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# Exploring the Potential of Nanotechnology in Fisheries and Aquaculture: Opportunities and Implications

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

Aquaculture has emerged as one of the fastest-growing global food industries in recent years, playing a vital role in meeting the increasing demand for animal protein. However, several challenges, such as disease prevalence, chemical contamination, environmental degradation and inefficient feed utilization, have significantly impeded the sector's ability to contribute effectively to global food security. To address these challenges, considerable efforts have been made to leverage advancements in science and technology within aquaculture. Nanotechnology has

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emerged as a promising and effective tool to tackle these challenges across various aspects of aquaculture, including fish nutrition, biotechnology, genetics, reproduction, pathology and environmental sustainability. The utilization of emerging nano-materials, such as nano-elements enriched feed, has notably enhanced fish growth and has been applied in aquatic systems to mitigate pollutants, thereby reducing treatment costs. Furthermore, integrating genetically manipulated techniques with nano-biotechnology has led to significant advancements in fish genetics research. Innovative nanotechnology applications, such as nano-sensors, DNA nano-vaccines and drug delivery systems, have revolutionized fish health, reproduction and immune system management. Additionally, nanotechnology is increasingly employed in the fish processing industry to ensure sterile packaging, precise flavoring and high-quality products. Moreover, bio-nano-engineering techniques for optimal utilization of fishery wastes and the implementation of green nanoparticles signify a promising era in post-harvesting practices. This comprehensive review aims to delve into nanotechnology's diverse and good applications in aquaculture, exploring its potential and the challenges it presents.

*Keywords: Nanotechnology; aquaculture; healthy fat; micronutrients; farming system; human life; physicochemical properties.*

## 1. INTRODUCTION

Aquaculture stands out as the most rapidly expanding sector within agriculture, boasting considerable growth prospects. It is a vital source of easily digestible protein, healthy fat, and a diverse array of essential micronutrients for nourishing worldwide populations [1]. Moreover, aquaculture holds significant potential for rural employment and livelihood improvement and offers substantial opportunities for generating income through high export earnings, thereby boosting national GDP. The production of farmed finfish and shellfish has experienced rapid growth; it is because of the adoption of advanced and intensive aquaculture techniques [2]. As aquaculture farming systems have expanded, there has been a reduced dependence on wild seed stock and fish supplies [3]. The intensive practice of aquaculture results in pond eutrophication, characterized by accumulating an excessive nutrient load [4]. The escalating impacts of global climate change, such as rising temperatures and increased levels of methane and $CO_2$, pose a significant threat to aquaculture [1].

Nanotechnology has arisen as a hopeful solution, introducing fresh avenues for exploration. It encompasses the development and utilization of materials at nanoscale dimensions (1-100 nm) with exceptional properties, offering novel possibilities for application [5] as illustrated in Fig. 1. Nanotechnology applications have permeated every aspect of human life, yielding numerous value-added products [6]. Becoming a crucial interdisciplinary field, nanotechnology integrates principles from physics, chemistry and biology [7]. Furthermore, nanotechnology garners global public interest due to its rapid evolution and widespread applications across various fields including engineering, electronics, agriculture, medicine, food industry and environmental sectors [8]. Nano-sized materials possess unique physicochemical properties that enable them to withstand high pressure and temperature, facilitating their involvement in numerous applications [9]. The revolution of nanotechnology has expanded to encompass fish farming, contributing to their growth and addressing associated challenges [10,11]. Nanotechnology applications in fisheries comprise both direct and indirect approaches.

Direct applications of nanotechnology primarily focus on enhancing various aspects of fish, including growth, reproduction and health. Nano-materials play a crucial role in efficiently delivering nutrients, trace elements and vitamins as feed supplements, such as selenium (Se) [12–14], iron (Fe) [15,16], zinc (Zn) [17–19] and vitamin-C [20,21].

“Feeding fish with nanoform of these ingredients enhances their absorption and allows them to pass through the intestinal wall, thereby improving growth performance, reproduction, and innate immunity in fish” [22,23]. Utilizing various nano-materials for controlling fish diseases proves to be more effective than traditional antibiotics and chemicals, which often lead to adverse side effects like developing resistant bacterial strains, water pollution and accumulating unwanted chemical residues. Nano-materials exhibit antiviral properties [24], act as antibacterial agents [25–28], demonstrate antifungal effects [29,30] and serve as anti-parasitic agents [31,32]. Additionally, chitosan and polylactic-glycolic acid (PLGA) nanoparticles are significant in facilitating drug and hormone delivery and vaccination [33–35]. "Certainly, nanovaccination offers numerous advantages compared to conventional methods, ensuring sustained release and enhancing stability, bioavailability and residence time" [36–38]. "Moreover, a notable application of nanotechnology in fish farming is its utilization for rapid and efficient diagnosis of various fish pathogens" [39,40].

"In today's era, nanotechnology has flourished into a multi-billion-dollar industry, experiencing rapid growth exemplified by over a thousand products incorporating nanomaterials in the market. Over the past decade, the international market has introduced more than 300 nanofood products" [41]. "The economic influence of nanotechnology sectors was estimated to exceed $3 trillion by 2020, with approximately 6 million individuals employed within these industries" [8]. Currently, there exists an abundance of published literature offering a thorough examination of the various uses of nanotechnology within the field of aquaculture (Fig. 2.) [42].

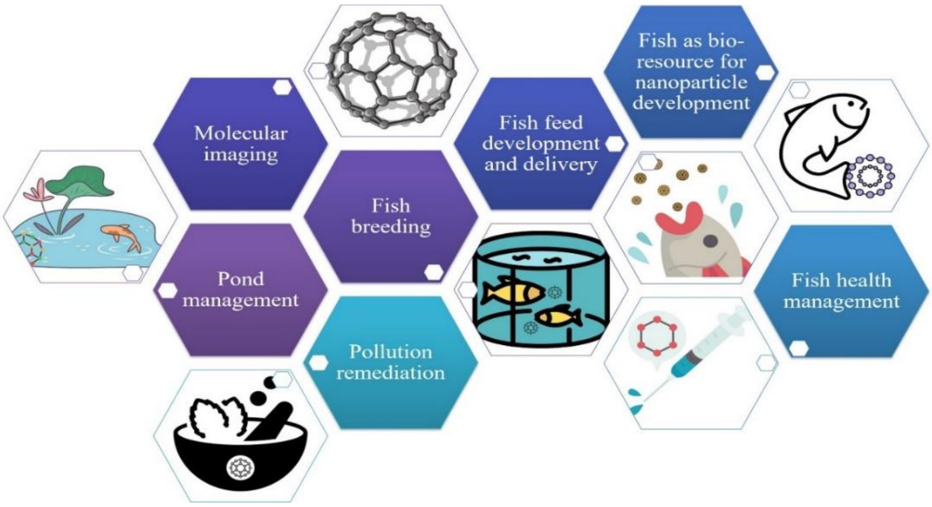


**Fig. 1. Applications of nanotechnology in aquaculture**

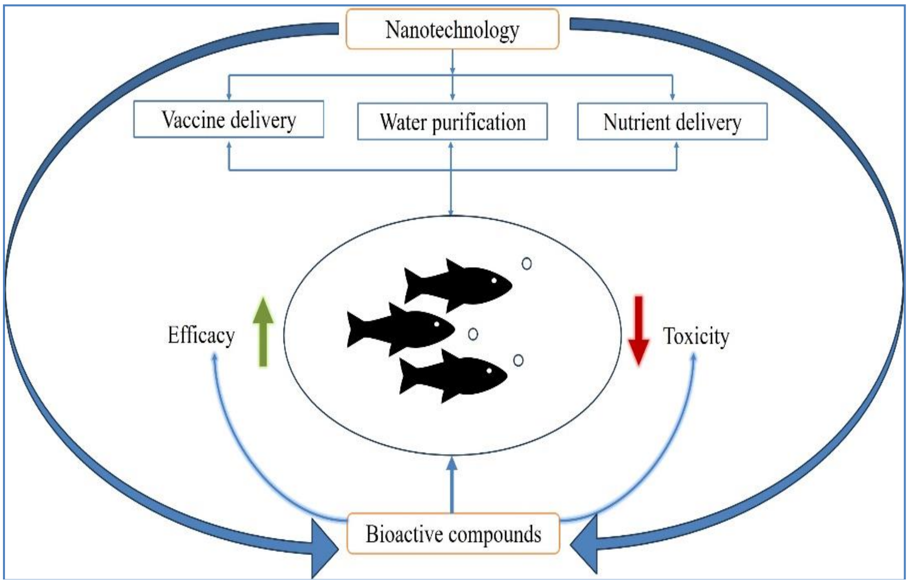


**Fig. 2. Visual depiction showcasing the implementation of nanotechnology within the realm of fishery**

## 2. ENRICHMENT IN FEED

"In natural habitat, fish source their food from phytoplankton, zooplankton and smaller organisms. However, in aquaculture settings, it becomes necessary to add complementary additives in fish feed to significantly increases the growth and production. Fish feed typically necessitates a balance of protein (32%), carbohydrates (20–35%), fats (4–6%), fiber (<4%), and dietary energy (8.5–9.5%) and these nutritional requirements may vary depending on the species and developmental stage of fish" [43]. "Including minute concentrations of organic and/or inorganic substances in fish feed has been a common practice to enhance growth and immunity. Feed supplements stand out as one of the crucial applications of nanotechnology in fish farming. Nano-scale materials are readily absorbed in small doses, traversing the gastrointestinal tract and small intestine to enter the bloodstream. Once distributed throughout vital organs, these nano-materials function more effectively than their bulk counterparts" [22]. "Introducing nano-metals such as selenium (Se), zinc (Zn) and iron (Fe) as feed supplements can offer several benefits for the survival, growth, and overall health of fish" [23]. Additionally, organic polymers such as chitosan play a significant role in delivering micronutrients [10].

Nutritional supplements and feed formulation are vital in commercial aquaculture for fish growth. Nanoparticles can modify feed consumption by enhancing flavor, color, or attractants. They also improve the bioavailability of water-insoluble vitamins and carotenoids when processed with nanoparticles for dietary supplements [44,45]. "Several market-available products utilize advanced micro/nano-encapsulation systems to enhance the delivery and bioavailability of nutrients in aquaculture. For instance, Ubisol-AquaTM Delivery System Technology was created by Zymes LLC (USA) and NovaSOL from AQUANOVA (Germany). Ubisol-AquaTM efficiently solubilizes bioactive compounds such as coenzyme Q10, vitamins A and B, squalene and fish oil (EPA/DHA). AQUANOVA's 'solubilisate' liquid carrier solutions enable the transportation of active raw materials in highly compact capsules" [46]. "Nano/microcarriers play a crucial role in protecting, encapsulating, stabilizing and delivering valuable bioactive compounds essential for fish growth. Numerous Indian startups have ventured into manufacturing nanotechnology products for aquaculture nutrition. Notably, Filo Life Sciences, an Indian-origin nanotech company, produces a range of important nutritional and nutraceutical products for aquaculture including ColloidAG Aqua (Nano silver), Fabgrow Aqua (Nano PUFA), Nanomin Aqua (Nano trace minerals), NannoCAL Aqua (Nano calcium), NanoPHOS Aqua (Nano phosphorus)" [47].

## 3. WATER FILTRATION AND REMEDIATION

Water treatment is crucial for sustainable aquaculture. Global water contamination, exacerbated by urban, industrial and agricultural waste discharge and the misuse of antibiotics and synthetic compounds in fisheries, poses a significant health hazard for consumption [42].

"Nano-enabled technologies are utilized for water purification, employing nanomaterials like activated carbon or alumina with additives such as zeolite and iron-containing compounds to foster aerobic and anaerobic biofilm for ammonia, nitrites and nitrate removal in aquaculture. Additionally, ultrafine nanoscale iron powder effectively cleans less toxic carbon compounds like trichloroethane, carbon tetrachloride, dioxins and polychlorinated biphenyls, advancing nano-aquaculture practices" [48].

"Researchers created magnetic konjac glucomannan (KGM) aerogels for arsenite water decontamination. The system exhibited a pH-dependent capacity and green step characteristics" [49]. "Recently, graphene oxide (GO) and graphene nanosheets (GNs) have garnered significant global attention for their effectiveness in removing various contaminants from water" [50,51]. "Hybrid GO-$TiO_2$ materials have been mainly focused on environmental and energy applications, including the adsorption of heavy metal ions and organic dyes from wastewater" [52,53]. $TiO_2$ is a promising candidate for wastewater treatment due to its non-toxic nature, chemical and biological stability, low cost and efficient photocatalytic properties. Numerous studies have explored its photocatalytic activity for inactivating pathogenic organisms like bacteria, viruses and algae [52,54,55]. The scientific community's attention to water treatment and contaminant removal is appreciated. Elevated concentrations of these contaminants pose potential threats to human health, as they can accumulate in aquatic animal tissues, notably fish, which are often consumed to combat cardiovascular diseases (CVDs) and cancer [56]. Due to their habitat and feeding habits, fish are highly vulnerable and extensively exposed to the harmful effects of pollutants in aquatic environments, with no means of escaping their impacts [57,58]. Reports indicate increased accumulation of heavy metals (Hg, Cd, and Pb) in marine animal tissues, attributed to both natural processes (e.g., volcanic activity) and human activities [59]. Likewise, research has shown that F-1 toxicity leads to enzyme dysfunction, gastric issues and immune system impairment in experimental fish [60], as well as habitat degradation and destruction of the freshwater snail *Physella acuta* [61]. Utilization of a 3D RGO hydrogel assessed for removing Hg and $F^{-1}$ from water. The aerogel showed high adsorption capacities of 185 mg/g for $Hg^{+2}$ and 31.3 mg/g for $F^{-1}$, indicating potential for environmental pollution management [62]. Additionally, Fig. 2 demonstrates the suggested mechanism by which various nanoparticle-based photocatalytic adsorbents and hydrogel biofilms function effectively in the practical purification of water, showcasing examples of fluoride (F-), nitrate (NO3-), and coliforms (E. Coli) removal from contaminated water [42].

### 3.1 Fish Harvesting

Fishing lures are often painted to attract fish with light, but they usually only reflect light in one direction. To improve effectiveness, lures are colored and coated with a polyimide film, increasing fish-catching probability by two to three times compared to uncoated lures [48].

### 3.2 Biofouling Control

“Nanotechnology can enhance aquaculture and shrimp culture productivity by improving disease control, feed formulation, and biofouling management. By incorporating metal oxide nanoparticles like ZnO, CuO and $SiO_2$ into coatings or paints, biofouling from unwanted bacteria, invertebrates (such as mussels and barnacles) and algae (like seaweeds and diatoms) can be monitored and controlled effectively. This creates antifouling surfaces and boosts antifouling control efficiency” [63,64]. The antifouling technology can be applied in fishing and aquaculture networks, aquaculture tank antibacterial substances and new marine product packaging materials.

### 3.3 Removal of Heavy Metals

Ligand-based nano-coating enables efficient and cost-effective heavy metal removal by high absorption capacity and renewability. Crystal precise technology purifies water by bonding multiple metal layers to one substrate [65]. Nanomaterials, like metal oxide nanoparticles, are commonly used for efficient heavy metal removal from water due to their high reactivity and large surface area. Ongoing research aims to develop new synthesis methods and practical applications, such as composite materials or granular oxides, to enhance heavy metal removal effectiveness and understand underlying mechanisms such as XAS and NMM [66,67]. Comprehensive research investigating the impact of humic acid and fulvic acid on heavy metal removal using a range of nanomaterials from aqueous solutions. The study focused mainly on iron-based, carbon-based and photocatalytic nanomaterials [68]. “The study also examined the interaction mechanisms and environmental implications of humic acid and fulvic acid. Chitosan nanoparticles are utilized as adsorbents for heavy metal removal. Recent research focuses on removing heavy metals from clays like kaolinite, bentonite and montmorillonite using chitosan nanoparticles, with studies on nano chitosan-clay composites for metal ion removal recently reported” [69,70]. “Chitosan-magnetite nanocomposites were also suggested for removing heavy metals from aqueous solutions” [71,72]. A schematic illustration highlights the process of zinc oxide nanoparticle-mediated degradation of significant pollutants (Fig. 4.) [47].

### 3.4 Fish Reproduction

Producing mono sex tilapia (Oreochromis sp.), fish farms aim to prevent uncontrolled spawning and overcrowding. This is achieved by applying steroid hormones, which can have unintended effects on fish consumers [73]. “Nanotechnology has been an effective drug carrier in delivering fadrozole (an estrogen synthesis inhibitor) to *O. niloticus*. Feeding *O. niloticus* with fadrozole overloaded on PLGA nanoparticles at 50–500 ppm concentrations for one month resulted in 100% male fish at both 350 and 500 ppm levels” [74]. “Nanotechnology plays a crucial role in improving reproduction in various fish species. Specifically, nano-chitosan has been utilized to deliver and release reproductive hormones” [75]. “A composite of chitosan-nano gold extended the duration of the presence of reproductive hormones in salmon blood and enhanced egg fertilization rates" [35]. "Nanoparticles of eurycomanone, extracted from *Eurycoma longifolia*, were combined with chitosan nanoparticles and injected into *Clarias magur* fish. Within seven days, this resulted in increased gonado-somatic index (GSI), Ca and Se concentrations, reproductive capacity and endocrine hormone gene expression levels" [33].

### 3.5 Nanotechnology for Fish Quality Testing

Quality testing is an essential post-harvesting technology and nanotechnology can be applied for quality improvement of fishes.

#### 3.5.1 Fish freshness testing

"A quantum dot-based nanosensor was created to address fishery product freshness concerns. Tin oxide quantum dots ($SnO_2$ QDs) were synthesized, dispersed in a colloidal solution, and deposited onto indium–tin–oxide (ITO) glass" [47]. This facilitated the development of a fish freshness biosensor by immobilizing xanthine oxidase. The sensor displayed heightened sensitivity, faster response time and an extensive linear range in electrochemical output [76].

## 4. DETERMINATION OF FORMALIN IN FISH SAMPLES

Formalin poses a significant threat to fish food safety in modern times. A market survey conducted in Bangladesh revealed formalin contamination in 50% of total fish samples, with 70% of rohu (*L. rohita*) affected. This preservative is commonly used to maintain freshness during transportation [77]. A report from the Somdet market in Kalasin Province, Thailand, highlighted the varying levels of formalin contamination across different fish products. White shrimp, mackerel, Shishamo fish, squid and other samples were found to have higher contamination levels [78]. A formaldehyde nano-biosensor was designed using formaldehyde dehydrogenase enzyme and nanomaterials like carbon nanotubes and chitosan. This sensor ensures precise detection of health hazards, with quick response times (≥5 s), high sensitivity (1-10 ppm), and reproducibility [79]. A reproducible formaldehyde biosensor was created by coating an ionic liquid, nanoscale gold, and chitosan onto a glassy carbon electrode. This biosensor detects formalin in the tissues of *Lutjanus malabaricus* and *Thunnus tonggol* [80].

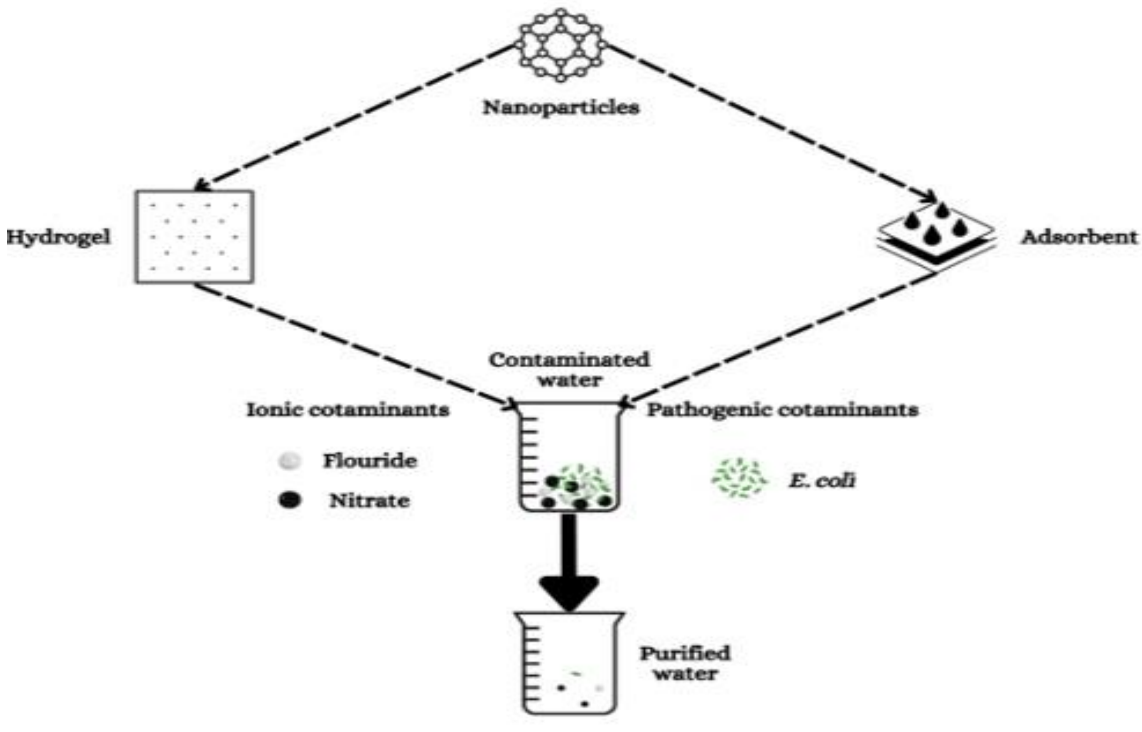


**Fig. 3. The operational mechanism of nanoparticle-loaded adsorbents and hydrogel films for eliminating F-, NO3-, and coliforms (E. coli) from polluted water**

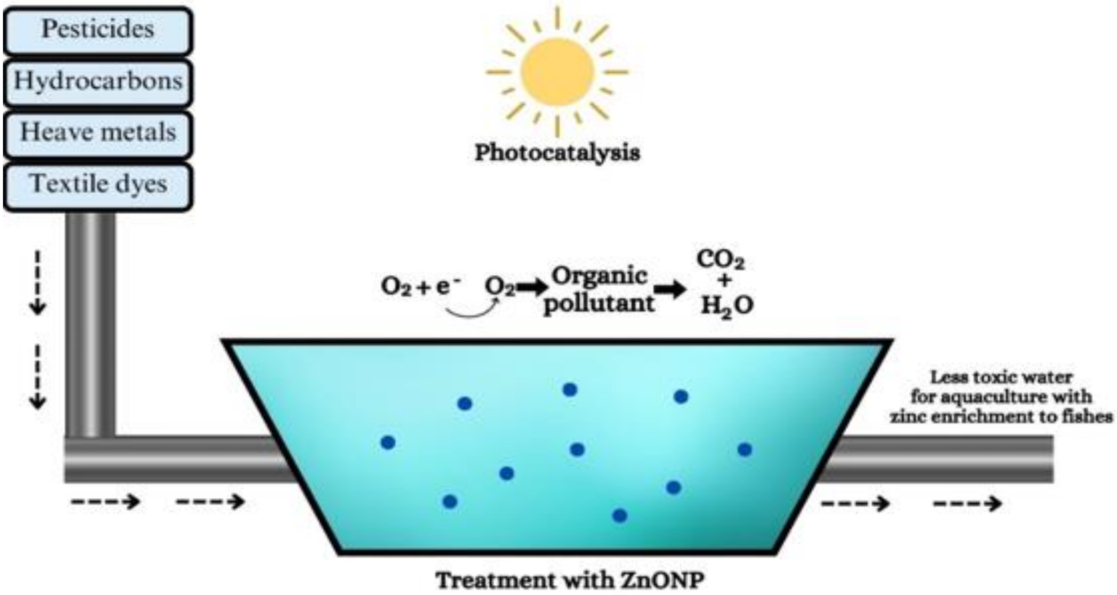


**Fig. 4. Nanoremediation by zinc oxide nanoparticles**

## 4.1 Fish Packaging

Nanotechnology enhances fish packaging by delaying spoilage and extending shelf life. Nano-materials in biodegradable packaging act as antimicrobial agents, remove oxygen, inhibit degradation and stabilize products [81–83]. Nano-composites derived from natural biopolymers (proteins, lipids, polysaccharides) are favored as healthy packaging alternatives to toxic petrochemical plastics [84].

## 4.2 Delivery of Vaccines

Vaccines are essential in aquaculture to defend against pathogens and safeguard host animals from infections. Oral or injectable methods are the most reliable ways of vaccination in fisheries. However, traditional injection practices with oil/water formulations often lead to adverse effects and occasional fish mortality [85]. To address these issues, the scientific community has proposed nano-delivery systems as safer and more effective alternatives for vaccine delivery in fish. Various encapsulation techniques, including alginate particles, have been developed and tested for oral vaccine delivery to aquatic animals [86]. Alginate, derived from brown algae or bacterial polysaccharides, is a copolymer of β-D-mannuronic acid (M) and α-L-guluronic acid (G). Its mechanical stability and mucoadhesive properties make it ideal for oral administration, enabling direct contact with epithelial cell walls [87,88]. For application in fish, alginate particles are generally produced by emulsification [89], one of the fastest methods for NP preparation and readily scalable [90] and to a lesser extent by other methodologies such as the orifice-ionic gelation and the spray method. Reports from different researchers presented alginate as an antigen adjuvant [91,92], survival and weight promoter of fish [93,94]. Additionally, alginate administration has demonstrated enhanced immune-stimulant responses in carp (*Cyprinus carpio* L.) and brown-marbled grouper (*Epinephelus fuscoguttatus*) [95–97]. It has also been shown to bolster defense against *V. anguillarum* in turbot (*Scophthalmus maximus* L.) [98] and against iridovirus and *Streptococcus sp*. in orange-spotted grouper (*Epinephelus coioides*) and brown-marbled grouper [95,97]. Chitosan (CS), derived from crustaceans and insects, is the second most abundant biopolymer. Its unique biological properties: bioadhesive, biodegradable, biocompatible and non-toxic—make CS-based formulations widely used in drug delivery, bio-nanosensors, edible coatings and various medical fields such as dentistry and surgery [99,100]. Furthermore, the oral administration of nano-chitosan encapsulated DNA or overloaded with DNA or recombinant DNA vaccine has been shown to positively enhance the immune response against specific fish pathogens, such as the European sea bass (*Dicentrarchus labrax*) against nodavirus [101], Asian sea bass (*Lates calcarifer*) against *V. anguillarum* [37], black seabream (*Acanthopagrus schlegelii*) against *V. parahemolyticus* [102] and Shrimp (*P. monodon*) against the white spot syndrome virus [63]. Similarly, nano-PLGA was employed in oral DNA vaccines for Japanese flounder (*Paralichthys olivaceus*) against lymphocytic disease virus [103] and for rainbow trout (*Oncorhynchus mykiss*) against infectious hematopoietic necrosis virus [104]. Using nanotechnology in fish vaccination is crucial for reducing reliance on toxic and carcinogenic chemical adjuvants. Oral or immersion vaccinations are preferred over injections to minimize stress [38].

Nanoparticles offer promising potential for enhancing siRNA delivery systems in molecular therapeutics. An assessment examined PAMAM nanoparticle-mediated delivery of siRNA to zebrafish cardiac wounds, quantitatively analyzing nanoparticle distribution in cardiac cells and monitoring their role in cellular uptake [105]. A schematic diagram of nanoparticle-mediated siRNA delivery in the fish system is presented in Fig. 5.

## 5. NANOTECHNOLOGY DEVICES FOR AQUATIC ENVIRONMENT MANAGEMENT

Nanotechnology application in seawater shrimp aquaculture demonstrated that nanodevices reduced water exchange rates, improved water quality, increased shrimp survival rates and ultimately boosted yield [106,107]. Among various nanodevices, nanonet treatment stood out as the most effective, with a 100% increase in fish survival rate and significant reductions in water nitrite and nitrate levels, with nitrite dropping to just a quarter of the control group. Nanotechnology also raised water pH and substantially enhanced water efficiency [108]. In China, Nano-863 is a popular high-tech agricultural product widely utilized in livestock, crop and aquaculture sectors. It incorporates high-temperature sintered nanomaterials with excellent light-absorbing properties into a ceramic carrier [106].

### 5.1 Nanotechnology as a New Tool in Fish Diseases

Nanotechnology operates at the nanometer scale, with one nanometer (nm) equaling one billionth of a meter, according to the International System of Units (SI) [84,109]. New materials, with distinct properties derived from their small size, form, surface area, conductivity, or surface chemistry, find extensive applications in textiles, electronics, engineering and medicine [110,111]. The term "nanomaterial" derives from "nano," originating from the Greek word for"dwarf." It typically refers to materials ranging from 1 to 100 nm [112]. Nanotechnology offers solutions to prevent and monitor diseases in aquaculture, enhancing its benefits. This includes developing antibacterial surfaces, using nanosensors for pathogen detection and delivering veterinary products through fish foods [113]. Nano-trace elements exhibit usage levels up to 100% higher than conventional inorganic trace elements, primarily due to their direct penetration into the animal body [11,42,113].

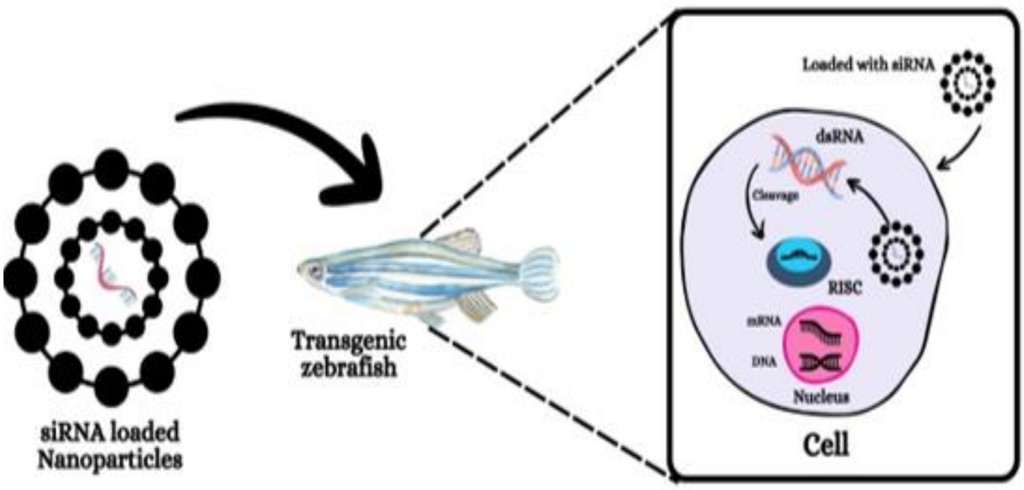


**Fig. 5. Nanoparticle-mediated Si RNA delivery in fish system**

## 5.2 Drug Delivery for Health Management

Disease outbreaks pose significant obstacles to the sustainability and development of aquaculture [11,48,117]. Nanotechnology is crucial in providing novel perspectives for disease diagnosis and health management in aquaculture [64]. Solid core drug delivery systems, involving coating solid nanoparticles with a fatty acid shell, are effective for protecting labile or thermo-sensitive drugs [118]. Porous nanomaterials serve as effective pharmaceutical delivery matrices. Mesoporous silica particles, for example, can be utilized for the controlled release of drugs [119].

Oral nano-delivery systems associated with nanoparticles offer several advantages, such as enhanced control over drug release [120], direct targeting of specific tissues [121], improved bioavailability of pharmaceuticals with low absorption rates [122], stabilization of drugs through prolonged residence time in the gut [123] and increased absorption capability due to higher dispersion rates at the molecular level [124].

## 5.3 Delivery of Nutrients

While nutraceuticals significantly enhance growth and immunological parameters in fish, their incorporation entails higher costs compared to minimal dietary requirements. Thus, careful management is essential to avoid wastage and maximize their utilization [125]. Nanotechnology enhances the delivery of dietary supplements and nutraceuticals in fisheries, improving nutrient bioavailability and efficacy by enhancing solubility and protecting against harsh gut conditions. For instance, adding 1 mg of nano-Selenium (Se) per kg of diet significantly boosts growth and antioxidant defense in common carp (*Cyprinus carpio*) compared to controls [12]. Supplementation of selenium (Se), zinc (Zn) and manganese (Mn) nanoparticles in early weaning diets enhanced stress resistance and bone mineralization in gilthead seabream (*Sparus aurata*) [126]. Solid lipid nanoparticles (SLNPs) containing 6-COUM demonstrated superior uptake compared to competitor 6-coumarin-loaded pectin microparticles (MPs) in gilthead seabream (*Sparus aurata* L.) cell types, including SAF-1 cells and primary head-kidney (HK) cultures. This suggests SLNPs as promising nanocarriers for delivering biologically active substances in fish [127]. In rainbow trout, the addition of iron nanoparticles (NPs) and Lactobacillus casei as a probiotic to the diet led to notable enhancements in growth parameters [128]. Similarly, supplementation of the diet with 16 mg $kg^{-1}$ of MnO nanoparticles (NPs) significantly boosted both growth and the antioxidant defense system in freshwater prawn (*Macrobrachium rosenbergii*) [129]. Copper nanoparticles at 20 mg $kg^{-1}$ notably enhanced growth, biochemical constituents, digestive enzymes, antioxidants, metabolic enzymes and immune response in freshwater prawn post-larvae (*Macrobrachium rosenbergii*) [130] and red sea bream, (*Pagrus major*) [131]. The hepatoprotective and antioxidant effects of Azolla microphylla-based gold nanoparticles (GNPs) against acetaminophen (APAP)-induced toxicity in freshwater common carp fish (*Cyprinus carpio L.*) has been investigated [132]. GNPs notably improved metabolic enzyme levels, hepatotoxic markers, oxidative stress markers, tissue enzymes, hepatic ion levels, and abnormal liver histology. Thus, Azolla microphylla phytochemically synthesized GNPs were recommended as effective protectors against acetaminophen-induced hepatic damage in freshwater common carp fish [132]. The effects of different levels (0.5%, 1%, and 1.5% of the diet) of Aloe vera nanoparticles on Siberian sturgeon's growth, survival rate, and body composition were examined. They found that supplementing the diet with 1% Aloe vera nanoparticles significantly improved the growth indices of Siberian sturgeon compared to controls [133].

## 5.4 Toxicity

Nano-materials' heightened reactivity and unique properties generate increased production of reactive oxygen species, leading to cellular dysfunction as they easily penetrate cell membranes and interact with intracellular organelles [134]. In general, when comparing the physiological effects of metals and nanometals, it is found that nanometals cause more toxic effects [135]. Various aquatic organisms exhibit diverse toxic responses to nanometals and bulk forms, with metal nanoparticles demonstrating notably higher toxicity than other nanoparticle types. Exposure of Medaka fish (*Oryzias latipes*) to nano-Se (3.2 mg/l) for 2 days resulted in 100% mortality, whereas sodium selenite at 2.0 mg/l caused only 10% mortality and 80% at 8.0 mg/l. Nano-Se accumulated six times more in fish liver compared to selenite [136]. Certain nano-materials employed in water remediation, such as nZVI, have been documented to induce toxicity in microorganisms, crustaceans, fish larvae, and other aquatic and soil-dwelling organisms [137]. Zebrafish exposed to both titanium dioxide nanoparticles (nano-$TiO_2$) and cypermethrin experienced increased accumulation of cypermethrin, leading to neurotoxic effects and reduced fish larvae locomotion [138]. Additionally, nano-$TiO_2$ enhanced uptake of an organophosphate compound in zebrafish tissues, decreasing reproductive hormones and inhibiting reproduction [139,140].

## 6. CONCLUSION

The emergence of nanotechnology presents a dual-edged sword, showcasing both its immense potential and inherent risks. The unique properties of nanoparticles give rise to both positive and negative effects. In the realm of fish culture, nanotechnology holds promise for revolutionizing various aspects, including enhancing growth performance, productivity, disease control and diagnosis, water purification, pollutant remediation and extending shelf life through improved packaging techniques. Despite its potential benefits, the application of nanotechnology in fish culture poses challenges, primarily concerning the potential toxicity of nanoparticles and their adverse effects on fish and non-targeted organisms, as well as their environmental impact. However, the concept of green nanotechnology offers eco-friendly alternatives to toxic metal nanoparticles. To ensure the safe and responsible application of nanoparticles in fish culture, it is imperative to address existing gaps in knowledge regarding the environmental fate of nanoparticles and their potential accumulation in the food chain. Comprehensive assessments are necessary to guarantee the safety of nanoparticle usage for fish, environmental sustainability and human consumption.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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