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REVIEW

Nanotechnology: applications and regulatory challenges in fish culture—a review

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Abstract

The application of nanotechnology is significantly revolutionizing the domain of fisheries. Nanotechnology tools are applied to tackle many challenges pertaining to fish productivity, health, reproduction, prevention and treatment of diseases. Fish growth performance can be improved by adding essential minerals in the form of nano-feed supplements. Moreover, nanotechnology is currently assuming a pivotal position in the domain of fish reproduction, alongside its application in fish medicine, including antibacterial therapies, medication delivery mechanisms, and nano-vaccination. Also, there are significant evidences supporting the use of nanotechnology techniques for fish packing and water purification and remediation. In contrast, numerous nanoparticles possess harmful characteristics towards living organisms as a result of their tiny sizes, potent reactivity, and capacity to cross boundaries. They have the ability to modify several physiological activities and induce cytotoxicity, DNA damage, and histopathological alterations. Although nanotechnology has potential for enhancing growth performance and disease resistance in fish, there is ongoing debate about the potential toxicity of nanomaterials, their interactions with the environment, and their propensity to accumulate in animals. This review aims to clarify and analyze the different benefits and challenges associated with the application of nanotechnology in fish farming.

Keywords Nanotechnology · Nanomaterials · Fish culture · Toxicity

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Introduction

The increasing world population and rapid economic growth have stressed up for the requirement for protein. Aquatic protein products are highly valued for their beneficial health impacts and significant food compositional features (Shah and Mraz 2020a). The consensus among nearly all nations globally is that fish is an essential component of a human diet (Mohanty 2015). In order to maintain livelihoods, guarantee nutrition, and improve food security, fish are essential. They provide vital fatty acids, amino acids, vitamins, and important nutrients like iodine and selenium that are frequently deficient in other foods or meats. They also function as a rich source of high-quality protein (Kwasek et al. 2020). Fish made up over 17% of all animal protein consumed worldwide in 2015; this percentage has been rising continuously (Action 2020). In fact, traditional fishing techniques in freshwater or marine habitats are unable to fulfil the growing demands of the increasing population. Fish farming must thus be given top priority, and deliberate measures must be made to achieve fish output self-sufficiency. The main elements essential to guaranteeing aquaculture's long-term

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survival and achieving a significant fish yield are optimal feeding, efficient disease control, and careful water quality management (Assefa and Abunna 2018; Khan et al. 2020).

Nanotechnology has become vital in its significance due to its explosive growth and development in a number of industries, including food, agriculture, medical, and environmental science (Subramani et al. 2019; He et al. 2019). International markets have over 300 nano-food items throughout the last decade (Narsale et al. 2024; Ramsden 2018). Nanomaterials possess distinct physicochemical features due to their small size, enabling them to endure high pressure and temperature (Ilangovan et al. 2021). Nanotechnology is also being used in order to increase development and mitigate the problems regarding fish farming (Khosravi-Katuli et al. 2017; Luis et al. 2019).

Nanotechnology has both direct and indirect uses in fish aquaculture. Direct use of nanotechnology is increasing to improve fish growth, reproduction, and health (Sarkar et al. 2022). For example, the use of nanomaterials can make feed supplementation easier, which usually entails adding vitamins, minerals, and trace elements to animal diets (Ashouri et al. 2015; Khan et al. 2017; Xia et al. 2019). Fish that consume component nano-forms have easier absorption and easier passage across the intestinal barrier, which improves fish immune system, development, and reproduction (Bhattacharyya et al. 2015; Chris et al. 2018). In a study, iron nanoparticles (NPs) were found to enhance the growth rate of *Carassius auratus* and *Acipenser gueldenstaedtii* by 30% and 24% respectively (Srinivasan et al. 2016a). Nano selenium (Se) source supplemented diets improved the growth, antioxidant status and muscle Se concentration of *Carassius auratus* (Zhou et al. 2009). A study has demonstrated that the inclusion of nano Zinc in the food of *Pangasius hypophthalmus* resulted in enhanced survival and growth (Kumar et al. 2018). The effective management of viruses, bacteria, and fungus necessitates the timely identification and eradication of pathogens. Nanomaterials, which function on a comparable magnitude to particle-infecting viruses or diseases, have been identified as a potential solution for this purpose (Ismael et al. 2021; Nasr-Eldahan et al. 2021). The uses of nanomaterials in fish health involve the use of porous nanostructures and nanosensors to create antibacterial or antifungal surfaces. These surfaces are used in aquaculture systems to detect pathogens in water and to deliver fish medicines through fish meals (Abbas 2021; Nasr-Eldahan et al. 2021). Additionally, the utilization of chitosan-based wrapping as a nano encapsulation carrier for the purpose of effectively treating fish diseases caused by bacteria and viruses has been well-documented. This approach is advantageous due to the durability of nano encapsulated materials, which can withstand high temperatures and acidic environments (Abimbola et al. 2023). Moreover, nanomaterials are more effective than conventional antibiotics in treating fish diseases. Traditional therapies may cause bacteria to develop antibiotic resistance, which would eventually reduce its effectiveness. These treatments may also leave behind toxic chemical residues and contaminate water supplies, creating threats to the environment. Chitosan and polylactic-glycolic acid (PLGA) nanoparticles have a wide range of applications, including vaccines, medication delivery and hormone administration (Bhat et al. 2019a, b; Fenaroli et al. 2014; Mohd Ashraf Rather et al. 2013). Nano-vaccination is superior to conventional methods due to its capacity to provide sustained release, enhance stability, improve absorption, and prolong residence duration (Kitiyodom et al. 2019; Rajesh Kumar et al. 2008; Rivas-Aravena et al. 2015).

The indirect uses of nanotechnology in aquaculture generally focus on improving water quality. This includes sterilizing ponds, reducing the need for water exchange, decreasing the concentration of nitrogenous compounds, and treating chemical or biological pollutants in the water (Huang et al. 2015; Khosravi-Katuli et al. 2017; Tayel et al. 2019). Furthermore, the utilization of nanotechnology in water purification serves as an additional benefits by effectively inhibiting the advancement of infectious disorders caused by diverse microorganisms (Tayel et al. 2019; Yu et al. 2002). Additionally, the anti-fouling property of certain nanomaterials is a suitable application of nanotechnology, to attain high water quality in fish ponds, by lowering phosphate content and reducing the development of algae and other microbes (Ashraf and Edwin 2016).

Although nanotechnology has several benefits in fish farming. There are concerns for its safety for fish health, human health, and the environment. The existence of nanoparticles, specifically those made of metals, may harm a number of fish physiological functions. Reproductive hormone levels may be disrupted antioxidant and enzyme activity can change, the survival of embryonic developmental stages may be impacted, and histopathological changes are possible (Aruoja et al. 2009; Jovanović et al. 2015; Klingelfus et al. 2019; Kumar et al. 2017; Rajkumar et al. 2016; Ren et al. 2018; Sumi and Chitra 2019; Zhu et al. 2012). There are still a lot of outstanding concerns about the possible toxicity of using nanotechnology in aquaculture, causing a need for further study in this particular field. Further research is required to determine the minimum effective dosage, duration and specially lethal and sublethal concentrations and also need to observe bioaccumulation, residue concentration, and environmental destiny. To protect the environment, laws regulating the creation and useful uses of nanomaterials should be implemented. The purpose of this study is to investigate the different uses of nanotechnology in fish production, both directly and indirectly, and to look at the potential benefits and difficulties associated with such applications.

Direct applications of nanotechnology in fish culture

Feed supplements

Fish in their natural environment feed on phytoplankton, zooplankton, and other tiny creatures. Fish cultured in fish farming need extra nutrients to ensure rapid and healthy growth. Fish meal should have protein (32%), carbohydrate (20–35%), fat (4–6%), fiber (< 4%), and dietary energy (8.5–9.5%). These main requirements differ by fish species and age (Abbas 2021). Fish feed supplements with minute organic and inorganic concentrations boost growth and immunity. Nano-materials are rapidly absorbed in low dosages and pass through the gastro-intestinal system and small intestine to enter the circulatory system, facilitating more efficient distribution to vital organs compared to bulk materials (Bhuvaneshwari et al. 2015). Selenium (Se), Zinc(Zn), and iron (Fe) nano-metals as feed additives may improve fish survival, growth, and health (Chris et al. 2018). Chitosan also delivers micronutrients (Khosravi-Katuli et al. 2017). Nano-Se high bioavailability, strong reactivity, low toxicity, antioxidant defense, immunomodulatory, and growth promoter effects have made it prevalent in aquaculture (Sonkusre et al. 2014; Xia et al. 2019). Studies has revealed that as compared to fish fed a basal diet, fish supplemented with nano-selenium (nano-Se) up to 0.68 mg n-Se/kg dry feed exhibited significantly higher weight gain, feed conversion efficiency, and specific growth rate specifically in masheer fish (*Tor pulitora*). It is important that fish provided the supplementary diet showed a significantly lower feed conversion ratio than fish fed the basal diet. Khan et al. (2017) conducted a 90-day feeding experiment to investigate the effects of zinc oxide (ZnO), zinc sulphate (ZnSO4), and zinc oxide nanoparticles (ZnO-NP) on the growth and haematological indicators of juvenile grass carp (*Ctenopharyngodon idella*). Fish given the ZnO-NP diet (30 mg Kg^{-1}) had significantly greater weight increases, specific growth rate, and feed conversion ratio. Faiz et al. (2015) conducted a research and found that giving grass carp (*C. idella*) nanoparticles as a food supplement improved their growth and red blood cell count. Supplementing the meal of *Cirrhuinus mrigala* with ZnO nanoparticles enhanced metabolism, although resulting in a decrease in the count of white blood cells (Rajan et al. 2021).

Supplementing fish diets with iron is critical as most natural iron sources have limited solubility and bioavailability, making it difficult to meet dietary needs (Hilty et al. 2011). Iron improves the immune system and oxygen transport, respiration, and fat oxidation. Due to its reduced solubility and bioavailability, bulk iron (Fe) sources cannot provide dietary iron (Fe) needs (V. Srinivasan et al. 2016b).The addition of iron nanoparticles, specifically iron oxide or iron nanoparticles (NPs), at a dosage of 63.75 mg/kg, has been observed to have prominent advantageous impacts on (*Oreochromis niloticus*) when included in their supplementary meal. The effects include enhanced growth, immune response, phagocytosis activity against foreign particles such as bacteria, decreased mortality rate, elevated protein and lipid content, heightened muscle concentration, improved red and white blood cell counts, increased antioxidant capacity, and fortified disease resistance (El-Shenawy et al. 2019). Other studies on Nile Tilapia (*O. niloticus*) indicated that chitosan had positive effects on fish development. The study initiate that supplementing Nile tilapia feed with chitosan at a dosage of 0–8 g/kg dry food for 56 days resulted in the determination that 4 g/kg of chitosan was the most effective dose for promoting the greatest rates of body weight gain (BWG) and specific growth rate (SGR) (Wu 2020). Moreover, the addition of chitosan at a dosage of 5 g/kg to the diet of Nile tilapia for a duration of 60 days resulted in enhanced growth performance, body weight gain (BWG), specific growth rate (SGR), and feed conversion ratio (FCR) (Fadl et al. 2020).It has been shown that chromium nanoparticles added to the supplemental feed improve growth metrics, boost immunity, and lower insulin and cortisol levels. In particular, it has been shown that adding chromium nanoparticles to meals based on sunflower seeds at a dose of 1.5–2 mg/kg – 1 body weight increases the growth factor of *C. mrigala*(Akter et al. 2018).Additionally, adding chromium to *Catla catla* fingerlings at a dose of 2 mg/kg body weight enhanced their development, digestion, and hematological parameters (Ahmad et al. 2022).Supplementing fish feed with selenium nanoparticles may successfully treat selenium insufficiency in fish. Insufficient presence of selenium nanoparticles in the feed might result in fish developing abnormalities (Abd El-Kader et al. 2021). Research was carried out on Nile tilapia (*O. niloticus*), which showed that the addition of selenium nanoparticles (1 mg/kg) to their diet led to enhanced immune response, increased antioxidant capability, and better intestinal morphology(Dawood et al. 2020a, b).

Fish reproduction

Incomplete vitellogenesis in females is a frequent issue in artificial reproduction of commercial aquatic animals because it prevents the final oocyte from maturing and ovulating. In order to solve this issue, we need to find ways to regulate reproduction. The endogenous hormone may be carried by chitosan NPs and released in a regulated manner (Khosravi-Katuli et al. 2017). Nanotechnology facilitated the delivery of fadrozole, an inhibitor of estrogen synthesis, to

Nile Tilapia (*O. niloticus*). Exposure to high concentrations of Fadrozole on PLGA nanoparticles, ranging from 50 to 500 parts per million (ppm), for a duration of one month, resulted in a complete male population at concentrations of 350 and 500 ppm (Joshi et al. 2019). In addition, (*Clarias magur*) fish were injected with chitosan nanoparticles and eurycomanone nanoparticles (extracted from *Eurycoma longifolia* plant, which had previously improved animal sexuality and fertility). The gonado-somatic index, calcium (Ca) and selenium (Se) concentrations, reproductive ability, and endocrine hormone gene expression increased after 7 days (Bhat et al. 2019a, b).

Selenium nanoparticles (Se-N) supplementation of a plant protein-rich diet (60% of fish meal was replaced with a mixture of alternative PP sources) for three months was tested on Arabian yellowfin sea bream (*Acanthopagrus arabicus*) males' sperm kinetics and fertilization capacity, and PP-rich diets received 0, 0.5, 1, 2, and 4 mg/kg Se-N. More sperm was detected in 2 mg Se-N/kg PP-fed fish. PP-rich foods improved Se-N, sperm motility, straight movement, lifespan, and fertilization. The maximum semen superoxide dismutase activity was found in fish given 4 mg Se-N/kg PP-rich diets, whereas the lowest was 2 mg. Semen glutathione peroxidase activity was highest in fish fed 4 mg Se-N/kg of PP-rich diet and lowest in those fed 0 and 0.5 mg. Fish given 1 or 4 mg Se-N/kg PP-rich diets have higher antioxidant capability. Fish given PP without Se-N had greater semen malondialdehyde levels. Arabian yellowfin seabream (*A. arabicus*) males had better sperm kinetics and fertility on a PP-rich diet with 2–4 mg Se-N/kg (Khademzade et al. 2022).

Fish medicine

Pathogens (viruses, bacteria, fungi, and parasites) cause substantial economic losses in fish aquaculture. The conventional fish treatment methods included antibiotics and chemicals, which created antibiotic-resistant microorganisms, water pollution, and chemical residues in fish tissues (Abbas 2021). One major problem in aquaculture was controlling infectious diseases produced by microbial pathogens. Antibiotic overuse in fish aquaculture has led to several disease-causing bacteria in fish developing resistance to frequently used antibiotics. This has necessitated the development of novel treatment strategies to address this difficulty. Nanoparticles are suggested as alternative antimicrobials to address the issue of bacteria resistance to antibiotics in aquaculture (Okeke et al. 2022). Metal nanoparticles have shown effective antimicrobial properties against bacterial, fungal, and viral infections by destroying the microbial cell membrane/cell wall, disrupting protein transports, inactivating key enzymes, and many other mechanisms (Nasr-Eldahan et al. 2021). The most common antimicrobial nanomaterials are metals and metal oxides: Silver (Ag), Gold(Au), Zincoxide (ZnO), Copper (Cu), and Titanium oxide (TiO_2) (Abbas 2021).

The most documented antibacterial is Nano-Ag (Abbas 2021). The biologically synthesized nano-Ag particles derived from red algae (*Portieria hornemannii*) has shown antibacterial efficacy against four strains of fish pathogens (*V. harveyi, V. anguillarum, V. vulnificus, and V. parahaemolyticus*) (Fatima et al. 2020). The ZnO nanoparticles also have shown significant antibacterial activity against a variety of microbes (Raghunath and Perumal 2017; Sirelkhatim et al. 2015). In a study was conducted to evaluate the in vitro antibacterial efficacy of ZnO nanoparticles (ZnO NPs) against a pathogenic strain of *Streptococcus parauberis*. Zinc oxide nanoparticles (ZnO NPs) demonstrated significant suppression of proliferation in a pathogenic strain of *Streptococcus parauberis* at concentrations of 0.125 mg/ml and 0.250 mg/ml (Fadl et al. 2021). Nano-Au also affect microbial cell activities after interacting with proteins and lipopolysaccharides (Sumbayev et al. 2013). Nano-Au biologically produced with cashew nut shell liquid inhibited the growth of *A. bestiarum* and *p. fluorescens* in laboratory tests (Velmurugan et al. 2014). A study showed the antibacterial activity of chitosan nanoparticles (CNP) against the bacteria isolated from Nile tilapia *(O. niloticus)*. The highest inhibitory zones were seen for *Aspergillus flavus*, Mucor sp., and Candida sp. at 80 µg/ml CNP dosages, although less impacted, as were *Aspergillus niger*, *A. fumigatus*, and Fusarium sp. The examined bacteria showed the greatest inhibitory zones with 20 µg/ml of CNP (Abdel-Razek 2019).

In a study the nano-ZnO exhibited antifungal properties against *Aphanomyces invadans*, the primary agent of red spot disease in fish (Shaalan et al. 2017). Instead of poisonous and carcinogenic malachite green, nano-Cu has shown antifungal activity against *Saprolegnia* sp. in vitro (Kalatehjari et al. 2015).

Metal nanoparticles have shown beneficial effects in the treatment of many parasitic diseases (Brahmchari et al. 2023). One treatment of nano-Ag in a concentration of 10 ng/ml of nano-Ag exhibited anti-parasitic effects against *Ichthyophthirius multifiliis* infection in rainbow trout (*Oncoryhnchus mykiss)* both in vitro and in vivo. It resulted in a 50% death rate of *I. multifiliis* after 30 min and a 100% mortality rate within 2 h (Abdel-Baki et al. 2017). A study was carried out to examine the anti-parasitic effects of biologically synthesized iron nanoparticles against *Argulus siamensis* in a controlled laboratory environment. The Fe-NPs had the highest argulocidal activity when used at a dose of 1.75 mg ml^{-1} for juveniles and 2.00 mg ml^{-1} for adult argulids. This resulted in a mortality rate of 100% for juveniles and 87% for adults over a period of 6 h (Brahmchari et al. 2023).

Producing efficient vaccinations and delivery systems to combat viral diseases is crucial to fish farming. Fish

are vaccinated by injection, immersion, or oral means. The orally encapsulated vaccine is the best because it inhibits antigens from exiting food granules, protects them from acidic stomachs, decreases fish stress, and is appropriate for mass vaccination purposes (Vinay et al. 2018). Nanotechnology supports to eliminate harmful and carcinogenic chemical adjuvants in fish vaccination, and oral or immersion vaccinations are better than injections to avoid stress (Rivas-Aravena et al. 2015). Fish vaccinations against the infectious salmon anemia virus (ISAV) have been created with the use of chitosan nanoparticles. One such vaccine uses an adjuvant made of the DNA coding for ISAV replicas. In terms of ISAV protection, this immunization showed > 77% protection rates (Rivas-Aravena et al. 2015). Kole et al. (2018) vaccinated rohu fish (*Labeo rohita*) using chitosan nanoparticles combined with a bicistronic DNA plasmid containing the antigen *Edwardsiella tarda* glyceraldehyde 3-phosphate dehydrogenase and the immune adjuvant gene *Labeo rohita* IFN-γ. Rainbow trout (*Oncorhynchus mykiss*) that were immunized against bacterial infection (*Lactococcus garvieae* and *Streptococcus iniae*) using a chitosan-alginate coated vaccine showed improved outcomes compared to fish who received a non-coated vaccination. These improvements included greater survival rates, increased expression of immune-related genes, and higher antibody levels (Halimi et al. 2019). Olive flounder (*Paralichthys olivaceus*) that received a vaccine against inactivated viral *haemorrhagic septicaemia* virus, which was encapsulated with chitosan, demonstrated successful immunization in the head kidney, the primary organ responsible for initiating adaptive immunity in fish. Additionally, the vaccine was effective in stimulating immune responses in the skin and intestine, which are the primary sites for antigen uptake and mucosal immunity. In addition to the increased expression of IgM, IgT, pIgR, MHC-I, MHC-II, and IFN-γ in the three tissues, caspase 3 was also significantly upregulated 48 h after the challenge. This indicates the presence of cytotoxicity caused by a rapid T-cell response and inhibition of viral replication (Kole et al. 2019). Chitosan-based bivalent nano-vaccines, which included *S. iniae* and *F. covae*, were administered to Asian Seabass (*Lates calcarifer*) using immersion immunization at 30 and 40 days after hatching. The third vaccine was administered orally by food at 50 days after hatching. The results showed a significant rise in the levels of total IgM and specific IgM for both *S. iniae* and *F. covae*. Significantly greater levels of IgT, IgM, MHCIIα, and TCRα were seen in all vaccinated groups. Every group that received immunizations had higher survival rates when faced with the *F. covae* challenge (Meachasompop et al. 2024).

Nanoparticles as hormone and drug delivery vehicles

Significant progress has been made recently in the use of nanoparticles to deliver medicinal medications to their target sites(Obeid et al. 2017).The use of nanotechnology in drug delivery allows for unique characteristics such as controlled release, precise control over the size, shape, and surface charge of targeted materials, location-specific and multi-route delivery methods, and regulated degradation of the nanocarrier (Patra et al. 2018). In fish, chitosan and polylactic acid (PLGA) nanoparticles have been studied for their potential as medication delivery vehicles (Shaalan et al. 2016). Polylactic-glycolic acid nanoparticles are a copolymer. It is FDA-approved as biodegradable and non -toxic (Abbas 2021).

Chitosan nanoparticles have been used for medication delivery in research focused on promoting appropriate gonadal development in aquaculture. Bhat et al. (2016) injected walking catfish (*Clarias batrachus*) with chitosan conjugated with salmon luteinizing hormone-releasing hormone (sLHRH) to stimulate gonadal development. Chitosan-conjugated sLHRH and naked sLHRH had comparable effects, causing a rise in Sox9 expression in the gonads and elevating levels of testosterone and 11-ketotestosterone in males, and testosterone and 17β-estradiol in females. Conjugating sLHRH with chitosan resulted in a continuous and regulated release of hormones, reaching maximum levels after 36 h. In contrast, administering naked sLHRH led to peak levels of circulating steroid hormones after 12 h (Bhat et al. 2016). Compared to administering naked kisspeptin-10, injecting chitosan-encapsulated kisspeptin-10 into immature female *Catla catla* caused a delayed but more significant increase in gonadotropin-releasing hormone, luteinizing hormone, and follicle-stimulating hormone expression, as well as circulating levels of 11-ketotestosterone and 17β-estradiol (Rather et al. 2016). Chitosan was tested for gene delivery to influence gonadal development in fish. Chitosan nanoparticles conjugated with a plasmid encoding steroidogenic acute regulatory protein (StAR) administered intramuscularly in walking catfish (*Clarias batrachus*) showed longer-lasting stimulatory effects on the expression of key genes involved in reproduction, such as cytochrome P450 (CYP) 11A1, CYP17A1, CYP19A1, 3β-hydroxysteroid dehydrogenase, and 173β-hydroxysteroid dehydrogenase, compared to administration of the naked plasmid construct (Rathor et al. 2017). To encourage goldfish oogenesis, research suggested oral delivery of chitosan nanoparticles along with a GnRH analog. Chitosan, 50 µg GnRHa/kg b.w., 100 µg, chitosan + 50 µg, and chitosan + 100 µg were administered to adult female goldfish. The width of the follicular layer (Fl), the thickness of the zona radiata (Zr), the diameter of the oocyte (OD), and the gonadosomatic index (GSI) were

measured. The metrics consistently rose in the group that received a dosage of 100 µg of GnRH or a combination of chitosan nanoparticles and 100 µg of GnRHa. The investigation discovered that the use of oral chitosan in conjunction with a dosage of 100 µg GnRHa/kg b.w. significantly enhanced the maturation and expansion of ovarian oocytes (Kookaram et al. 2021). Direct applications of nanotechnology in fish culture are summarized in Table 1.

Indirect applications of nanotechnology in fish culture

Water purification

Due to their unique features, greater surface area, and numerous absorption sites, nanomaterials immobilize and adsorb metals well, allowing them to remediate contaminated water and sediments. A variety of nanomaterials, including metal oxide nanoparticles, nano zero-valent iron, carbon nanotubes, and natural adsorbents, have been utilized in the remediation of heavy metals (Cai et al. 2019).

Metal oxide nanoparticles (MON) are Fe_2O_3, Al_2O_3, MnO, MgO, and TiO_2. MON also catalyzes the degradation of non-degradable pesticides including PCBs and

Table 1 Direct applications of nanotechnology in fish culture

Applications	Nano material	Major Impacts	References
Feed supplements	Se	Increase of immunological response, higher levels of total protein, enhanced antioxidant activity	Dawood et al. (2019)
	Zn	Enhancement in the rates of development, hematological parameters, and immune system reaction	Faiz et al. (2015)
	Fe	Improvement in survivability, growth, digestive enzymes activities, biochemical and hematological parameters	Srinivasan et al. (2016b)
	Chitosan	Activate antioxidants, growth and immune response enhancement	Abd El-Naby et al. (2020), Abd El-Naby et al. (2019), Abdel-Tawwab et al. (2019)
Fish reproduction	PLGA	Overloading PLGA nanoparticles with fadrozole induced 100% male at 350 and 500 ppm	Joshi et al. (2019)
Antimicrobial	Ag	Antifungal and antiparasitic properties to prevent red spot and white spot disorders; anti-parasitic action against *Ichthyophthirius multifiliis*	Daniel, Sironmani, Dinakaran, & Studies, (2016), Mona Saleh et al. (2017)
	Au	Antibacterial activity towards *P. fluorescens and A. bestiarum*, upregulation in immune genes, the high survival rate, and no hepato-pancreas toxicity	Tello-Olea et al. (2019), Velmurugan et al. (2014)
	ZnO	Antibacterial role against *V. harveyi, A. hydrophila, F. branchiophilum*,*E. tarda, S. aureus, and P. aeruginosa*, antifungal effect against *Aphanomyces invadans*	Gunalan et al. (2012), Ramamoorthy et al. (2013), Shaalan et al. (2017), Swain et al. (2014)
	TiO_2	Antibacterial effect against *E. tarda, S. iniae, Photobacterium damselae* infections and *E. coli*	Alhadrami & Al-Hazmi, (2017), Cheng et al. (2009), Cheng et al. (2011)
	Cu	Antifungal effect against Saprolegnia sp.,	Kalatehjari, M. Yousefian, & M. A. Khalilzadeh (2015)
Vaccination	Chitosan	Orally injected nano-chitosan containing inactivated contagious anemia virus protected against viral infection	Rivas-Aravena, Fuentes, Cartagena, Brito, Poggio, La Torre, Mendoza, Gonzalez-Nilo, Sandino, & Spencer, (2015)
	PLGA	Oral ingestion of outer membrane protein W with PLGA NPs prevents *Acinetobacter hydrophila* infection	Dubey et al. (2016)
Drug and hormone delivery vehicle	Chitosan	Injection of luteinizing Hormone conjugated with nanochitosan increase the egg fertilization rates	Mohd Ashraf Rather et al. (2013)
	PLGA	Injecting PLGA nanoparticles containing rifampicin boosted *Mycobacterium marinum* infection treatment	Fenaroli et al. (2014)

organochlorines (Abbas 2021). Nano zero-valent iron allows metal adsorption with its metallic iron core and iron oxide shell (Yirsaw et al. 2016). Bentonite, kaolinite, and montmorillonite can remove heavy metals, hence several research mixed them with chitosan nanoparticles to improve their adsorption (Abbas 2021).

Pathogens in the water supply are known to multiply in fish farms owing to the high population density and leftover food particles. Many infectious disorders in fish are caused by pathogens such viruses, fungus, bacteria, and protozoa. Risks to pathogen resistance, user health, aquatic wildlife, and the environment are only some of the consequences of using traditional anti-pathogen chemicals (Abbas 2021). Nanotechnology could solve water sterilization and disinfection issues (Tayel et al. 2019).

Moreover, the presence of heavy metals and microbes in these waterways results in fish mortality and growth retardation, which causes a significant economic loss for the fishing sector. Nanotechnology is widely used in aquaculture to clean water to provide a safe and favorable environment for fish to spawn. From this angle, the scientific community supports photocatalysis and adsorption as the most cost-effective and efficient methods of water filtration. Furthermore, Fig. 1 demonstrates the practical functioning of several nanoparticle-based photocatalytic adsorbents and hydrogel biofilms in water purification. It demonstrates the recommended approach by showcasing the removal of nitrate ($NO3^-$), fluoride (F^-), and coliforms (*E. Coli*) from contaminated water (Shah and Mraz 2020b).

Bio-fouling control

Nanoparticles that function as the major oxides of the metals may combat biofouling caused by bacterial assault. When additional contaminants, including poisonous metals, build up in the water, biofouling may seem much more perilous and cause the deaths of many fish and other aquatic species. Aquaculture production and prawn culture may both benefit from the advancements in disease management, feeding formulation, and biofouling control that nanotechnology has made possible. To keep an eye out for undesired bacteria (as biofilm), nanostructures may be painted or coated with metal oxide nanoparticles like zinc oxide (ZnO), copper oxide (CuO), and silicon dioxide (SiO_2), allowing for the monitoring of invertebrates like mussels and barnacles and algae like seaweeds and diatoms. Since nanotechnology is the primary scientific technique by which such severe environmental contamination may be managed, this is the case (Munawar et al. 2021).Anti-fouling agents made from lanthanides (La) oxides nanoparticles have been shown to inhibit algal and microbial development by absorbing phosphate from the surrounding water (Ashraf et al. 2011; Gerber et al. 2012). One of the commercial solutions that deal with the management of fish culture is called Nano-Check. Its structure is built on 40 nm nano La, which has the ability to absorb phosphate from the water and, as a result, limit the production of algae (Ashraf et al. 2011). In addition, because of nano-Ag's antibacterial properties, biofouling may be prevented and controlled (Hassan and Abd El-latif 2018; Vijayan et al. 2014a).

Fish packaging

Plastics, such as polyolefins, polyesters, and polyamides are gaining popularity among the wide variety of fish packaging materials due to the fact that they are readily available in large quantities at a low cost and have favorable functionality characteristics. These characteristics include good tensile

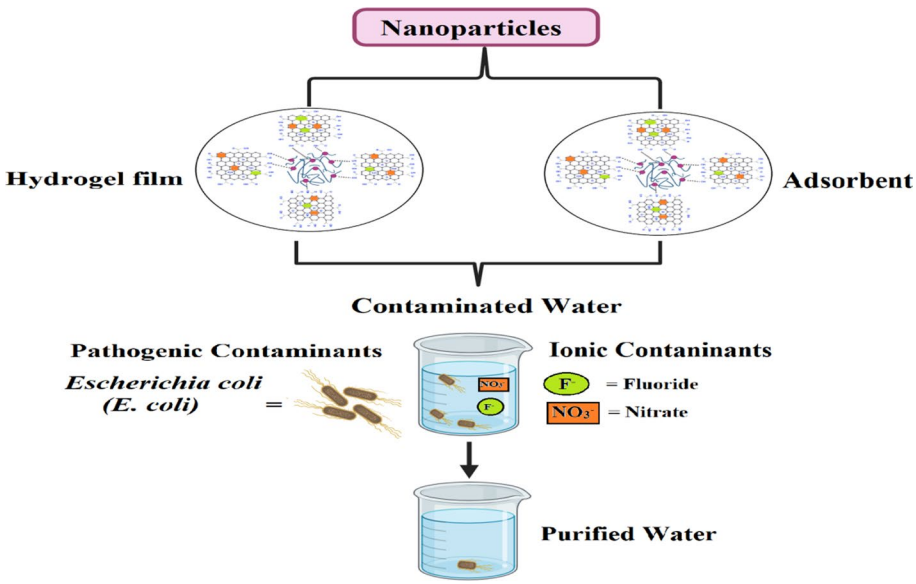

Fig. 1 Process of NPs-based adsorbents and hydrogel films remove *E.coli*, $NO3^-$, and F^- from polluted water

and tear strength, good barrier properties to O_2 and aroma compounds, and the ability to be heat sealed. Unfortunately, with the exception of cellophane, the majority of polymers are not biodegradable, and as a result, they contribute to environmental contamination and the subsequent severe ecological difficulties. In order to solve these problems, its use in any way, shape, or form ought to be limited and ought to be phased out gradually (Agarwal 2020).

Finally, nanotechnology can delay microbiological and enzymatic degradation to extend fish packaging and marketing shelf life. Nano-materials in biodegradable food packaging act as antibacterial and antifungal agents, eliminate oxygen, limit biological deterioration, and immobilize enzymes to promote product stability, according to several studies (Jiang et al. 2015; Kuswandi 2017; Rhim et al. 2013). Furthermore, nano-composites made from proteins, lipids, or polysaccharides are considered healthier packaging materials than petrochemical-based plastics (Can et al. 2011). Overview of indirect applications of nanotechnology in fish culture are given in Table 2 (Fig. 2).

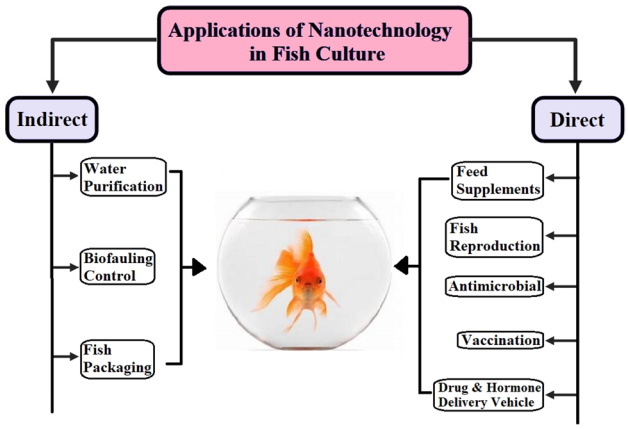

Fig. 2 An illustration of the potential applications of nanotechnology in the fish culture

Challenges of nanotechnology applications in fish culture

Environmental risk

Environmental concerns have been raised over the widespread use of nanoparticles in several industries. However, nanoparticles and other foreign contaminants eventually find their way into the aquatic environment. In water, NPs can undergo chemical, physical, and biological changes through aggregation, adsorption, dissolution, and redox reaction. Because of this, NPs are modified to generate materials with novel attributes and reactivity (Odzak et al. 2017; Yin et al. 2015). The interaction of new materials with the biological system, both inorganic and organic components, and live organisms that are not specifically targeted causes damage to all of these entities. Cytotoxicity, malfunction of various cell organelles (including the cell membrane, mitochondria, and ribosomes), DNA

Table 2 Indirect applications of nanotechnology in fish culture

Applications	Nano material	Example	References
Water purification	TiO2	TiO2 alters pollutant movement, accumulation, and toxicity	Li et al. (2018), Luo et al. (2018)
	zero valent iron	Reduced heavy metal availability and mobility, reducing their environmental toxicity	Fajardo et al. (2012)
	Natural adsorbents	Nano-Ag attracts to zeolite pores and reduces ammonia and nitrate in fish farms synergistically	Johari, Kalbassi, Soltani, & Yu, (2016)
	Ag	Nano-Ag-coated zeolite reduces Salmonella infection in rainbow trout eggs during water filtration	Johari et al. (2016)
Bio fouling control	Ag	Antibacterial effect	W. T. J. E. S. Abbas & Research, (2021), Vijayan et al. (2014b)
Fish packaging	Chitosan	Nano-coating showed antibacterial action after 9 days at 4℃, extending sample shelf life	Hajji et al. (2019)
	T TiO_2	coloring agents	Baranowska-Wójcik et al. (2020), Sungur et al. (2020)
		The antimicrobial active films reduced Shewanella spp., *Pseudomonas putida*, and *Aeromonas hydrophila* and increased *macrobrachium rosenbergii* product shelf life by 1–2 days	Tang et al. (2018)
	ZnO	PE sheets with ZnO nanoparticles decreased gumminess, water loss, and adhesiveness in cod samples contained in boxes	Mizielińska et al. (2018)

damage and genetic toxicity meant that toxic effects might be passed to the fetus and increased while the fetus was developing (Fig. 3) (Zhang et al. 2018). Nanomaterials can be coated and interacted with organic compounds like humic acid and fulvic acid to change their physicochemical properties, behavior, and harmful impacts on living beings (Cai et al. 2019; Tang et al. 2014). Additionally, nanomaterials like apatite and biochar supported by Fe-phosphate increase water phosphorus levels, causing eutrophication, a major issue in fish culture (Qiao et al. 2017).

Technical producing difficulties

Nanoparticles are especially difficult to manufacture because they are prone to re-aggregation, transformation, and reaction with an extensive range of environmental variables (Zhang et al. 2018). Nanoparticles are difficult to characterize because of the high expense of the procedures required to determine their shape, size, and morphology (Patil and Kim 2017).

High cost

Until now, the high price of nanotechnology has prevented its widespread use in fish farming. This is especially true of nano-filters, nano-membranes, and nano-sensors. But its uses in egg and hatching ponds, as well as in the case of prized broad-stocks, have been documented (Bhattacharyya et al. 2015).

Lack of information

There is a lack of information regarding how nanoparticles are absorbed, distributed, accumulate in the food chain, and excreted from living creatures, despite the widespread use of nanotechnology over the past decade (Tripathi et al. 2017). Most research on nanoparticles and their impact on fish have only been conducted in the laboratory or in vitro. Without further information and more study, it will be very difficult to move forward with field application.

Toxicity

Since nanoparticles are being used in so many different applications, scientists will inevitably look into their potential effects on humans as well as the environment. Overuse and incorrect disposal of nanoparticles lead to harmful consequences and negative impacts on the environment, which in turn have detrimental effects on the health of living beings (Hu et al. 2016; Samrot et al. 2019).

Nanoparticles are so tiny that they may cross cell membranes and induce genotoxicity within the cell. One of the primary toxicity mechanisms of nanoparticles is the increased synthesis of free radicals and reactive oxygen species (ROS). It is possible that this will not only cause oxidative stress and inflammation, but it may also cause problems with DNA and proteins. Evidence shows that exposure to nanomaterials may cause mutations in DNA and severe damage to mitochondrial structure, which may ultimately lead to cell death (Majumder and Dash 2017; Meghani et al. 2020; Vicari et al. 2018). Studies in nanotoxicology have been

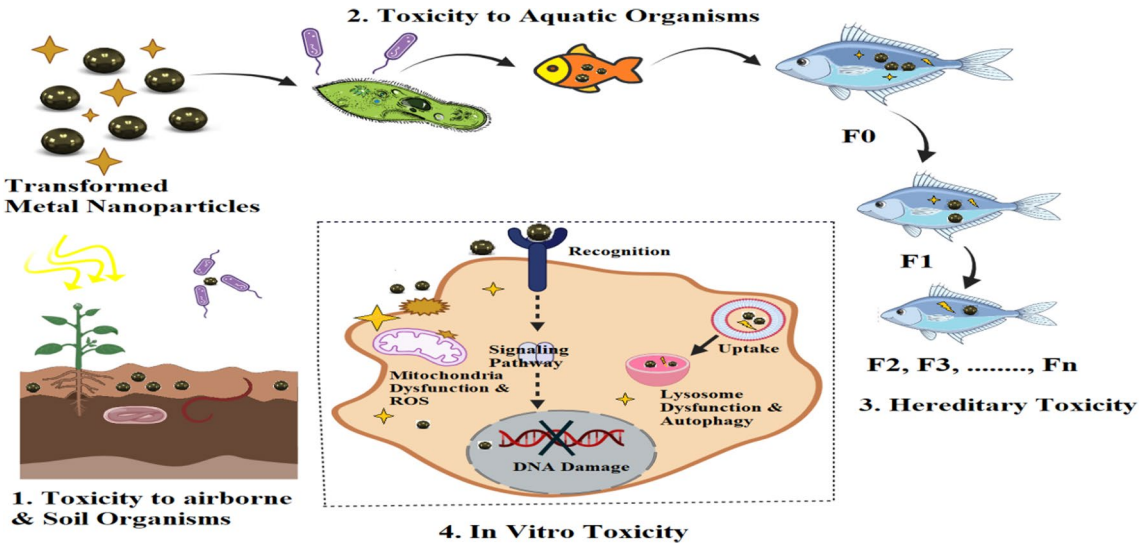

Fig. 3 Toxicity of metal nanoparticles that have been transformed in the environment

Table 3 Toxicity evaluation of most frequently used NPs in fish culture using different parameters

Metal NPs	Fish species	System action, cell, tissue target	Concentration and size	Duration of exposure (days)	Major effects	References
CuO	*Labeo rohita*	ecotoxicological	70.79 and 117.99 mg/L (32.84 nm)	15, 30, and 45	oxidative stress and genotoxicity after chronic exposure	Aziz et al. (2023)
MgO	*Cirrhinus mrigala*	gills, muscle, and live	3, 6, 12, and 24 mg/L (< 100 nm)	7th and 14th	Increased white blood cells, red blood cells, hematocrit, hemoglobin, and platelets. Severely damaged gills, muscle, and liver	Sudhabose et al. (2023)
Ag	*Tor putitora*	Behavior changes, metabolic, Histological and biochemical parameters	5, 10, 15, 20, and 25 mg/L, (85 nm)	7	Na got better K, Fe, P, and Ca dropped, uric acid, cholesterol, creatinine, and proteins decreased, HCT, Hb, Erythrocytes, MCHC, and WBCs decreased, Gill and liver histological abnormalities, blood coagulation and pyknosis	Waheed et al. (2023)
ZnO	*Cyprinus carpio*	liver, gills, kidney, and ovaries	250, 500 mg/L (10–30 nm)	42	Moderate gill hyperplasia of primary lamellar cells, disappearance of secondary lamellar. hepatocytes filled with cytoplasmic glycogen granules, moderate vascular degeneration, renal tubular cast and collecting and proximal tubular necrosis	
NiO	*Heteropneustes fossilis*	Muscles	12, 24, 36 and 48 mg/L, (< 50 nm)	14	Boost Ni accumulation, metallothione in content, lipid peroxidation, antioxidant enzyme activity, while decrease SOD activity, fluctuate alanine amino transferase, aspartate amino transferase, and alkaline phosphatase activity	Samim and Vaseem, (2023)

Table 3 (continued)

Metal NPs	Fish species	System action, cell, tissue target	Concentration and size	Duration of exposure (days)	Major effects	References
Ag	*Oreochromis niloticus*	Hematological and biochemical response	1.95, 3.9 ppm (5–16 nm)	28	Decrease in hemoglobin, red blood cells, white blood cells, hematocrit, MCV, and lymphocyte levels. Elevated levels of MCHC, micronuclei, activated cells, and neutrophils	Ibrahim, (2020)
	Clarias garepinus	liver	10, 100 mg/L (10 and 100 nm)	15	Significant hepatic injury with amelioration after the recuperation phase	Naguib et al. (2020)
	Clarias garepinus	Gills, muscles tissues	10, 100 mg/L (20 and 40 nm)	15	Tissue and cell alterations	Sayed et al. (2020)
	Cyprinus carpio	Intestine, muscles, liver, gills	0.03, 0.06, 0.09 mg/L (20 to 50 nm)	20	Alteration and damaged to the Gills, intestine, muscles, and liver	Kakakhel et al. (2021)
	Oreochromis mossambicus	gills	25, 50, 75, 100 mg/L (20–30 nm)	7	Hyperplasia of epithelial cells and telangiectasia	Sibiya et al. (2022)
	Rhamdia quelen	liver, kidney	0.03, 0.3, and 3 mg/L (< 10 nm)	15	Injury to the liver and kidney, including hepatic steatosis and vascular congestion	López-Barrera et al. (2021)
A	*Danio rerio*	Embryoniccells	2.5, 5, and 10 mg mL_1 (10, 30 and 100 nm)	1	lipid peroxidation, boosted ROS generation, cell death	Quevedo et al. (2021)
	Oreochromis mossambicus	Behavioural changes and body weight	50, 100, 150, 200, 250 mg/L (14.748 nm)	4	Non-toxic, altered fish physiology	Yallappa et al. (2020)
CuO	*Oreochromis niloticus*	Liver, gills, kidney	10, 20, 50 mg/L (68.92 ± 3.49 nm)	25	Liver and pancreatic tissues, posterior kidneys, and the gills show histopathological lesions	Abdel-Latif et al. (2021a, b)
ZnO	*Carassius auratus*	Kidneys, gills, liver	0.5, 1, 1.5 mg/L (20–30 nm)	14	The liver, kidney, and gills exhibit significant histological changes and oxidative stress	Ghafarifarsani et al. (2023)
	Cirrhinus mrigala	Blood profile	5,10,15,20, and 25 mg/100 g of fish feed (10 nm)	21	Histology, Red Blood Cell Count, Hematocrit, MCV, MCH, and MCHC rose while WBC and platelets dropped	Rajan et al. (2021)
	Cyprinus carpio	Muscles, gills, liver,	0.382, 0.573, 1.146 mg/L	28	Histological alterations	Krishnasamy Sekar Rajkumar et al. (2022)
TiO2	*Oreochromis mossambicus*	Gills, liver	0.5, 1, 1.5 mg/L (< 100 nm)	14	stimulated genotoxicity	Shahzad et al. (2022)
As	*Labeo rohita*	Kidney, gills, liver	1, 10, 20 mg/L (40 ± 10 nm)	30	Liver, kidney and gills damage	Raza et al. (2021)

Table 3 (continued)

Metal NPs	Fish species	System action, cell, tissue target	Concentration and size	Duration of exposure (days)	Major effects	References
IO	*Cyprinus carpio*	(immunotoxicity)Blood, liver, intestine	25%, 50%, and 75% of LC50 (96 h) (20–40 nm)	21	changes to blood chemistry, reduced white blood cell count, elevated glucose and cortisol levels, Immune responses decreased in serum and skin mucus, accumulated in liver tissue	Khoei, (2021)

performed to better understand the regulatory framework and bio-distribution of these substances while also assessing the possible molecular hazards they pose to ecosystems (Bello and Leong 2017).

It has been shown that several nano-materials employed in water remediation, such as nanoscale metallic iron (nZVI), are harmful to bacteria, crustaceans, fish larvae, and other aquatic and soil dwelling creatures(Stefaniuk et al. 2016).After being exposed to Al_2O_3-NPs, Nile tilapia (*Oreochromis niloticus*) displayed symptoms of oxidative stress, as shown by a decrease in antioxidant enzyme (SOD, CAT, and GPx) activity (Temiz and Kargın 2022). Nile tilapia (*Oreochromis niloticus*) cytokine transcription was affected by copper oxide nanoparticles (Abdel-Latif et al. 2021a, b). Cells exposed to Cu-NPs or $CuSO_4$ may cause an elevation in malondialdehyde and reactive oxygen species levels. This can lead to a decline in mitochondrial bioenergetics and impair physiological functions. After then, caspase-3 and caspase-9 were activated due to the release of Cyt-c from mitochondria into the cytosol, which prompted apoptosis. Cu-induced apoptosis in adolescent *E. coioides* was mediated via the mitochondrial route (Wang et al. 2015). The inability of cells to repair the damage to their membranes that had been caused by lipid peroxidation as a result of being exposed to AgNP was what ultimately led to the death of the cells. The autophagy process was impacted by the nanoparticles that were internalized, which resulted in the discharge of nanoparticles into the cytosol. Because of this, the lysosomes were unable to function properly, and the mitochondrial membrane became more permeable (Quevedo et al. 2021). Toxicity NPs in fish culture using different parameters are also illustrated in Table 3.

Conclusion

The preceding situation suggests that, similar to other developing technologies, nanotechnology possesses positive as well as negative aspects. The use of nanotechnology in fish culture has the potential to completely transform them and address several fish culture challenges with more efficiency compared to traditional approaches. They have the ability to contribute to improving fish development performance and production, managing fish illnesses, purifying water, remediating contaminants, and ultimately prolonging the shelf-life of fish in packaging. Simultaneously, the use of nanotechnology in fish farming encounters several obstacles, with the most significant being the potential toxicity of nanoparticles and their harmful effects on fish and other unintended creatures. However, it is essential to evaluate the absolute safety of using nanoparticles in fish farming and to determine their potential accumulation in the food chain to

ensure the health of the fish, the environment, and human consumption.

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Declarations

Conflict of interests Authors do not have any financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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