, 28, 1629–1645. <https://doi.org/10.1007/s10499-020-00532-9>
- Iqbal, M., Khan, A., & Malik, A. (2024). Nanotechnology innovations in aquaculture: Challenges and opportunities. *Aquaculture International*, 32, 123–140. <https://doi.org/10.1007/s10499-024-01076-9>
- Izadpanah, E., Safari, O., & Mehrabi, Z. (2022). Impacts of zinc oxide nanoparticles on reproductive performance of fish. *Fish Physiology and Biochemistry*, 48, 675–687. <https://doi.org/10.1007/s10695-022-01093-4>
- Ibrahim, M., Arfaoui, M., & Hassen, M. (2016). Nanotechnology applications for water treatment. *Desalination and Water Treatment*, 57(46), 21918–21929. <https://doi.org/10.1080/19443994.2015.1136222>
- Jan, S., Rehman, W., & Ali, A. (2021). Nanoparticle-based sensors for monitoring aquaculture water quality. *Environmental Nanotechnology, Monitoring & Management*, 16, 100480. <https://doi.org/10.1016/j.enmm.2020.100480>
- Johari, S. A., Keyvanshokoh, S., & Salati, A. P. (2015). Silver nanoparticles as antimicrobial agents in aquaculture. *Iranian Journal of Fisheries Sciences*, 14(3), 567–583. <https://doi.org/10.22092/ijfs.2015.109137>
- Kalita, S., & Baruah, S. (2020). Antimicrobial applications of silver and titanium dioxide nanoparticles in aquaculture. *Applied Nanoscience*, 10, 3055–3067. <https://doi.org/10.1007/s13204-020-01365-2>
- Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications, and toxicities in aquaculture. *Arabian Journal of Chemistry*, 12(7), 908–931. <https://doi.org/10.1016/j.arabjc.2017.05.011>
- Khursheed, A., Ahmad, S., Wani, A. H., & Dar, P. A. (2023). Nanotechnology in aquaculture: A sustainable approach for fish health management. *Aquaculture Reports*, 30, 101586. <https://doi.org/10.1016/j.aqrep.2023.101586>
- Khursheed, A., Ahmad, S., Wani, A. H., & Dar, P. A. (2023). Nanotechnology in aquaculture: A sustainable approach for fish health management. *Aquaculture Reports*, 30, 101586. <https://doi.org/10.1016/j.aqrep.2023.101586>
- Kolupula, V., Sridhar, K., & Reddy, P. S. (2024). Environmental implications of engineered nanomaterials: Challenges and future perspectives. *Environmental Nanotechnology, Monitoring & Management*, 21, 100803. <https://doi.org/10.1016/j.enmm.2023.100803>

# Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

- Kumar, V., Pandey, A., Sharma, N., & Singh, R. (2022). Nano-feed additives: Promising tools for improving aquaculture production. *Aquaculture International*, 30, 2369–2385. <https://doi.org/10.1007/s10499-022-00918-1>
- Lu, Y., Liang, X., Niyungeko, C., Zhou, J., Xu, J., & Tian, G. (2016). A review of nanosensors for monitoring water quality. *TrAC Trends in Analytical Chemistry*, 85, 73–82. <https://doi.org/10.1016/j.trac.2016.02.011>
- Miller, S. M., Zhu, J., & Li, Q. (2023). Wireless nanosensors for aquaculture systems. *Biosensors*, 13, 211. <https://doi.org/10.3390/bios13020211>
- McClements, D. J., & Rao, J. (2011). Food-grade nanoemulsions for nutraceutical delivery. *Critical Reviews in Food Science and Nutrition*, 51(4), 285–330. <https://doi.org/10.1080/10408398.2011.556842>
- Mishra, S., Chauhan, A., & Yadav, A. (2021). Real-time monitoring of aquaculture water quality using nanotechnology. *Ecotoxicology and Environmental Safety*, 220, 112401. <https://doi.org/10.1016/j.ecoenv.2021.112401>
- Moges, F., Alemayehu, T., & Tesfaye, S. (2020). Carbon nanomaterials in nutrient delivery for aquaculture. *Aquaculture International*, 28, 2509–2523. <https://doi.org/10.1007/s10499-020-00626-4>
- Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2022). Applications of metal oxide nanoparticles in agriculture and aquaculture. *Journal of Nanoscience and Nanotechnology*, 22(5), 3205–3221. <https://doi.org/10.1166/jnn.2022.18837>
- Nascimento, R., Lima, S. M., & Silva, A. (2018). Metallic nanoparticles in aquaculture: Opportunities and risks. *Environmental Research*, 165, 365–373. <https://doi.org/10.1016/j.envres.2018.04.013>
- Nasr-Eldahan, S., Abdelaziz, A., & Khalil, A. (2021a). Nanoparticle-based vaccines for aquaculture: Current status and future perspectives. *Fish & Shellfish Immunology*, 113, 45–56. <https://doi.org/10.1016/j.fsi.2021.03.004>
- Nasr-Eldahan, S., Khalil, A., & Abdelaziz, A. (2021b). Antimicrobial nanoparticles in fish health management: A sustainable alternative to antibiotics. *Aquaculture*, 543, 736980. <https://doi.org/10.1016/j.aquaculture.2021.736980>
- Naylor, R. L., Kishore, A., Sumaila, U. R., Issifu, I., Hunter, B. P., Belton, B., Bush, S. R., Cao, L., Crona, B., Max Troell, M., & Thilsted, S. H. (2023). Blue food demand across geographic and temporal scales. *Nature Sustainability*, 6, 95–106. <https://doi.org/10.1038/s41893-022-00964-2>
- Oddsoson, G. (2020). Global aquaculture production trends. *Aquaculture Economics & Management*, 24(4), 291–303. <https://doi.org/10.1080/13657305.2020.1749251>
- Otoni, C. G., Moura, M. R., Mattoso, L. H. C., & Ham-Pichavant, F. (2014). Nanoemulsions in food and aquaculture applications. *Food Hydrocolloids*, 38, 20–30. <https://doi.org/10.1016/j.foodhyd.2013.11.007>
- Pati, R., Mehta, R. K., Mohanty, S., Padhi, A., Sengupta, M., Vaseeharan, B., & Goswami, C. (2018). Topical delivery of nano-vaccines for fish health management. *Frontiers in Immunology*, 9, 562. <https://doi.org/10.3389/fimmu.2018.00562>
- Puri, A., Loomis, K., Smith, B., Lee, J. H., Yavlovich, A., Heldman, E., & Blumenthal, R. (2009). Lipid-based nanoparticles as pharmaceutical drug carriers: From concepts to clinic. *Critical Reviews in Therapeutic Drug Carrier Systems*, 26(6), 523–580. <https://doi.org/10.1615/CritRevTherDrugCarrierSyst.v26.i6.10>
- Radhakrishnan, K., Ashraf, M. A., & Nazir, R. (2023). Nano-encapsulation of fish vaccines: A review. *Aquaculture Reports*, 31, 101635. <https://doi.org/10.1016/j.aqrep.2023.101635>
- Rezaei, M., Asghari, S., & Ahmadi, R. (2024). Stress mitigation in aquaculture using nano-selenium and chitosan nanoparticles. *Fish & Shellfish Immunology*, 145, 108874. <https://doi.org/10.1016/j.fsi.2023.108874>
- Saba, H., Tariq, M., & Ali, S. (2024). Toxicological risks of nanomaterials in aquatic ecosystems. *Journal of Hazardous Materials*, 458, 132005. <https://doi.org/10.1016/j.jhazmat.2023.132005>
- Saffari, H., Mirdar, S., & Karimi, M. (2022). Reproductive improvements in aquaculture species using selenium and silver nanoparticles. *Aquaculture Research*, 53(11), 3792–3801. <https://doi.org/10.1111/are.16065>
- Scown, T. M., Santos, E. M., Johnston, B. D., Gaiser, B., Baalousha, M., Mitov, S., & Tyler, C. R. (2010). Effects of silver nanoparticles of different sizes on rainbow trout. *Environmental Science & Technology*, 44(13), 5120–5125. <https://doi.org/10.1021/es9030799>
- Shafi, M., Ahmad, M., & Nazir, R. (2024). Emerging role of carbon-based nanosensors in aquaculture water monitoring. *Sensors and Actuators B: Chemical*, 403, 134022. <https://doi.org/10.1016/j.snb.2023.134022>
- Sharif-Kanani, N., Heidari, M., & Mohammadi, H. (2024). Plant-based aquafeeds fortified with nanoparticles: Opportunities and challenges. *Aquaculture Nutrition*, 30, 543–556. <https://doi.org/10.1111/anu.13785>
- Tayel, A. A., El-Trass, M., & Moussa, S. H. (2019). Dendrimer nanoparticles as potential carriers in fish vaccine delivery. *Aquaculture Research*, 50(12), 3593–3605. <https://doi.org/10.1111/are.14289>
- Trapani, A., De Giglio, E., & Garcia-Fuentes, M. (2022). Lipid-based nanocarriers for aquaculture. *Advanced Drug Delivery Reviews*, 187, 114368. <https://doi.org/10.1016/j.addr.2022.114368>
- Technavio. (2019). *Global nanofood market 2019–2023*. Technavio. <https://www.technavio.com/report/global-nanofood-market-industry-analysis>
- U.S. Environmental Protection Agency (EPA). (2023). *Aquaculture wastewater treatment guidelines*. <https://www.epa.gov/aquaculture>

## Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”

Verma, A., Rani, P., & Singh, D. (2020). Carbon nanomaterials: Antimicrobial and antioxidant properties. *Journal of Nanobiotechnology*, 18, 120. <https://doi.org/10.1186/s12951-020-00691-3>

Verma, A., Thakur, P., & Singh, D. (2020). Applications of graphene oxide and carbon nanotubes in aquaculture diagnostics. *Aquaculture Reports*, 18, 100444. <https://doi.org/10.1016/j.aqrep.2020.100444>

Vijayaram, R., Ghafarifarsani, H., Vuppala, S., & Al-Ansari, N. (2024). Green nanotechnology: Sustainable approaches in aquaculture and beyond. *Journal of Cleaner Production*, 430, 139894. Alexpandi, R., Thiyagarajan, D., Veeraraghavan, B., & Ravi, A. V. (2020). Applications of quantum dots in biosensing and aquaculture: A review. *Journal of Applied Microbiology*, 128(5), 1303–1316. <https://doi.org/10.1111/jam.14552>

Wang, Y., Yang, F., Zhang, H., & Zhong, Z. (2017). Nanoparticles as therapeutic agents for fish diseases. *Aquaculture Research*, 48(9), 4706–4716. <https://doi.org/10.1111/are.13235>

Yaqoob, A. A., Parveen, T., Umar, K., & Ibrahim, M. N. M. (2020). Role of nanomaterials in the treatment of wastewater: A review. *Water*, 12(2), 495. <https://doi.org/10.3390/w12020495>

Zhang, X., Li, Y., & Chen, Z. (2023). Lipid-based nanocarriers for nutraceuticals and aquaculture applications. *Food Hydrocolloids*, 137, 108346. <https://doi.org/10.1016/j.foodhyd.2023.108346>

Zhao, X., Wei, C., & Li, H. (2018). Nanotechnology-based biosensors for pathogen detection in aquaculture. *Biosensors and Bioelectronics*, 119, 235–246. <https://doi.org/10.1016/j.bios.2018.08.032>

**Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”**

# **Nanotechnology in Aquaculture: A Novel Tool for Sustainable Fish Health Management and Future Food Security”**