Proceedings of the Indian National Science Academy
https://doi.org/10.1007/s43538-024-00238-5

REVIEW ARTICLE

Harnessing nanotechnology for advancements in fisheries and aquaculture: a comprehensive review

Kolupula Akhil Kumar[1] · Gora Shiva Prasad[1] · Bhanu Prakash Ch.[2] · Nagaraju Shiga[3] · Pagala Jasmeen[4] · Suhashini Battapothula[5]

Received: 25 September 2023 / Accepted: 11 January 2024

Abstract

With the technological advances, aquaculture and fisheries industries are benefiting a lot. Nanotechnology is among the most emerging and vital driving tools for the thriving aquaculture and fisheries sectors. In recent years, the antimicrobial resistance in pathogenic microbes due to uncontrolled use of antimicrobials and the environmental impact with aquaculture intensification are the major issues of concern. In this context, nanotechnology has profound advantages in enhancing the aquaculture and fisheries industries and ensuring the surrounding environment's quality. Nanoparticles aid in the well-being (improves growth, health, reproduction, and so on) of the culturing species. Recently, nanocarriers are well-popularized because of their immense potential in delivering encapsulated substances to aquatic organisms. Nanotechnology also promises to preserve the quality and freshness of aqua foods by preventing the growth of harmful microorganisms and increasing the product's shelf life. Nano-sensors were in use to detect the presence of contaminants in fish samples and water. Moreover, nano-tracing devices helps in tracking a product and also to monitor the aquatic animals. Additionally, nanoparticles benefit aquatic systems by eliminating environmental pollutants (nano-remediation). Conversely, due to the pollution and the overuse of nanoparticles may adversely affect the freshwater and marine water ecosystems. Therefore, this review critically analyses the advances of nano-technological applications in aquaculture and fisheries and outlines their negative impacts on aquatic organisms. More importantly, to determine the precise relevance of nanoparticles, further research must be conducted on the implications of various nanoparticles on aquatic life in the lab and at large-scale applications.

Keywords Nanoparticles · Nano-remediation · Nano toxicity · Aquaculture

Introduction

The significance of fisheries and aquaculture sectors towards global food security and nutrition has become increasingly apparent in the twenty-first century (FAO 2022). About 17% of the world's population currently relies on aquatic food for animal protein needs (Shah and Mraz 2019). By 2030, the average annual consumption of aquatic foods is expected to rise by 15%, which is around 21.4 kg per capita (FAO 2022). Over the previous seven decades, total fisheries and aquaculture production have increased dramatically. It was only 19 million tonnes in 1950, but it reached an all-time high of around 179 million tonnes in 2018. Then, in 2019, production dropped drastically (1% less than in 2018) and only slightly increased (0.2%) in 2020, reaching 178 million tonnes (FAO 2022). Although aquaculture is growing due to the advances in farming practices and the adoption of innovative technologies, aquaculture still faces many significant obstacles (Shah and Mraz 2019). One of the major issues the aquaculture industry faces is increasing the production of aquatic organisms without increasing resource utilization or environmental damage (FAO 2018).

✉ Kolupula Akhil Kumar
kolupula4@gmail.com

1 Faculty of Fishery Sciences, WBUAFS, Kolkata, West Bengal 700094, India

2 College of Fishery Science, PVNRTVU, Wanaparthy, Pebbair, Telangana 509 104, India

3 Fisheries Research Station, PVNRTVU, Palair, Khammam, Telangana, India

4 National Institute of Animal Biotechnology, Hyderabad, Telangana, India

5 Yogi Vemana University, Kadapa, Andhra Pradesh, India

Published online: 19 February 2024

Nanotechnology has emerged as one of the most rapidly developing scientific technologies in recent years (Bayda et al. 2019). The National Nanotechnology Initiative (NNI) of the United States defined nanotechnology as "the understanding and controlling of molecules at nanometer scale between 1–100 nm, as the matter becomes smaller, take up unique qualities that are not seen in bulk materials" (NNI 2022). Moreover, these unique properties enable the nanoparticles to have a wide range of novel applications in many fields of science and technology (Shaalan et al. 2016; Matteucci et al. 2018; Rather et al. 2018, 2021) and this usage of nanoscale materials in biological fields is termed as "nanobiotechnology" (Fakruddin et al. 2012; Rather et al. 2021). Nanoparticles have gained widespread usage in various sectors such as agriculture, food, cosmetics, medicine, textiles, and public health due to their potential to boost solubility and bioavailability while conserving bioactive components during processing and storage (Fu 2014; Ali et al. 2023).

In recent years, the food industry has made significant progress, especially in the areas of improved new packaging products, development of new functional products, transport and controlled release of bioactive substances, detection of pathogens using nano-sensors and indicators, and the purification of water using nanoparticles (Senturk et al. 2013). According to current forecasts, the global nanotechnology market applied to the food industry is growing at a CAGR (compounded annual growth rate) of 25.32% from 2020 to 2025, reaching $ 187.84 billion (Technavio 2022). Today companies like AQUANOVA AG, Trendlines Group Ltd., Nanophase Technologies Corp., BASF SE, Honeywell International Inc., Blue California Inc., CHASM Advanced Materials Inc. and Nanocyl SA etc. are among the leading firms in the nano food sector (Technavio 2022; Fajardo et al. 2022).

Nanoparticles (NPs) that form the core of nanotechnology are very tiny in size (less than 100 nm in size) and are made from diverse materials such as carbon, metals, metal oxides, and many other inorganic and organic substances (Matteucci et al. 2018). Various physical, chemical, and biological approaches for manufacturing nanoparticles have been developed with recent technological breakthroughs. Nanoparticles can be synthesized by reducing bulk material to nanometric scale (top-down approach) or by arranging atoms into nanoparticles (bottom-up approach) (Daraio and Jin 2011; Ealia and Saravanakumar 2017; Sakhare et al. 2022). Various organic and inorganic compounds, such as lipids, proteins, synthetic and natural polymers, and metals, can be used to manufacture nanoparticles (Yhee et al. 2014; Kim et al. 2013; Kuppusamy et al. 2016; Khan et al. 2019; Vijayaram et al. 2023). Recently, biosynthesis has become more popular since the nanoparticles are produced utilizing bacteria, plant extracts, fungi, etc., as precursors and are safe for the humans and environment (Hasan 2015; Kuppusamy et al. 2016).

Recently, several studies have reported regarding viability of using nanoparticles in the aquaculture and fisheries sectors (Fig. 1) (Khosravi-Katuli et al. 2017; Ogunkalu 2019; Nasr-Eldahan et al. 2021; Sarkar et al. 2022; Jimenez-Fernandez et al. 2014; Bhattacharyya et al. 2015; Huang et al. 2014; Luis et al. 2017; Rather et al. 2021; Vijayaram et al. 2023; Vibhute et al. 2023). Different forms and shapes of nanoparticles (NPs), such as nanospheres, nanotubes, nanoemulsions, nanocomposites, dendrimers, and so on, are found to have many positive outcomes in various areas of aquaculture and fisheries (Table 1). Nanotechnology/nanobiotechnology has the capability to enhance the aquaculture and fisheries sectors with its efficient pond sterilization and water treatment, rapid disease detection tools, improved gut absorption of medications, vaccinations, nutrients, and other applications (Fig. 2) (Rather et al. 2011; Jimenez-Fernandez et al. 2014; Bhattacharyya et al. 2015; Huang et al. 2014; Khosravi-Katuli et al. 2017; Luis et al. 2017; Rather et al. 2021; Sarkar et al. 2022; Vijayaram et al. 2023). Nanoparticles are particularly useful in delivering substances because they aid in tissue-specific targeting, dosage reduction, increased bioavailability, efficacy of the drug and reduction in the toxic or secondary adverse effects etc. (Xu et al. 2018). Additionally, nanoparticles enhance the yield in several ways by lowering feed nutrient losses, improving fish growth rates, and decreasing production costs (Luis et al. 2017).

Apart from the positive aspects, nanoparticles also have negative impacts on the aquatic organisms due to pollution, which is mostly unknown or neglected at present moment (Mehboob et al. 2014; Huang et al. 2014; Sarkar et al. 2022). Therefore, the present comprehensive review, is mainly focused on the various applications of nanoparticles in the aquaculture and fisheries sectors. Herein, we have also detailed some of the consequences of nanotechnology, emphasizing the risks posed by nanoparticles to aquatic organisms.

Applications of nanotechnology in fisheries and aquaculture

Nanoparticles in aiding the well-being of culturing species

Growth and nutrition

Nanotechnology provides many novel opportunities for aquaculture by lowering nutrient losses in the feed, accelerating fish growth, and making aquaculture more sustainable (Luis et al. 2021). Nanoparticles increase the amount

Table 1 Beneficial effects of NPs in breeding & reproduction of fish

s.no.	Purpose	Nanoparticles	Remarks	Reference
1	Growth and nutrition	Nano chitosan; nano *Arthrospira platensis* (NAP); Se-NP; Zn-NP; ZnO-NPs; GBGS-SeNPs; Nano-Fe; Cu-NPs; nano Cr_3O_4; nano Co_3O_4; MgO-NPs and MnO NPs etc.	Improves: – Survival – Growth performance and feed utilization – Digestive enzymes activity – Protein and fat content – Total body weight and – Growth-related gene expression	Bhattacharyya et al. (2015); Satgurunathan et al. (2018); Ogunkalu (2019); Abdel-Tawwab et al. (2019); Abdel-Warith et al. (2020); Ghazi et al. (2021)
2	Health and stress mitigation	AgNPs; CuCS; ZnO-NPs Se-NP; nano chitosan; Nano-Fe etc.	– Enhance Innate and humoral immunity – Improve hemato-biochemical parameters – Boosts antioxidant profile and stress resistance – Act against Antimicrobial resistant bacteria – Reduce many diseases (bacterial, fungal, viral, and parasitic) – Enhance immune related gene expressions	Nguyen et al. (2020); Johari et al. (2015); Kalatehjari et al. (2015); Kandasamy et al. (2013); Shalaan (2020); Li et al. (2015); Elgendy et al. (2021); Masimen et al. (2022); Jhanani et al. (2021); Selvaraj et al. (2014); Ghetas et al. (2022); Naiel et al. (2020); Ismael et al. (2021); Sun et al. (2022)
3	Breeding and reproduction	Chitosan NPs; Poly lactic-co-glycolic acid (PLGA) NPs; Selenium NPs; Fe_3O_4 NPs; Aluminium NPs, etc.	– Improve reproductive performance – All male/female production – Efficient hormone delivery for breeding and maturation – Gonadal development etc.	Sharma et al. (2014); Bhat et al. (2019); Kookaram et al. (2021); Hajiyeva et al. (2022a, 2022b)
4	Delivering substances	Chitosan NPs; halloysite nanotubes (HNTs); SWCNTs etc.	Improves efficacy and efficient delivery of various drugs, vaccines, hormones, genes, and other nutraceuticals	KhaniOushani et al. (2020); Ghanbary et al. (2022); Rajeshkumar et al. (2009); Vimal et al. (2012); Ramya et al. (2014); Rivas-Aravena et al. (2015); Ramesh Kumar et al. (2016); Hu et al. (2020);Subramanian (2021)
5	Remediation of aquatic environment	Carbon nanotubes; Fe_3O_4/CSNPs composites; sulfonated magnetic NPs; iron NPs etc.	Eliminates: – Organic pollutants like ammonia, nitrites, and nitrates etc. – Inorganic pollutants like lead, cadmium and arsenic, etc. – Chemicals like trichloroethane, C_2Cl_2, dioxins, and PCBs etc. – reduce eutrophication	Gupta and Saleh (2013); Fan et al. (2017); Chen et al. (2017); Martinez-Vargas et al. (2017); Gillman (2006); Duke et al. (2013); Rather et al. (2011); Kumar et al. (2019)
6	Preservation and quality control	Nanofibers; nano-ZnO; nano-chitosan	Antimicrobial properties; improves organoleptic qualities; Improves shelf life of the products	Ozogul et al. (2017); Perreault et al. (2015); Pati et al. (2022); Wang et al. (2014); Chouljenko et al. (2017)

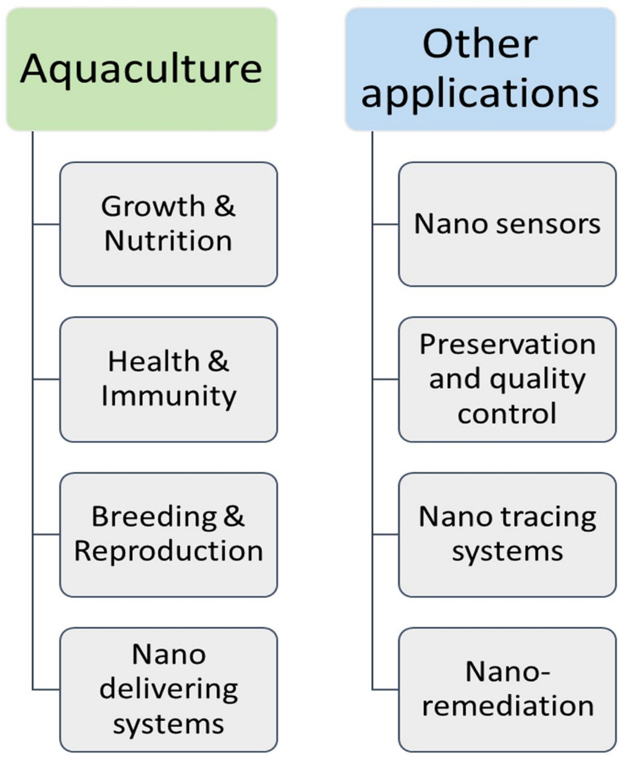

Fig. 1 Various areas of nanotechnology applications in aquaculture and fisheries

of nutrients absorbed through the gut instead of being excreted (Handy 2012; Ogunkalu 2019) and thus promoting aquatic animals' growth (Bhattacharyya et al. 2015). Many researchers have reported the growth-promoting effects of nanoparticles in aquatic species (Bhattacharyya et al. 2015; Satgurunathan et al. 2018; Ogunkalu 2019; Abdel-Tawwab et al. 2019; Abdel-Warith et al. 2020; Ghazi et al. 2021). The nanoparticles, such as nano-chitosan, stimulate growth in aquatic organisms by improving the feed conversion ratio and total body weight (Wang et al. 2011; Abdel-Ghany and Salem 2019). Many studies have found that dietary inclusion of nano chitosan between 1 and 5 g/kg promotes fish growth and feed utilization in Nile tilapia (*Oreochromis niloticus*). The dietary supplementation of nano chitosan enhances growth by improving digestive enzyme activity while limiting intestinal bacteria populations' growth. Moreover, it also helps improve several markers of innate immunity and antioxidant levels in the fish (Abdel-Tawwab et al. 2019; Abd El-Naby et al. 2019; Kumaran et al. 2021).

Similarly, in shrimp (*Litopenaeus vannamei*), feeding the diets incorporated with 2.13–2.67 g/kg of chitosan nanoparticles (NPs) promoted growth performance by increasing the rate of digestion and absorption of ingested food (NIU et al. 2011). Likewise, Abdel-Warith et al. (2020) have found that feeding shrimp (*P. monodon*) with diets containing 44% protein and fortified with *Spirulina*

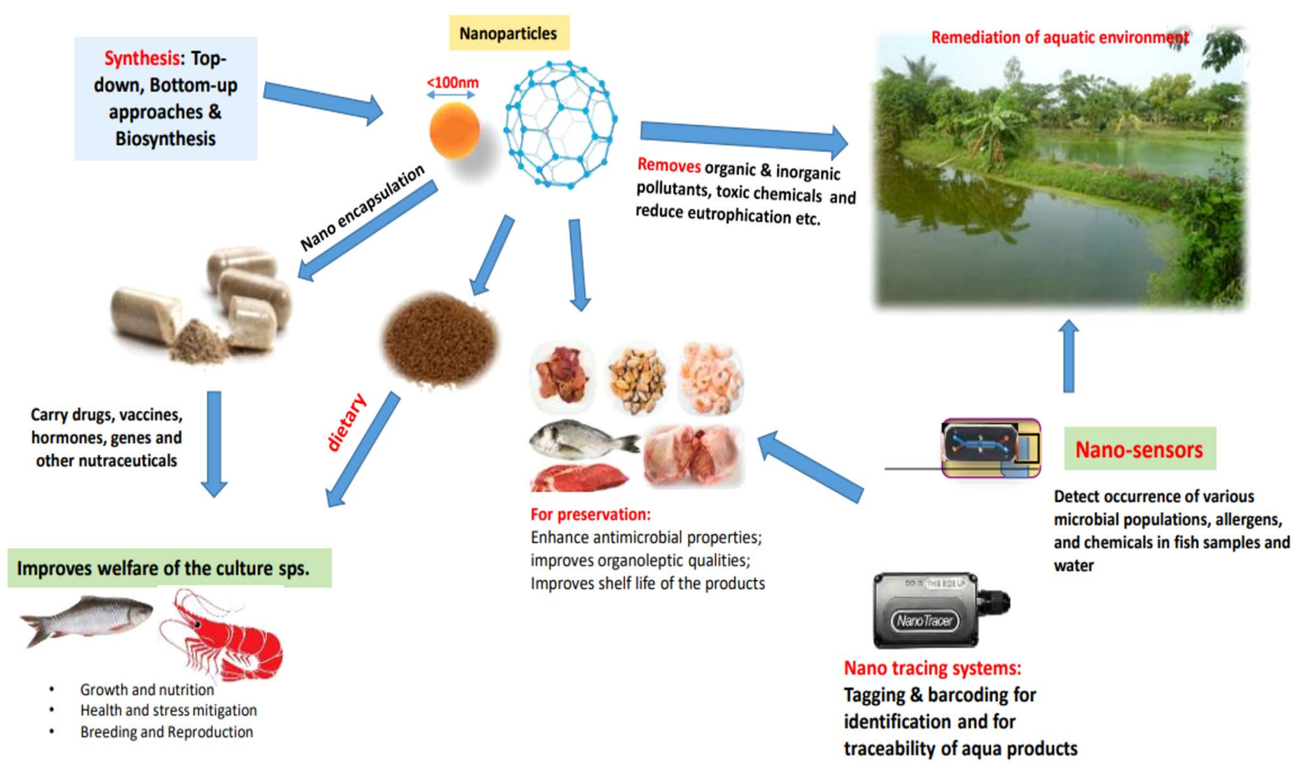

Fig. 2 Utilities of nanoparticles in aquaculture and fisheries sectors

platensis and chitosan nanoparticles could improve the growth performance and nutritional contents. This supplementation, however, significantly increased the protein and fat content of the shrimp's body. Nevertheless, alone supplementation of 1% nano *Arthrospira platensis* (NAP) to shrimp (*Litopenaeus vannamei)* can also improve growth performance, feed utilization, and various growth-related gene expressions compared to the control groups (Sharawy et al. 2022).

Selenium (Se) is considered one of the essential trace elements for animal life. Compared to inorganic and organic forms of selenium, the novel nano form is more studied because of its higher bioavailability and low toxicity (Khurana et al. 2019; Sun et al. 2022). Khosravi-Katuli et al. (2017) have summarized various benefits to aquatic species and cattle by using Se nanoparticles in reproduction, digestion, development, immunomodulation, and toxin concentration. Nano form of selenium helps in promotes body development by enhancing various growth parameters. For instance, a little (0.2 mg/kg) dietary inclusion of Se NPs results in superior weight gain, growth rate, and feed coefficient. It also increases fish resistance to illness and the effects of hypoxia (Qin et al. 2016). Studies have found that adding nano-Se and seleno-methionine in feed increases the final weight and relative growth rate and boosts antioxidant status, GSH-Px activity, and muscle Se concentrations in fish, helping in stress mitigation (Handy et al. 2012; Sekhon 2014). Likewise, a blend of Se-NP and Zn-NP supplied via feed have synergistic effects and boosts the growth performance, feed utilization, immunological responses, oxidative stress responses, and intestinal histomorphology of fish (Ghazi et al. 2021). However, another essential element, zinc, also plays a significant role in living organisms' body growth. Swain et al. (2018) have reported that the dietary supplementation of feed composed of 10 mg/kg of ZnO-NPs and 0.3 mg/kg of Se-NPs to the fish (*L. rohita*) improved its growth performance by boosting various enzyme activities and also promotes the non-specific immune response in fish. While in shrimp (*Litopenaeus vennamei*), Karamzadeh et al. (2022) have observed that when compared to Se-NPs or Zn-NPs given alone, co-supplementation of these two NPs results in improved performance, antioxidant status, and immunological responses. Furthermore, iron also shows synergistic effects with selenium when supplied both in a nano form, enhancing the welfare of the culture species. Studies revealed that a blend of iron (Fe) and selenium (Se) nanoparticles supplied through diet have growth-promoting effects in fish (Fonghsu et al. 2008; Frederick et al. 2010).

Many studies have revealed that nano forms are more efficient than bulk ones. Further, Behera et al. (2013) reported that supplementing both the Nano-Fe and ferrous sulfate in the basal diet has improved the welfare of fish by increasing final body weight, improving various antioxidant enzymatic activities, and also stimulating hematological and immunological markers in *Labeo rohita*. But in addition to that, the nano-Fe supplement also increased the muscle iron and hemoglobin content more effectively than the bulk form, ferrous sulfate. When fed with iron nanoparticles, it dramatically boosts the growth rates, likewise in juvenile carp by 30% and sturgeon fish by 24% (ETC 2003). Akter et al. (2018) reported that the optimal dosage of iron NPs for dietary inclusion is about 40 mg/kg feed would be more advantageous in improving the growth and health of fish (*C. batrachus*). Nonetheless, using more than the specified dose may negatively affect growth. Meanwhile, Elabd et al. (2022) have found that the nano iron oxide (nFe_2O_3) incorporation at a dose of up to 1 g/kg feed also shows good results such as improved growth, hemato-biochemical parameters, immune response, antioxidative profiles, and related gene expression in fish, *O. niloticus.*

Similarly, nanoparticles are very prominent in crustacean species. Also, Satgurunathan et al. (2022) have recently observed the growth-inducing effects of green-synthesized selenium nanoparticles derived from garlic cloves in *Macrobrachium rosenbergii*. The results showed a significant rise in protein, essential amino acids, lipids, monounsaturated fatty acids, polyunsaturated fatty acids, carbohydrates, and ash contents in the shrimp feeding with GBGS-SeNPs. These findings indicate that GBGS-SeNPs potentially stimulate prawn growth. Furthermore, nanoparticles such as Cu-NPs were reported for their growth-inducing effects in post-larvae (PL). Cu-NPs at 20 mg/kg would enhance survival, growth, and immune response in *M. rosenbergii*, but at higher concentrations, it may cause toxicity (Muralisankar et al. 2016); however, to counteract these toxic effects, Satgurunathan et al. (2018) suggested that feeding Cu NPs-enriched Artemia nauplii resulted in significant improvements in nutritional indices like growth and survival, as well as concentrations of tissue biochemical constituents like total protein, amino acid, carbohydrate, and lipid of M. *rosenbergii* post-larvae. In prawns, *Macrobrachium rosenbergii*, supplementing a post-larval diet with nano magnesium oxide (Srinivasan et al. 2016) and manganese oxide nanoparticles (Asaikkutti et al. 2016), promotes survival and growth performance and improves dietary enzyme activities. Few other nanoparticles, such as chromium oxide (Cr_3O_4) and cobalt oxide (Co_3O_4), are efficient in increasing the protein content of *Labeo rohita* (Kanwal et al. 2019).

Therefore, incorporating minimal amounts of nanoparticles into the diet improves aquatic animal's welfare. Recently, several chemical companies have started producing nutrients using nanotechnology in aquaculture. Filo Life Sciences, a nanotech-based company in India, manufactures various essential nutritional and nutraceutical products such as ColloidAG Aqua (nanosilver), Fabgrow

Aqua (nano polyunsaturated fatty acids), Nanomin Aqua (nano trace minerals), NanoCAL Aqua (nano calcium), and NanoPHOS Aqua (nano phosphorus) (Sarkar et al. 2022).

Health and immunity

Aquaculture faces many severe challenges from pathogens like bacteria, fungi, and viruses. However, controlled traditionally by using chemical disinfectants and antibiotics (Huang et al. 2014) but develop resistance. Bacterial diseases are the most common cause of death in aquaculture, mainly in hatcheries. The water source used and the feed given to the fish play a role in determining the prevalence of bacteria in aquaculture (Jamabo et al. 2019). Over many decades, antibiotics have been used to treat bacterial diseases. Nonetheless, if antibiotic usage is not strictly regulated, bacteria immune to antibiotics can evolve (Pelgrift et al. 2013; Cabello et al. 2013).

In recent years, antibiotic resistance has persisted and even increased due to the overuse of antibiotics. Antibiotic resistance occurs when bacteria acquire the ability to resist the medications designed to kill them (Perez-Sanchez et al. 2018). Many antibiotic-resistant bacterial strains emerged, like Methicillin-resistant *Staphylococcus aureus* (MRSA) and other multi and super-drug-resistant bacterial strains (Atyah et al. 2010; Davies and Davies 2010). Furthermore, several *Aeromonas hydrophila* isolates from captive tilapia were resistant to broad-spectrum antibiotics such as tetracycline, streptomycin, and erythromycin. Some others include *Aeromonas salmonicida, Photobacterium damselae* subsp. *piscicida, Yersinia ruckeri, Vibrio, Listeria, Pseudomonas*, and *Edwardsiella* species were antibiotic-resistant (Swain et al. 2014; Wu et al. 2020; Sherif et al. 2020).

However, extraordinary new opportunities have emerged with the development of nanotechnology for increasing productivity and preserving the health of aquatic species (Can et al. 2011). While antibiotic-resistant bacteria are a growing problem in aquaculture, researchers are investigating using nanoparticles as an alternative antimicrobial (Shaalan et al. 2016). In particular, metal nanoparticles have attracted much interest as potent antibacterial agents because of their wide-ranging antimicrobial action, stability, resistance, selectivity, and specificity (Swain et al. 2014). These perform antibacterial activity by forming oxygen species around the bacterial cell and causing cell rupture, especially against *E. coli* and MRSA (Das et al. 2017). Various nanoparticles, such as nano-silver and nano-zinc oxide, were already being used because of their antimicrobial and prophylactic characteristics in reducing the prevalence of pathogens in aquaculture (Siddiqi et al. 2018).However, silver nanoparticles (AgNPs) have a broad range of activity and work on various bacteria, fungi, parasites, and viruses by disrupting the enzymes required for their metabolism (Selvaraj et al. 2014; Ghetas et al. 2022; Jhanani et al. 2021). Studies found that Silver NPs can significantly reduce the growth of many studied isolates of disease-causing micro-organisms such as *Lactococcus garvieae*, A. *hydrophila*, *Streptococcus iniae* as well as *Yersinia ruckeri* after 30 to 90 min of exposure (Soltani et al. 2009), and a few antibiotic-resistant bacteria such as *Aeromonas veronii* and MRSA (Methicillin-Resistant *Staphylococcus aureus*) can also be eliminated (Elgendy et al. 2021; Masimen et al. 2022). However, a dose of 0.8 mg/L AgNPs can improve the immune functions suppressed by *Aeromonas hydrophila* in Nile tilapia (El-Houseiny et al. 2021). Likely a dose of 100 µg/L AgNPs in water was effective against *Flavobacterium johnsoniae* infection in common carp (Shalaan 2020). Li et al. (2015) reported that Ag_3PO_4-loaded hydroxyapatite nanowires could prevent the growth of *E. coli* and S. *aureus* in water systems to a significant amount. Moreover, Silver (Ag) NPs considerably improve the survival and tolerance against vibriosis disease in shrimps such as *Penaeus monodon* (Kandasamy et al. 2013).

Recently, researchers have reported that a 2.5 ppm dose of a copper nanoparticles-chitosan composite (CuCS) is very effective in combating the *Vibrio parahaemolyticus*, which causes Early Mortality Syndrome (EMS) in shrimp (Nguyen et al. 2020). Similarly, Behera et al. (2013) have reported that supplementing Nano-Fe and ferrous sulfate in the basal diet improves the immunity in *Labeo rohita*. The nano form of iron (Fe) supplement elevates muscle iron and hemoglobin content more effectively than ferrous sulfate. Therefore, it may help treat anemia disease in fish.

Recent studies revealed that nanoparticles are highly efficient when applied directly to water (Johari et al. 2015; Kalatehjari et al. 2015). A silver nanoparticle-coated water filter can mitigate fungal infections in rainbow trout aquaculture (Johari et al. 2015). Similarly, in-vitro application of nanoparticles, such as colloidal nano-copper particles at a concentration of 10 ppm, can inhibit fungus growth, such as Saprolegnia sp. Therefore, Cu NPs act as potential antimicrobial agents by applying them to the structural system of aquaculture equipment like fiberglass troughs, rearing tanks, and hatchery apparatus (Kalatehjari et al. 2015).

Pesticide-laden runoff from agriculture is a major issue in the aquaculture sector. Nevertheless, nanoparticles would help to decrease the adverse effects of these chemicals. For example, the pesticide imidacloprid causes toxicity in aquatic organisms. According to a study, vitamin C and chitosan nanoparticles can attenuate the adverse effects via immuno-modulation when provided in combination. When fed as a supplement, this combination promotes growth and feed utilization. It also improves the antioxidative state and non-specific immunity in *O. niloticus* when exposed to sub-lethal imidacloprid concentrations (Naiel et al. 2020). Similarly, dietary supplementation of zeolites, either alone or in conjunction with chitosan nanoparticles, also reduces the toxicity induced by imidacloprid exposure (Ismael et al. 2021).

Furthermore, heat stress is one of the critical causes of death in most aquatic organisms. It reduces animal productivity, damages vital organs (such as the liver), and may lead to sudden death (Yin et al. 2018). However, using nanoparticles such as Selenium (Se) NPs has been shown to preserve the hepatocytes in cold-water fish like rainbow trout. In mild heat stress, these nanoparticles have synergistic effects and activate the pathway that produces heat shock proteins (HSPs) in response, resulting in elevated levels of HSP expression. Thus, nanoparticles act as potential therapeutic agents by protecting the cells from heat damage (Sun et al. 2022).

Breeding and reproduction

Like other organisms on planet Earth, reproduction is crucial to the viability of the fish population. With the advancements in aquaculture practices, the number of aquatic species for domestication is increasing, and controlled reproduction plays a vital role in maintaining sustainability (Duarte et al. 2010; Pei et al. 2014). Controlling fish reproduction can be accomplished by using steroid hormones, but these compounds have an unfavorable effect on fish consumers (El-Greisy and El-Gamal 2012). Nevertheless, the potential benefits of nanotechnology are becoming more considerable in the reproduction and breeding of fish. Nanotechnology currently finds its applications in delivering various drugs, vaccines, genes, and hormones in fish to progress gonadal development, induce breeding, or enhance the reproductive output (Wu et al. 2020). Multiple applications of NPs in the realm of fish breeding and reproduction are listed out in the following Table 2. Many nanoparticles such as nano-chitosan, PLGA NPs, selenium NPs etc. have great role in reproductive success of fish. These NPs are supplemented directly through the feed, injection or immersion method. Few were also been conjugated with other substances for their efficient delivery into the fish (Sharma et al. 2014; Bhat et al. 2019; Kookaram et al. 2021; Hajiyeva et al. 2022a, 2022b).

Nano delivery systems in aquaculture

Substances such as drugs, genes, nutraceuticals, vaccines, etc., are delivered into the organism's body by encapsulating with the nanoparticles, a process known as 'Nano-encapsulation.' It is a technique of enclosing materials using films, layers, or nano-dispersions on a nanometer scale. The resulting capsule provides a nanoscale barrier for the food, nutraceutical, or ingredient contents (Jafari 2017). Therefore, it makes the ingredients available more readily and accessible by loading them onto a food product (Veisi et al. 2021). Encapsulation ensures a site-specific, controlled release of hydrophobic (lipophilic) and hydrophilic (lipophobic) molecules into a food preparation system (Toniazzo et al. 2014). However, nanoparticles ensure a high potential to direct molecules to specific target organelles, hence having increased usage in drug delivery, illness screening, and tissue engineering (Mirza and Karim 2021). Recent studies have demonstrated that numerous bioactive compounds, including phenolics, essential oils, carotenoids, and vitamins, can be successfully encapsulated and distributed more efficiently in aquatic feeds by using nanostructures like nano-hydrogels and nanofibers generated from natural biopolymers (Muller and Keck 2004; Akbari-Alavijeh et al. 2020; Oliveira Lima et al. 2021). Mostly chitosan, a naturally occurring biodegradable polysaccharide, is used as encapsulating agent. Because of its non-toxic, biocompatible, and mucus-adherent nature, allowing an efficient drug delivery capacity (Alishahi et al. 2011; Vendramini et al. 2016).

Moreover, the free amine groups in chitosan allow a more robust cross-linking reaction, aiding a very efficient encapsulation process (Liu et al. 2014). Nano chitosan form has emerged as a preferred vector for delivering therapeutic agents and genetic material in aquaculture (Ji et al. 2015). Likewise, several nanoparticles were used in aquaculture to deliver various compounds efficiently.

Nano delivery of drugs

To be effective, a drug delivery system must regulate the rate at which the drug is released and transported to the target site of action (Mirza and Karim 2021). However, nano-encapsulation increases drug stability, regulates the interaction with the food matrix, and protects the drug from moisture and heat (Ubbink and Kruger 2006). Few hydro-soluble micronutrients, such as vitamin C, can be significantly delivered with increased stability and shelf life by using nano chitosan as a carrier in rainbow trout (Alishahi et al. 2011).

Oxytetracycline is one of the most widely used antibiotics in aquaculture. However, it accumulates ten times higher in zebrafish when delivered using synthetic iron oxide NPs than via water (Chemello et al. 2016). Whereas, Nano-chitosan-loaded clinoptilolite at a dose of 0.05 g/kg was reported to stimulate growth and strengthen the immune systems of rainbow trout (KhaniOushani et al. 2020). Similarly, when *Thymbra spicata* plant extract is loaded on chitosan NPs for carrying, it increases the extract's efficacy. It enhances

Table 2 Potential uses of nanoparticles in aquaculture and fisheries

S.no.	NP's	Size	Purpose	Delivering/conjugated substances	Species	Observed results	References
1	Chitosan NPs	157 nm	Reproductive performance	Pheromones, 17 20 dihydroxy-4-pregnen-3-one (17a 20b P), and prostaglandin F 2	Indian catfish (*Clarias batrachus*)	Serum reproductive hormones i.e., FSH and LH are sustained for a longer period	Sharma et al. (2014)
		136 nm	To extend hormone retention duration in blood	GnRHa	Goldfish (*Carassius auratus*)	Improved egg diameter and ovarian development	Kookaram et al. (2021)
		133 nm	Reproductive performance and gonadal development	LHRH	Indian catfish (*Clarias batrachus*)	sLHRH treatment increased Sox9 mRNA expression and the chitosan nanoparticles uphold the drug's surge.	Bhat et al. (2016)
		125 nm	Reproductive maturation	kisspeptin-10	Catla (*Labeo catla*)	Enhanced the mRNA expression of reproductive genes and serum hormones for longer periods; improved ovarian development; increase the shelf life of the kisspeptin 10 peptide	Rather et al. (2016a, b)
		47.6 nm	Gonadal development	FZ and letrozole (LZ)	Male Indian catfish (*Clarias magur*)	Improved testicular development	Wisdom et al. (2018)
		127 and 126.2 nm	Testicular development	17α-methyltestosterone	C. *magur*	Compared to non-injected groups the treated are show better gonadal development	Saha et al. (2018); Bhat et al. (2019)
2	Poly lactic-co-glycolic acid (PLGA) NPs	136 nm	All-male population	fadrozole (FZ)	Tilapia (*Oreochromis niloticus*)	Enabling less dosage application of FZ for maximal effects	Joshi et al. (2019)
		132 nm	All-male population	letrozole	Guppy (*Poecilia reticulata*)	At lower dosage levels showed higher male population	Joshi et al. (2015)
3	Selenium NPs	80–250 nm	Reproductive performance		Rainbow trout (*Oncohynchus mykiss*)	Enhanced sperm quality, egg quality, fertilisation rate, hatching rate and larval survival	Jahaabad et al. (2020); Jehanabad et al. (2019)
4	Fe_3O_4 NPs	20–30 nm	Reproductive performance		Common carp	Increased semen parameters, egg quality, embryonic development and hatching rate	Hajiyeva et al. (2022a)

Table 2 (continued)

S.no.	NP's	Size	Purpose	Delivering/conjugated substances	Species	Observed results	References
5	Aluminium NPs	18 nm	Reproductive performance		Rainbow trout	Improved the fertilisation rate and hatching rate	Hajiyeva et al. (2022a)

growth, blood parameters, immunity, and stress response in rainbow trout (Ghanbary et al. 2022).

Recently, a USA-based company, Bio Delivery Sciences International (BDSI), has developed a new drug delivery device, the Bioral® (a Nanocochleate Delivery System). Bioral® can encase a drug without chemically adhering to it, protecting it so that it can be taken orally instead of intravenous injection (Aklakur et al. 2015).

Nano delivery of vaccines

Vaccines stimulate the immune system to induce protection and immunity against pathogens (Sahdev et al. 2014). Vaccination is a proven, low-cost strategy that has gained widespread acceptance in aquaculture during the last two decades. However, nano vaccination is a novel approach for bulk immunization in the aquaculture industry (Assefa and Abunna 2018). Because traditional vaccines typically affect the whole body, whereas nano-vaccines target the specific area of the body where the illness or infection first appeared (Gheibi Hayat et al. 2019). Nano-vaccines protect antigens from degrading, stabilize medicinal substances such as peptides, proteins, and nucleic acids, and minimize vaccination dosages (Shahbazi and Santos 2015).

However, gene therapy involves altering the expression of a gene or influencing the biological properties of living cells and helps induce therapeutic effects (Eugene et al. 2001). For effective response to obtain, using the non-viral delivery methods would be more beneficial than the viral ones because of their more reliability and larger scale applicability (Yang et al. 2015). Since nanoparticles facilitate easy gene transfer and effective responses, they are more suitable for application in aquaculture. DNA vaccines delivered by the nanoparticle carriers such as chitosan and polylactide-co-glycolide acid (PLGA) can significantly protect against bacterial infections and some viral illnesses with vaccine-induced side effects (Rajesh Kumar et al. 2009).

In fish, nano chitosan tripolyphosphate were used for efficient delivery of DNA vaccines (Vimal et al. 2012). Because, chitosan NPs increases the efficacy of vaccines when administered in conjugation with DNA complexes made of lipids, proteins, and ligands (which drive the DNA complex to receptors on the surface of target cells and DNA into the nucleus) (Roy et al. 1997). A successful oral vaccination was reported in Asian sea bass (*Lates calcarifer*) using a nano-chitosan& DNA vaccine complex provided through feed, but the fish shown only a moderate resistance to experimental *Vibrio anguillarum* infection (Kumar et al. 2008). Whereas the oral vaccination in Atlantic salmon against Infectious Salmon Anaemia Virus (ISAV) using nano chitosan loaded with DNA encoding for the replicas of alphavirus as adjuvant and an inactivated ISAV showed more than 77% protection against the disease (Rivas-Aravena et al. 2015). However, high levels of protection against A. *hydrophila* are observed on supplying single-wall carbon nanotubes (SWCNTs) loaded with DNA vaccine due their more robust immunological response than free vaccine in fish (Zhang et al. 2019; Gong et al. 2015; Liu et al. 2016). Furthermore, functionalized SWCNT loaded with a KHV ORF149 gene expression vector provides long-lasting and substantial protection to koi fish against a KHV challenge. Intramuscular administration of 10 µg of SWCNTs-p149 is the most effective treatment for eliciting maximum immune protection (Hu et al. 2020). Few modified nano-clay, such as chitosan functionalized halloysite nanotubes (HNTs), can be a carrier for whole-cell inactivated vaccines against *streptococcus* infection in tilapia, on altering their structure into a hollow and tubular shape used for oral vaccination. These HNTs provide higher vaccine bioavailability and improve vaccine loading efficacy and immunological response against disease (Pumchan et al. 2022).

According to a study, shrimp challenged with white spot syndrome virus have shown positive response to dietary supplementation of DNA vaccines encapsulated with nano chitosan (Rajeshkumar et al. 2009). The DNA–chitosan complex provided with appropriate ligands transport genes more effectively via receptor-mediated endocytosis than with chitosan used alone (Murata et al. 1997). In *Penaeus monodon*, on administrating dsRNA using a chitosan-dextran sulphate and silica nanoparticle complex as carrier vehicle suppresses the structural gene (p74) and thus helps in controlling the effect of Monodon baculovirus (MBV) (Ramesh Kumar et al. 2016). Similarly, Ramya et al. (2014) also reported that providing M. *rosenbergii* with an extra small virus antisense (XSVAS) gene of nodavirus encapsulated with chitosan nanoparticles in the DNA construct increases the survival tolerance against nodavirus. Therefore, compared to the synthetic vectors, using nanoparticles as a gene-delivery vehicle in vivo appears to be more advantageous (Rajeshkumar et al. 2009; Vimal et al. 2012; Ramya et al. 2014; Rivas-Aravena et al. 2015; Ramesh Kumar et al. 2016; Hu et al. 2020).

According to a report from the ETC group, the USDA is working on a fish vaccination technique that uses ultrasound to break open the nanocapsules containing short strands of DNA so that the fish can easily absorb the DNA. Through this, an effective immunological response can be induced to help in the mass vaccination of fish. Clear Springs Foods, a company in the United States, has tested this method on rainbow trout and is now selling it to the public (ETC 2003; Mongillo 2007).

Nano delivery of nutraceuticals

Encapsulating technologies are also widely used in the field of nutraceuticals. The term "nutraceutical" refers to any food or component of food apart from its nutritional value; it also provides extra health benefits and plays a crucial role in the disease-prevention (Brower 1998). Most nutraceuticals are administered orally because certain lipophilic compounds cannot be digested in the digestive tract and must be supplied via specialized carrier systems (Subramanian 2021). Developing nano-delivery technologies for these substances may address the obstacles of commercializing them in aquaculture. These nano-formulations of feed maintain the consistency and flavour of the feed more efficiently (FOE 2008).

Many products are currently in the market that utilizes advanced nutraceutical delivery systems. Some of these include Ubisol-AquaTM Delivery System Technology developed by an American company Zymes LLC (Limited Liability Company), the NovaSOL® Delivery System Technology developed by a German company AQUANOVA, and the Nano-sized Self-assembled Structured Liquids (NSSL) technology, developed by an Israeli company Nutralease (Agrifood market report 2010).

Nano-sensing devices in aquaculture and fisheries

Sensors are devices capable of detecting and measuring the presence of contaminants in a sample using receptors and transducers. In biosensors, the acceptor is a biological element (Huang et al. 2021).The use of nanostructures in biosensors gives rise to the term "Nano-biosensors". These were characterized by a high degree of sample stability, contributing to their high efficiency and sensitivity levels (Huang et al. 2021). Nano-sensing devices are potentially used in fisheries and aquaculture to detect the occurrence of various contaminants like microbial populations, allergens, and chemicals in fish samples and water (ETC 2003; Marzuki et al. 2012; Yu et al. 2014; Teymouri and Shekarchizadeh 2022). According to a report from ETC (2003), NASA researchers developed a sensitive carbon nanotube-based biosensor that can detect minute amounts of bacteria, viruses, parasites, and heavy metals in water and food. Similarly, to detect the allergens (histamine) and toxins present in water and food products, Northwestern Engineering and Iowa State University researchers also developed a biosensor based on graphene nanoparticles.

Nevertheless, the nano biosensors are also helpful in determining the freshness of a fish sample. Several different compounds, amines, and poisons are detected. Due to its widespread usage as a preservative in fish transportation, formalin appears to pose the greatest threat to the safety of fish consumed by humans. According to a market survey conducted by Uddin et al. (2011) in Bangladesh, around 50% of total fish samples showed formalin contamination, with 70% being rohu (*L. rohita*) exclusively. However, a formaldehyde nano-biosensor was developed to solve this problem using an enzyme, formaldehyde dehydrogenase, and nanomaterials (carbon nanotubes, chitosan) to precisely detect this upcoming threat to human health. This sensor has a quick response time (5 s), a higher sensitivity (1–10 ppm), and can be used repeatedly (Marzuki et al. 2012).

The aqua drugs such as triphenylmethane dyes, crystal violet and malachite green, and the antibiotic furazolidone were once widely used in aquaculture due to their potential against many bacterial, fungal, and parasitic diseases. These chemicals are banned in many countries due to their genotoxicity, carcinogenicity, and many other adverse effects; however, these are still used illegally in some parts of the world (Olivera Conti et al. 2015; Srivastava et al. 2004). In this case, using nanosensors to detect these chemical compounds in fish samples or feed is very effective. The nano-sensitive detectors, such as Colorimetric biosensors, produce color gradients and visible color changes in response to antibiotic concentrations in aquatic settings or aquaculture. Because antibiotics like Tetracycline (TCs) have a high affinity for Fe (II) and Fe (III) and form complexes, Fe_3O_4 magnetic nanoparticles (MNPs) have been employed to construct colorimetric biosensors. When TCs are present in a solution, it produces a $TCFe_3O_4$ complex, facilitating H_2O_2 oxidation of 3,3′,5,5′-tetramethylbenzidine (TMB) to produce a dark visible solution. UV spectroscopy can quantify TCs and their derivatives in the medium with a detection limit of 12 to 48 nM (Wang et al. 2016).

Yu et al. (2014) have developed a sensor that is developed through incorporating Fe_3O_4/Ag hybrid NPs in SERS (Surface Enhanced Raman Scattering) substrates. Similarly, the residues of Crystal violet and malachite green present in fish samples were also traced by SERS using Silver -coated gold bimetallic nanoparticles as substrates (Pei et al. 2014). Moreover, to detect amines such as histamine and cadaverine that occurred in the fish samples, Hasanzadeh et al. (2013) have developed a sensor by employing Fe_3O_4 NPs along with cetyltrimethylammonium bromide and a stable magnetic mobile crystalline material-41. More recently, Teymouri and Shekarchizadeh (2022) have developed a colorimetric indicator based on copper nanoparticles (CuNP's) to detect volatile sulfur compounds in fish. The indicator's noticeable color changes are highly correlated with the quality of the fish. Colors that indicate the freshness of fish are white for fresh fish, yellow indicates partially fresh, and brown indicates spoiled fish. In innovative packaging, this indicator can be utilized; it is a simple, low-cost, and valuable technique to monitor fish deterioration in real-time, with color changes visible to the human eye (Teymouri and Shekarchizadeh 2022).

Besides the analytes, nanosensors were also used in the sex determination of fish. Esmaeili et al. (2017) have demonstrated about gender determination of Arowana fish (*Scleropages formosus*) using a DNA biosensor. He developed a sensor with a nano-biocomposite comprising kappa-carrageenan-polypyrrole-gold nanoparticles (KC-PPyAuNPs), forming this sensor's basis. The sensor is incorporated with a DNA probe sequence isolated from male arowana fish scales. However, when a test sample used is of male arowana fish, the hybridization between the probe and sample sequence occurs. In contrast, if the sample is of female arowana fish, the hybridization does not occur. Thus the gender of the fish can be detected using the nano-sensing device (Esmaeili et al. 2017).

Therefore, using Aquaculture nanotechnologies, for example, nano-porous structures to carry veterinary drugs directly and nanosensors for disease detection in aqua farming can influence aquatic animal health and well-being. Due to this reason, nanomaterials have proven to be very useful in many types of pond environments (Gustavo and Dominguez 2014).

Processing, preservation and quality control of aqua food products

Nanotechnology has many potential uses, including alternative conservation and packaging methods to ensure the quality and freshness of seafood by preventing the growth of harmful microorganisms (Can et al. 2011). Moreover, the rapid deterioration of fish's sensory qualities, such as color and flavor, can be delayed using nanostructures such as nanoparticles, nano-emulsions, and nanofibers (Chellaram et al. 2014; Ozogul et al. 2017; Rather et al. 2021; Handy et al. 2023). The nano-emulsions help in the effective reduction of microbial growth and also improve the organoleptic qualities in fish fillets (Ozogul et al. 2017). Similarly, when applied on the outer layer of fish, nanofibers are shown to have antimicrobial properties. They could be a novel method for preventing the spread of bacteria in fish products (Perreault et al. 2015). Moreover, few applications of nano sensors related to fish processing were also discussed in the above Sect. 2.3.

For example, Tilapia (*Oreochromis niloticus*) mince fortified with zinc oxide nanoparticles has a significant antimicrobial effect and raises dietary Zn requirement during storage at 4 ± 1 °C for 18 days. Therefore, adding zinc to tilapia mince is not only a beneficial food fortification strategy for preventing zinc deficiency but also improves the shelf life of the mince (Pati et al. 2022). Similarly, Wang et al. (2014) have demonstrated using chitosan nanoparticles for efficient shrimp quality retention during storage at 4 °C. They observed chitosan nanoparticles have improved the TVB-N levels, K values, TVC, hardness, and springiness of post-harvest shrimp, *Litopenaeus vannamei*. Chitosan (CH) also exhibits antimicrobial activity in shrimp; however, its large particle size slows its penetration rate into shrimp muscle tissues.

According to a study, vacuum tumbling with sonicated and ultra-sheared chitosan nanoparticle solution could prevent shrimp from spoiling due to microbial proliferation. Because of their small size, these are more effective at penetrating shrimp muscle during refrigerated storage. Thus, it helps preserve physicochemical properties by reducing aerobic plate counts and lipid oxidation during frozen storage (Chouljenko et al. 2016, 2017). Also, the consumers and producers would benefit from maintaining the quality of shrimp intact throughout the storage period and potentially extending the product's shelf life with this method (Chouljenko et al. 2017). Nanoparticles are having only a minimal applications in post-harvest technology; hence, more investigation of their applications in this area is required.

Nano tracing systems in aquaculture and fisheries

At each stage of the seafood supply chain, it is often required to use trustworthy technologies to validate species identity because the raw species are no longer identifiable by simple 'morphology-based' inspection (Maggioni et al. 2020). Nano tagging and nano barcoding were employed to trace a product or to monitor aquatic organisms' metabolism, swimming patterns, and feeding habits. Likewise, a Radio Frequency Identification (RFID) chip contains an identifying code fused with a nanoscale component and carries information. The code can be scanned from a distance and included in the product to identify anything automatically. However, to encode the data, a metallic stripe with nanoparticles embedded in it is striped with different patterns, thus creating a "nano-barcode" (Rather et al. 2011). Nano barcoding helps to keep an eye on where the aqua product is coming from and where it is going, all the way to your customers' doors. When used in conjunction with color-coded probes and synthetic DNA, a nano-barcode device could also identify infections and monitor changes in temperature, leakage, and other factors that affect product quality (Rather et al. 2011).

Food product substitutions can be quickly and easily identified using a combination of DNA-based and nano-biotechnology methods. In recent times, Valentini et al. (2017) devised an efficient calorimetric-based method to detect adulteration and substitution in high-priced fish and spices called "Nano-Tracer". DNA barcoding and nanoparticle-based naked-eye detection together form the basis of this system (Valentini et al. 2017). It is also applied successfully to authenticate commercially available cuttlefish (*Sepia officinalis*) (Maggioni et al. 2020). However, Nano-Tracer enables a simple, rapid, inexpensive (less than 1€ each test), and analytically uncomplicated molecular tracing of food. Therefore, researchers suggest that the method could be used for various seafood and other foods (Valentini et al. 2017; Maggioni et al. 2020).

Nano-remediation for aquatic environment management

Rapid industrialization, urbanization, advances in agricultural methods, and economic development in the last few decades have all put significant strain on the world's water resources and environment (Alcamo et al. 2017); consequently, the present unconventional water sources are frequently contaminated with a wide range of pollutants (Bora and Dutta 2014). However, nano-remediation is a cutting-edge cleanup method that makes use of nanomaterials. It provides many novel solutions for rapidly and effectively removing pollutants from a contaminated environment (Das et al. 2019). Many studies have reported on the remediation of aquatic systems using various nano adsorbents. It is also expected that nano adsorbents will play significant roles in maintaining the aquatic environment because of their ability to effectively remove any types of pollutants from contaminated water while also minimizing the formation of secondary waste using fewer resources (Kurniawan et al. 2012). For example, carbon nanotubes (CNTs) are highly efficient at removing inorganic and organic pollutants from water (Gupta and Saleh 2013). Inorganic pollutants like lead, Pb (II), and cadmium, Cd (II) are efficiently removed from water by using Fe_3O_4/CSNPs, a nanoparticle composite of magnetite and chitosan (Fan et al. 2017). However, sulfonated magnetic NPs are also highly effective at adsorbing Pb (II) and Cd (II) due to their active Sulphur group, demonstrating a 99% adsorption rate within 24 h of contact (Chen et al. 2017). Similarly, arsenic could be removed from water using NPs made of synthetic cobalt and manganese ferrite nanoparticles (Martinez-Vargas et al. 2017).

Organic pollutants like ammonia, nitrites, and nitrates are efficiently removed by using a combination of zeolite and iron-containing compounds, along with a small amount of activated carbon or alumina nanomaterials, which could be employed in aquaculture to maintain aerobic and anaerobic biofilms (Gillman 2006). Also, iron nanoparticles can eliminate chemicals like trichloroethane, C_2Cl_2, dioxins, and PCBs from water (Duke et al. 2013).

However, the major problem in aquaculture is eutrophication, which occurs when phosphorous loads are increased and promotes the expansion of algal blooms (Sarkar et al. 2022). For removing phosphates from the water and inhibiting algae development, a lanthanum-based chemical at a 40 nm particle size can be used (Mongillo et al. 2007; Rather

Table 3 Adverse effects of nanoparticles on aquatic organisms

Nanoparticles	Species	Observed effects	References
Carbon nanotubes (CNTs)	*Channa punctatus*	Decreased glutathione-s-transferase enzyme activity and increased lipid oxidation	Ali et al. (2019)
	Danio rerio and Astyanax altiparanae	oxidative stress & neurotoxicity at sub chronic and acute exposure	Cimbaluk et al. (2018)
Silver (Ag) NPs	Rock oyster (*Saccostrea glomerata*)	Increased DNA and lipid oxidation and changes in antioxidant defenses	Carrazco-Quevedo et al. (2019)
	Zebra fish	Histopathological alterations in liver; lipid localization and transportation and cellular response to chemical stimulus and xenobiotics alterations in liver	Lacave et al. (2017)
	Juvenile Salmon	Necrosis of gill lamellae, increased stress molecule HSP 70 levels and mortality at high concentrations	Matranga et al. (2012)
	Sphaerium corneum	Considerable ROS production and antioxidant enzyme activity at lower concentrations.	Völker et al. (2015)
	Labeo rohita	Increase in anti-oxidative enzymes, histological abnormalities and reduction of haemotological markers	Rajkumar et al. (2016)
	Danio rerio	Liver, gut, and gill accumulates the most silver nanoparticles after oral ingestion; humic acid and fulvic acid decreased silver nanoparticle uptake.	Xiao et al. (2020)
	D.magna and *Thamnocephalus platyurus*	Negative effects on the growth	Blinova et al. (2013)
	Cyprinus carpio	Histopathological alterations; gill tissue necrosis	Kakakhel et al. (2021)
ZnO NPs	*Macrobrachium rosenbergii*	Reproduction, offspring development, X-organ CHH release, and antioxidant enzyme activity	Tavabe et al. (2020)
	Labeo rohita	Oxidative stress in terms of superoxide dismutase, lipid peroxidation, and catalase	Aziz et al. (2020)
	Rainbow trout	Oxidative stress in the liver and EROD activity and disrupt cytochrome P450 metabolism.	Connolly et al. (2016)
Au NPs	*Sparus aurata*	Genotoxicity at cellular and molecular level	Barreto et al. (2019)
	Sparus aurata juveniles	Apoptosis and liver damage; alterations in gene expression, oxidoreductase activity and immunomodulation	Teles et al. (2019)
Ceric Oxide NPs	*P. lividus*	Complete mortality at 10ppm/2days	Falugi et al. (2012)
	Artemia salina	Behavioral changes in swimming and elevated cholinesterase activity	Gambardella et al. (2014)
Cu NPs	*Labeorohita*	Oxidative stress and genotoxicity	Aziz and Abdullah (2023)
	M. *galloprovincialis*	Genotoxicity	Gomes et al. (2013)
	Rainbow trout	Olfactory dysfunction	Razmara and Pyle (2022)
Copper oxide NPs	Crab, (*Carcinus aestuarii*)	Iono-regulatory and osmoregulatory toxicity, inhibits Na+, K+-ATPase activity in gill, reduction of ion concentrations in hemolymph and carcass	Gürkan (2018)
	Guppy	Changes in skin colour to dark, stress and dying with an open mouth observed.	Forouhar Vajargah et al. (2019)

Table 3 (continued)

Nanoparticles	Species	Observed effects	References
Fe NPs	Zebra fish	Mortality, hatching delay, and malformation of embryo.	Zhu et al. (2012)
	Crab, (*Carcinus aestuarii*)	changes in antioxidant enzyme activity and lipid peroxidation	Gürkan (2018)
Plastic (polystyrene) NPs	Crucian carp (*Carassius carassius*)	Brain damage and behavioural changes in fish	Mattsson et al. (2017)
	Litopenaeus vannamei	Growth inhibition, intestinal and hepatopancreatic tissue damage, altered gene expression associated with immunity, and intestinal microbiota dysbiosis	Zhu et al. (2022)
Al_2O_3 NPs	*Cyprinus carpio*	Oxidative stress	García-Medina et al. (2022)
	Dunaliella salina	Inhibit the growth of*Dunaliella salina*	Shirazi et al. (2015)
	Zebra fish	Oxidative stress and disruption of dopaminergic transmission	Chen et al. (2020)
	larval zebrafish	DNA damage, and change the stress-related gene expression	Boran and Şaffak (2020)
	Oreochromis niloticus	Hepatic tissue degeneration	Murali et al. (2017)
Titanium oxide (TiO_2) NPs	*Oreochromis niloticus*	Oxidative stress; mostly affect gills	Firat and Bozat (2018)
	Zebra fish	Inhibition of growth and reduced liver weight	Shah et al. (2017)

et al. 2011; Sarkar et al. 2022). Based on this solution, "Altair Nanotechnologies (Nevada, USA)" has developed a water-purifying product called "Nano-check" for use in fish ponds to reduce eutrophication caused by algal blooms (Rather et al. 2011; Kumar et al. 2019). Nonetheless, developing a nanoscale delivery of weedicides and soil-wetting agents would be effective, particularly for aquatic weed management in large water bodies and mitigating climate change's effects and pollution on aquatic ecosystems.

Consequences of nanotechnology (nano toxicity)

Besides contributing significantly to the development and success of aquaculture and fisheries, there are mounting evidences that nanotechnology-based materials and products have devastating effects on both human and environmental health (Shah and Mraz 2019). Nanoparticles enter the aquatic environment through industrial release, dumping wastewater treatment effluents, and soil surface runoff. In the aquatic system, they undergo aggregation and sedimentation with other suspended particulate matter, organic materials, and colloids in the water (Rocha et al. 2015). However, when NPs mixed with other substances in water, they are more likely to become entangled with other solids rather than distributed in aqueous suspensions (Grillo et al. 2015). The degree of aggregation of NPs in water is influenced by the particle parameters such as size, type, and surface area and the aquatic system variables such as ionic strength, pH, and dissolved organic carbon content (Baker et al. 2014). These nanoparticle aggregates show harmful effects on the aquatic flora and fauna.

In a few studies, aquatic animals exposed to NPs have been shown to suffer from adverse effects such as DNA damage and mortality, as well as oxidative stress and growth reduction (Baker et al. 2014; Grillo et al. 2015; Rocha et al. 2015). Due to their toxicity, some nanoparticles, such as Carbon nanotubes (CNT), cause physical and oxidative stress in the organism's body. It has also been shown that CNT exposure adversely affected marine species' larvae (Kwoket al. 2010). In several freshwater crab species, carbon nanotubes and their metabolites have been linked to an increased risk of death (Khalid et al. 2016).

Many studies have found that nanoparticles have a broad spectrum of toxic effects on aquatic microbes. When entered into an aquatic system, engineered nanomaterials, even at very low concentration can disrupt the cell membranes and destroy the aquatic bacteria (Tong et al. 2015; Li et al. 2017) for example: ZnO-Nps and TiO_2-NPs at a concentrations of 25 and 10 mg/L respectively can adversely affect aquatic bacteria (Tong et al. 2015). The direct interaction with ZnO-NPs is detrimental to the growth phase of algae. The half maximal effective concentration (EC_{50}) of nano ZnO particles is very low about 3.66–4.14 and 0.96–1.57 mg Zn/L for green microalgae and diatoms respectively (Li et al. 2017). Despite the fact that, these studies are carried out at lab level only. In contrast, in vivo, the aquatic species may expose to nanotoxicity for an extended period in their natural environments and experience various deleterious effects of nanoparticles on aquatic life (Table 3) (Sarkar et al. 2022). NPs show many harmful effects, such as inhibition of Na^+/K^+ ATPase, oxidative stress, genotoxicity, neurotoxicity, tissue alterations, body pigmentation, brain damage, behavioral changes in fish in aquatic organisms, etc. (Farmen et al. 2012; Cimbaluk et al. 2018; Forouhar Vajargah et al. 2019; Kakakhel et al. 2021; Aziz and Abdullah 2023). Nonetheless, nanomaterials must be investigated for their life cycle and shelf-life to evaluate potential health and environmental hazards such as exposure, uptake, accumulation, release, and deposition, to make nanotechnology sustainable and used for more applications (Handy 2012).

Conclusion

Based on the above scenario, nanotechnology has positive and negative impacts on aquaculture and fisheries. The nanoparticles are beneficial in improving the growth and health of aquatic organisms and also help in delivering various immunity-boosting substances such as medicines, vaccines, and many other nutraceuticals. The dietary supplementation of nanoparticles is highly recommended to alleviate multiple negative impacts of climate change on aquatic animals. Although nanotechnology is enhancing aquatic production by improving the welfare of culture species, somehow, there is a lack of efficient application of nanoparticles at the field level.

Aside from these benefits, using nanoparticles that exceed a specific dose limit may also harm aquatic animals and human life. However, the direct assessment of nanoparticles in fish tissues can't be performed using conventional methods. So, it is essential to apply advanced techniques to identify and quantify the nanomaterials' residues in the fish tissue after utilizing them in an application to ascertain how harmful they are. Moreover, the toxicity caused by metal nanoparticles in aquatic ecosystems has become a significant issue of concern in recent years. Direct or indirect release of wastewater from industries, agriculture runoff water, and inefficient removal of nanoparticles in the wastewater treatment plant system (WWTPs) into the surrounding water bodies leads to this Nano-toxicity.

Therefore, more toxicological research needs to be conducted for better understanding of how the nanoparticles behave in aquatic environments and their interactions with one another and living organisms. Furthermore, standard rules and regulations are necessary for regulated production, applications, and safe disposal of nanoparticles. Green biosynthesized nanoparticles have recently become more popular because of their enhanced biodegradability than metal nanoparticles. Green synthesis of nanoparticles forms an excellent alternative in reducing the risk to aquatic animals. Use the nanoparticles only for the actual problem raised. Limiting the excessive inclusion of nanoparticles in food, medications, and cosmetics and controlling industrial effluents' release into natural systems are mitigation approaches to reduce the nontoxicity.

Acknowledgements The author thankful to the West Bengal University of Animal and Fishery Sciences of West Bengal state, India and the National Institute of Animal Biotechnology, Hyderabad, Telangana State, India for their expertise and assistance throughout all aspects of helping in writing this review.

Author contributions KAK: Conceptualization, Writing—original draft preparation, Review & editing, Visualization. GSP: Review & editing. CBP: Conceptualization & Supervision. SN: Review & editing. PJ: Writing. SB: Validation.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abd El-Naby, F.S., Naiel, M.A.E., Al-Sagheer, A.A., Negm, S.S.: Dietary chitosan nanoparticles enhance the growth, production performance, and immunity in *Oreochromis niloticus*. Aquaculture. **501**, 82–89 (2019). https://doi.org/10.1016/j.aquaculture.2018.11.014

Abdel-Ghany, H.M., Salem, M.E.: Effects of dietary chitosan supplementation on farmed fish; a review. Rev. Aquac. **12**, 438–452 (2019). https://doi.org/10.1111/raq.12326

Abdel-Tawwab, M., Razek, N.A., Abdel-Rahman, A.M.: Immunostimulatory effect of dietary chitosan nanoparticles on the performance of Nile tilapia, *Oreochromis niloticus* (L.). Fish & Shellfish Immunology (2019). https://doi.org/10.1016/j.fsi.2019.02.063

Abdel-Warith, A.-W.A., Fath El-Bab, A.F., Younis, E.-S.M.I., et al.: Using of chitosan nanoparticles (CsNPs), Spirulina as a feed additives under intensive culture system for black tiger shrimp (*Penaeus monodon*). J. King Saud Univ. Sci. **32**, 3359–3363 (2020). https://doi.org/10.1016/j.jksus.2020.09.022

Agrifood Market report: Nanotechnologies: where should they take us? Have your say. nano-opinion. https://nanopinion.archiv.zsi.at/en/reading-material/market-report-2-agrifood.html. (2010) Accessed 7 January 2023

Akbari-Alavijeh, S., Shaddel, R., Jafari, S.M.: Encapsulation of food bioactives and nutraceuticals by various chitosan-based nanocarriers. Food Hydrocoll. **105**, 105774 (2020). https://doi.org/10.1016/j.foodhyd.2020.105774

Akter, N., Alam, M.J., Jewel, M.A.S., Ayenuddin, M., Haque, S.K., Akter, S.: Evaluation of dietary metallic iron nanoparticles as feed additive for growth and physiology of Bagridae catfish, *Clarias batrachus* (Linnaeus, 1758). Int. J. Fisheries Aquat. Stud. **6**(3), 371–377 (2018)

Aklakur, Md., Asharf Rather, M., Kumar, N.: Nanodelivery: an emerging avenue for nutraceuticals and drug delivery. Crit. Rev. Food Sci. Nutr. **56**, 2352–2361 (2015). https://doi.org/10.1080/10408398.2013.839543

Alcamo, J., Henrichs, T., Rösch, T.: World Water in 2025: Global modeling and scenario analysis for the world commission on Water for the 21st Century. Report A0002. Centre for environmental systems research, University of Kassel, Kurt Wolters Strasse 3:34109 Kassel, Germany (2017)

Ali, D., Falodah, F.A., Almutairi, B., et al.: Assessment of DNA damage and oxidative stress in juvenile *Channa punctatus* (Bloch) after exposure to multi-walled carbon nanotubes. Environ. Toxicol. **35**, 359–367 (2019). https://doi.org/10.1002/tox.22871

Ali, M.K., Javaid, S., Afzal, H., et al.: Exploring the multifunctional roles of quantum dots for unlocking the future of biology and medicine. Environ. Res. **232**, 116290 (2023). https://doi.org/10.1016/j.envres.2023.116290

Alishahi, A., Mirvaghefi, A., Tehrani, M.R., et al.: Chitosan nanoparticle to carry vitamin C through the gastrointestinal tract and induce the non-specific immunity system of rainbow trout (*Oncorhynchus mykiss*). Carbohydr. Polym. **86**, 142–146 (2011). https://doi.org/10.1016/j.carbpol.2011.04.028

Asaikkutti, A., Bhavan, P.S., Vimala, K., et al.: Dietary supplementation of green synthesized manganese-oxide nanoparticles and its effect on growth performance, muscle composition and digestive enzyme activities of the giant freshwater prawn *Macrobrachium rosenbergii*. J. Trace Elem. Med Biol. **35**, 7–17 (2016). https://doi.org/10.1016/j.jtemb.2016.01.005

Assefa, A., Abunna, F.: Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. Vet. Med. Int. **2018**, 1–10 (2018). https://doi.org/10.1155/2018/5432497

Atyah, M.A.S., Zamri-Saad, M., Siti-Zahrah, A.: First report of methicillin-resistant *Staphylococcus aureus* from cage-cultured tilapia (*Oreochromis niloticus*). Vet. Microbiol. **144**, 502–504 (2010). https://doi.org/10.1016/j.vetmic.2010.02.004

Aziz, S.: Effects of engineered zinc oxide nanoparticles on freshwater fish, *Labeo rohita*: characterization of ZnO nanoparticles, acute toxicity and oxidative stress. Pak. Vet. J. **40**, 479–483 (2020). https://doi.org/10.29261/pakvetj/2020.030

Aziz, S., Abdullah, S.: Evaluation of toxicity induced by engineered CuO nanoparticles in freshwater fish, *Labeo rohita*. Turkish J. Fisheries Aquat. Sci. **23**(8), TRJFAS18762 (2023). https://doi.org/10.4194/trjfas18762

Baker, T.J., Tyler, C.R., Galloway, T.S.: Impacts of metal and metal oxide nanoparticles on marine organisms. Environ. Pollut. **186**, 257–271 (2014). https://doi.org/10.1016/j.envpol.2013.11.014

Barreto, A., Luis, L.G., Pinto, E., et al.: Genotoxicity of gold nanoparticles in the gilthead seabream (*Sparus aurata*) after single exposure and combined with the pharmaceutical gemfibrozil. Chemosphere. **220**, 11–19 (2019). https://doi.org/10.1016/j.chemosphere.2018.12.090

Bayda, S., Adeel, M., Tuccinardi, T., et al.: The history of nanoscience and nanotechnology: from chemical–physical applications to nanomedicine. Molecules **25**, 112 (2019). https://doi.org/10.3390/molecules25010112

Behera, T., Swain, P., Rangacharulu, P.V., Samanta, M.: Nano-Fe as feed additive improves the hematological and immunological parameters of fish, *Labeo rohita* H. Appl. Nanosci. **4**, 687–694 (2013). https://doi.org/10.1007/s13204-013-0251-8

Bhat, I.A., Rather, M.A., Saha, R., et al.: Expression analysis of Sox9 genes during annual reproductive cycles in gonads and after nanodelivery of LHRH in *Clarias batrachus*. Res. Vet. Sci. **106**, 100–106 (2016). https://doi.org/10.1016/j.rvsc.2016.03.022

Bhat, I.A., Ahmad, I., Mir, I.N., et al.: Chitosan-eurycomanone nanoformulation acts on steroidogenesis pathway genes to increase the reproduction rate in fish. J. Steroid Biochem. Mol. Biol. **185**, 237–247 (2019)

Bhattacharyya, A., Reddy, J., Hasan, M.M., et al.: Nanotechnology-a unique future technology in aquaculture for the food security. Int. J. Bioassays. **4**(7), 4115–4126 (2015)

Blinova, I., Niskanen, J., Kajankari, P., et al.: Toxicity of two types of silver nanoparticles to aquatic crustaceans *Daphnia magna* and *Thamnocephalus platyurus*. Environ. Sci. Pollut. Res. **20**(5), 3456–3463 (2013)

Bora, T., Dutta, J.: Applications of nanotechnology in wastewater treatment—a review. J. Nanosci. Nanotechnol. **14**, 613–626 (2014). https://doi.org/10.1166/jnn.2014.8898

Boran, H., Şaffak, S.: Transcriptome alterations and genotoxic influences in zebrafish larvae after exposure to dissolved aluminum and aluminum oxide nanoparticles. Toxicol. Mech. Methods. **30**, 546–554 (2020). https://doi.org/10.1080/15376516.2020.1786759

Brower, V.: Nutraceuticals: poised for a healthy slice of the healthcare market? Nat. Biotechnol. **16**, 728–731 (1998). https://doi.org/10.1038/nbt0898-728

Cabello, F.C., Godfrey, H.P., Tomova, A., et al.: Antimicrobial use in aquaculture re-examined: Its relevance to antimicrobial resistance and to animal and human health. Environ. Microbiol. **15**(7), 1917–1942 (2013)

Can, E., Kizak, V., Kayim, M., et al.: Nano technological applications in aquaculture-seafood industries and adverse effects of nanoparticles on environment. J. Mater. Sci. Eng. **5**(5), 605 (2011)

Carrazco-Quevedo, A., Römer, I., Salamanca, M.J., et al.: Bioaccumulation and toxic effects of nanoparticulate and ionic silver in *Saccostrea Glomerata* (rock oyster). Ecotoxicol. Environ. Saf. **179**, 127–134 (2019). https://doi.org/10.1016/j.ecoenv.2019.04.032

CDC [Centers for Disease Control and Prevention]:, Available at (2022). https://www.cdc.gov/index.htm. Accessed 2 December 2022

Chellaram, C., Murugaboopathi, G., John, A.A., et al.: Significance of nanotechnology in food industry. APCBEE Procedia **8**, 109–113 (2014). https://doi.org/10.1016/j.apcbee.2014.03.010

Chemello, G., Piccinetti, C., Randazzo, B., et al.: Oxytetracycline delivery in adult female zebrafish by iron oxide nanoparticles. Zebrafish **13**, 495–503 (2016). https://doi.org/10.1089/zeb.2016.1302

Chen, K., He, J., Li, Y., et al.: Removal of cadmium and lead ions from water by sulfonated magnetic nanoparticle adsorbents. J. Colloid Interface Sci. **494**, 307–316 (2017). https://doi.org/10.1016/j.jcis.2017.01.082

Chen, J., Fan, R., Wang, Y., et al.: Progressive impairment of learning and memory in adult zebrafish treated by Al_2O_3 nanoparticles when in embryos. Chemosphere. **254**, 126608 (2020). https://doi.org/10.1016/j.chemosphere.2020.126608

Chouljenko, A., Chotiko, A., Solval, M.J.M., et al.: Chitosan nanoparticle penetration into shrimp muscle and its effects on the

microbial quality. Food Bioprocess Technol. **10**, 186–198 (2016). https://doi.org/10.1007/s11947-016-1805-z
Chouljenko, A., Chotiko, A., Bonilla, F., et al.: Effects of vacuum tumbling with chitosan nanoparticles on the quality characteristics of cryogenically frozen shrimp. LWT. **75**, 114–123 (2017). https://doi.org/10.1016/j.lwt.2016.08.029
Cimbaluk, G.V., Ramsdorf, W.A., Perussolo, M.C., et al.: Evaluation of multiwalled carbon nanotubes toxicity in two fish species. Ecotoxicol. Environ. Saf. **150**, 215–223 (2018). https://doi.org/10.1016/j.ecoenv.2017.12.034
Connolly, M., Fernández, M., Conde, E., et al.: Tissue distribution of zinc and subtle oxidative stress effects after dietary administration of ZnO nanoparticles to rainbow trout. Sci. Total Environ. **551–552**, 334–343 (2016). https://doi.org/10.1016/j.scitotenv.2016.01.186
Daraio, C., Jin, S.: Synthesis and patterning methods for nanostructures useful for biological applications. Nanatechnol. Biol. Med. (2011). https://doi.org/10.1007/978-0-387-31296-5_2
Das, B., Dash, S.K., Mandal, D., et al.: Green synthesized silver nanoparticles destroy multidrug resistant bacteria via reactive oxygen species mediated membrane damage. Arab. J. Chem. **10**, 862–876 (2017). https://doi.org/10.1016/j.arabjc.2015.08.008
Das, A., Kamle, M., Bharti, A., Kumar, P.: Nanotechnology and it's applications in environmental remediation: an overview. Vegetos **32**, 227–237 (2019). https://doi.org/10.1007/s42535-019-00040-5
Davies, J., Davies, D.: Origins and Evolution of Antibiotic Resistance. Microbiol. Mol. Biol. Rev. **74**, 417–433 (2010). https://doi.org/10.1128/mmbr.00016-10
Duarte, C.M., Marbá, N., Holmer, M., Fostier, C.C., Zanuy, A.: Broodstock management and hormonal manipulations of fish reproduction. Gen. Comp. Endocrinol. **165**(3), 516–534 (2010)
Duke, M., Zhao, D., Semiat, R.: Functional nanostructured materials and membranes for water treatment. Wiley, Hoboken (2013)
Ealia, S.A.M., Saravanakumar, M.P.: A review on the classification, characterisation, synthesis of nanoparticles and their application. In: IOP conference series: materials science and engineering. IOP Publishing 263(3):032019 (2017)
El-Greisy, Z.A., El-Gamal, A.E.: Monosex production of tilapia, *Oreochromis niloticus* using different doses of 17α-methyltestosterone with respect to the degree of sex stability after one year of treatment. Egypt. J. Aquat. Res. **38**, 59–66 (2012). https://doi.org/10.1016/j.ejar.2012.08.005
El-Houseiny, W., Mansour, M.F., Mohamed, W.A.M., et al.: Silver nanoparticles mitigate *Aeromonas hydrophila*-induced immune suppression, oxidative stress, and apoptotic and genotoxic effects in *Oreochromis niloticus*. Aquaculture. **535**, 736430 (2021). https://doi.org/10.1016/j.aquaculture.2021.736430
Elabd, H., Youssuf, H., Mahboub, H.H., et al.: Growth, hematobiochemical, immune-antioxidant response, and gene expression in Nile tilapia (*Oreochromis niloticus*) received nano iron oxide-incorporated diets. Fish Shellfish Immunol. **128**, 574–581 (2022). https://doi.org/10.1016/j.fsi.2022.07.051
Elgendy, M.Y., Shaalan, M., Abdelsalam, M., et al.: Antibacterial activity of silver nanoparticles against antibiotic-resistant *Aeromonas veronii* infections in Nile tilapia, *Oreochromis niloticus* (L.), in vitro and in vivo assay. Aquac. Res. **53**, 901–920 (2021). https://doi.org/10.1111/are.15632
Esmaeili, C., Heng, L.Y., Chiang, C.P., et al.: A DNA biosensor based on kappa-carrageenan-polypyrrole-gold nanoparticles composite for gender determination of Arowana fish (*Scleropages formosus*). Sens. Actuators B. **242**, 616–624 (2017). https://doi.org/10.1016/j.snb.2016.11.061
ETC (Action Group on Erosion, Technology and Concentration): Down on the farm. the impact of nanoscale technologies on food and agriculture (2003). https://www.etcgroup.org/content/etc-group-releases-down-farm-impact-nano-scale-technologies-food-and-agriculture
Eugene, K., Jeffery, L.: Gene and stem cell therapies. JAMA. **285**(5), 545–550 (2001)
Fajardo, C., Martinez-Rodriguez, G., Blasco, J., et al.: Nanotechnology in aquaculture: applications, perspectives and regulatory challenges. Aquac. Fisheries **7**, 185–200 (2022). https://doi.org/10.1016/j.aaf.2021.12.006
Fakruddin, M., Hossain, Z., Afroz, H.: Prospects and applications of nanobiotechnology: a medical perspective. J. Nanobiotechnol. **10**, 31 (2012). https://doi.org/10.1186/1477-3155-10-31
Falugi, C., Aluigi, M.G., Chiantore, M.C., et al.: Toxicity of metal oxide nanoparticles in immune cells of the sea urchin. Mar. Environ. Res. **76**, 114–121 (2012). https://doi.org/10.1016/j.marenvres.2011.10.003
Fan, H.-L., Zhou, S.-F., Jiao, W.-Z., et al.: Removal of heavy metal ions by magnetic chitosan nanoparticles prepared continuously via high-gravity reactive precipitation method. Carbohydr. Polym. **174**, 1192–1200 (2017). https://doi.org/10.1016/j.carbpol.2017.07.050
FAO: The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. FAO, Rome (2018)
FAO: The state of World fisheries and Aquaculture 2022. Towards blue transformation. FAO, Rome (2022)
Farmen, E., Mikkelsen, H.N., Evensen, Ø., et al.: Acute and sub-lethal effects in juvenile Atlantic salmon exposed to low µg/L concentrations of Ag nanoparticles. Aquat. Toxicol. **108**, 78–84 (2012)
Fırat, Ö., Bozat, R.C.: Assessment of biochemical and toxic responses induced by titanium dioxide nanoparticles in Nile tilapia *Oreochromis Niloticus*. Hum. Ecol. Risk Assessment: Int. J. **25**, 1438–1447 (2018). https://doi.org/10.1080/10807039.2018.1465338
FOE (Friends of the Earth): Out of the laboratory and onto our plates: nanotechnology in food and agriculture. (2008). https://foe.org/blog/2008-03-out-of-the-laboratory-and-on-to-our-plates/
Fonghsu, K.: Nanoemulsions for pharmaceutical and nutraceutical delivery in cancer and inflammation. Ph.D. thesis, University of Massachusetts Lowell. (2008)
Forouhar Vajargah, M., Mohamadi Yalsuyi, A., Sattari, M., et al.: Effects of copper oxide nanoparticles (CuO-NPs) on parturition time, survival rate and reproductive success of Guppy Fish, *Poecilia reticulata*. J. Cluster Sci. **31**, 499–506 (2019). https://doi.org/10.1007/s10876-019-01664-y
Frederick, K., Kuhn, M.E., Tarver, T.: New insights into food and health. Food Technol. Champaign Then Chic. **64**(5), 44–49 (2010). https://www.ift.org/news-and-publications/food-technology-magazine/issues/2010/may/features/new-insights-into-food-and-health
Fu, P.P.: Introduction to the special issue: nanomaterials—toxicology and medical applications. J. Food Drug Anal. **22**, 1–2 (2014). https://doi.org/10.1016/j.jfda.2014.01.013
Gambardella, C., Mesaric, T., Milivojevi´c, T., et al.: Effects of selected metal oxide nanoparticles on *Artemia salina* larvae: evaluation of mortality and behavioural and biochemical responses. Environ. Monit. Assess. **186**, 4249–4259 (2014)
García-Medina, S., Galar-Martínez, M., Cano-Viveros, S., et al.: Bioaccumulation and oxidative stress caused by aluminium nanoparticles and the integrated biomarker responses in the common carp (*Cyprinus carpio*). Chemosphere. **288**, 132462 (2022). https://doi.org/10.1016/j.chemosphere.2021.132462
Ghanbary, K., Firouzbakhsh, F., Arkan, E., Mojarrab, M.: The effect of *Thymbra Spicata* hydroalcoholic extract loaded on chitosan polymeric nanoparticles on some growth performances, hematology, immunity, and response to acute stress in rainbow trout (*Oncorhynchus mykiss*). Aquaculture. **548**, 737568 (2022). https://doi.org/10.1016/j.aquaculture.2021.737568

Ghazi, S., Diab, A.M., Khalafalla, M.M., Mohamed, R.A.: Synergistic effects of selenium and zinc oxide nanoparticles on growth performance, hemato-biochemical profile, immune and oxidative stress responses, and intestinal morphometry of Nile Tilapia (*Oreochromis niloticus*). Biol. Trace Elem. Res. **200**, 364–374 (2021). https://doi.org/10.1007/s12011-021-02631-3

Gheibi Hayat, S.M., Darroudi, M.: Nanovaccine: a novel approach in immunization. J. Cell. Physiol. **234**(8), 12530–12536 (2019)

Ghetas, H.A., Abdel-Razek, N., Shakweer, M.S., et al.: Antimicrobial activity of chemically and biologically synthesized silver nanoparticles against some fish pathogens. Saudi J. Biol. Sci. **29**, 1298–1305 (2022). https://doi.org/10.1016/j.sjbs.2021.11.015

Gillman, G.P.: A simple technology for arsenic removal from drinking water using hydrotalcite. Sci. Total Environ. **366**(2–3), 926–931 (2006). https://doi.org/10.1016/j.scitotenv.2006.01.036

Gomes, T., Araújo, O., Pereira, R., Almeida, A.C., Cravo, A., Bebianno, M.J.: Genotoxicity of copper oxide and silver nanoparticles in the mussel, *Mytilus galloprovincialis*. Mar. Environ. Res. **84**, 51–59 (2013)

Gong, Y.-X., Zhu, B., Liu, G.-L., et al.: Single-walled carbon nanotubes as delivery vehicles enhance the immune protective effects of a recombinant vaccine against *Aeromonas hydrophila*. Fish Shellfish Immunol. **42**, 213–220 (2015). https://doi.org/10.1016/j.fsi.2014.11.004

Grillo, R., Rosa, A.H., Fraceto, L.F.: Engineered nanoparticles and organic matter: a review of the state-of-the-art. Chemosphere **119**, 608–619 (2015)

Gupta, V.K., Saleh, T.A.: Sorption of pollutants by porous carbon, carbon nanotubes and fullerene- an overview. Environ. Sci. Pollut. Res. **20**, 2828–2843 (2013). https://doi.org/10.1007/s11356-013-1524-1

Gürkan, M.: Effects of three different nanoparticles on bioaccumulation, oxidative stress, osmoregulatory, and immune responses of *Carcinus Aestuarii*. Toxicol. Environ. Chem. **100**, 693–716 (2018). https://doi.org/10.1080/02772248.2019.1579818

Gustavo, A., Dominguez: Nanotechnology in the aquaculture industry. Sustainable Nano 1. (2014). https://sustainable-nano.com/2014/02/11/nanotechnology-in-the-aquaculture-industry/

Hajiyeva, A.D., Mamedov, C.A., Khalilov, R.I.: Influence of nanoparticles on the yield of embryos of the roe rainbow trout (*Oncorhynchus mykiss* Walbaum) in the fermentation process. J. Oceanogr. Mar. Res. **6**, 183 (2022a)

Hajiyeva, A.D., Mamedov, C.A., Khalilov, R.I.: Influence of nanoparticles on the yield of embryos of the roe common carp (*Cyprinus carpio* Linnaeus, 1758) in the fermentation process. Adv. Biol. Earth Sci. **7**(1), 5–12 (2022)

Handy, R.D.: FSBI briefing paper: nanotechnology in fisheries and aquaculture. Fisheries Soc. Br. Isles **1**, 29 (2012)

Handy, R.D., Clark, N.J., Vassallo, J.: Nanotechnology for aquaculture and fisheries. Nano-Enabled Sustain. Precis. Agric. (2023). https://doi.org/10.1016/b978-0-323-91233-4.00006-5

Hasan, S.: A review on nanoparticles: their synthesis and types. Res. J. Recent Sci. **2277**, 2502 (2015)

Hasanzadeh, M., Arash, B., Alizadeh, M., Shadjouc, N.: Magnetic nanoparticles loaded on mobile crystalline material-41: preparation, characterization and application as a novel material for the construction of an electrochemical nanosensor. RSC Adv. **3**, 24237–24246 (2013)

Hu, F., Li, Y., Wang, Q., et al.: Carbon nanotube-based DNA vaccine against Koi Herpesvirus given by intramuscular injection. Fish Shellfish Immunol. **98**, 810–818 (2020). https://doi.org/10.1016/j.fsi.2019.11.035

Huang, S., Wang, L., Liu, L., et al.: Nanotechnology in agriculture, livestock, and aquaculture in China a review. Agron. Sustain. Dev. **35**, 369–400 (2014). https://doi.org/10.1007/s13593-014-0274-x

Huang, X., Zhu, Y., Kianfar, E.: Nano biosensors: Properties, applications and electrochemical techniques. J. Mater. Res. Technol. **12**, 1649–1672 (2021)

Ismael, N.E.M., Abd El-hameed, S.A.A., Salama, A.M., et al.: The effects of dietary clinoptilolite and chitosan nanoparticles on growth, body composition, haemato-biochemical parameters, immune responses, and antioxidative status of Nile tilapia exposed to imidacloprid. Environ. Sci. Pollut. Res. **28**, 29535–29550 (2021). https://doi.org/10.1007/s11356-021-12693-4

Jafari, S.M.: An overview of nanoencapsulation techniques and their classification. Nanoencapsulation Technol. Food Nutraceutical Ind. (2017). https://doi.org/10.1016/b978-0-12-809436-5.00001-x

Jahaabad, M.J., Ziaenejad, S., Ghayedi, A., Moradian, H., Seyyedi, A.M.: The effects of selenium nanoparticles enriched food on sperm quality and fertilization of rainbow trout (*Oncorhynchus mykiss*) male breeders. Iran. Vet J. **16**(3), 106–115 (2020)

Jamabo, A., Ukwe, N.O.K., Amachree, I.: Growth assessment and microbial flora presence in African Catfish (*Clarias gariepinus*) larvae fed live and commercial feeds. Int. J. Sci. **8**, 1–6 (2019). https://doi.org/10.18483/ijsci.2058

Jhanani, G., Pappuswamy, M., Meyyazhagan, A., et al.: Toxic effects of nanoparticles on Fish embryos. Res. J. Biotechnol. **16**, 140–149 (2021). https://doi.org/10.25303/1612rjbt140149

Ji, J., Torrealba, D., Ruyra, À., Roher, N.: Nanodelivery systems as new tools for immunostimulant or vaccine administration: targeting the fish immune system. Biology **4**, 664–696 (2015). https://doi.org/10.3390/biology4040664

Jiménez-Fernández, E., Ruyra, A., Roher, N., et al.: Nanoparticles as a novel delivery system for vitamin C administration in aquaculture. Aquaculture. **432**, 426–433 (2014). https://doi.org/10.1016/j.aquaculture.2014.03.006

Johari, S.A., Kalbassi, M.R., Soltani, M., Yu, I.J.: Application of nanosilver-coated zeolite as water filter media for fungal disinfection of rainbow trout (*Oncorhynchus mykiss*) eggs. Aquacult. Int. **24**, 23–38 (2015). https://doi.org/10.1007/s10499-015-9906-7

Joshi, H.D., Ghode, G.S., Gore, S.B.: Efficiency of letrozole loaded PLGA nanoparticles on sex reversal of *Poecilia reticulata* (Peters, 1859). J. Appl. Nat. Sci. **7**(1), 394–399 (2015)

Joshi, H.D., Tiwari, V.K., Gupta, S., Sharma, R., Lakra, W.S., Sahoo, U.: Application of nanotechnology for the production of masculinized tilapia, *Oreochromis niloticus* (Linnaeus, 1758). Aquaculture. **511**, 734206 (2019)

Kakakhel, M.A., Wu, F., Sajjad, W., et al.: Long-term exposure to high-concentration silver nanoparticles induced toxicity, fatality, bioaccumulation, and histological alteration in fish (*Cyprinus carpio*). Environ. Sci. Europe (2021). https://doi.org/10.1186/s12302-021-00453-7

Kalatehjari, P., Yousefian, M., Khalilzadeh, M.A.: Assessment of antifungal effects of copper nanoparticles on the growth of the fungus Saprolegnia sp. on white fish (*Rutilus frisii Kutum*) eggs. Egypt. J. Aquat. Res. **41**, 303–306 (2015). https://doi.org/10.1016/j.ejar.2015.07.004

Kandasamy, K., Alikunhi, N.M., Manickaswami, G., et al.: Synthesis of silver nanoparticles by coastal plant *Prosopis chilensis* (L.) and their efficacy in controlling vibriosis in shrimp *Penaeus monodon*. Appl. Nanosci. **3**, 65–73 (2013)

Kanwal, Z., Raza, M.A., Manzoor, F., et al.: A comparative assessment of nanotoxicity induced by metal (silver, nickel) and metal oxide (cobalt, chromium) nanoparticles in *Labeo rohita*. Nanomaterials. **9**(2), 309 (2019)

Karamzadeh, M., Yahyavi, M., Salarzadeh, A., Nokhbe, Z.D.: Effects of dietary selenium and zinc nanoparticles on growth performance, immune responses, and antioxidant enzymes activities of white leg shrimp (*Litopenaeus vannamei*). Iran. J. Fisheries

Sci. **21**(5), 1125–1140 (2022). https://doi.org/10.22092/ijfs.2022.127677

Khalid, P., Hussain, M., Suman, V., Arun, A.: Toxicology of carbon nanotubes-a review. Int. J. Appl. Eng. Res. **11**(1), 148–157 (2016)

Khan, I., Saeed, K., Khan, I.: Nanoparticles: properties, applications and toxicities. Arab. J. Chem. **12**, 908–931 (2019)

Khani Oushani, A., Soltani, M., Sheikhzadeh, N., et al.: Effects of dietary chitosan and nano-chitosan loaded clinoptilolite on growth and immune responses of rainbow trout (*Oncorhynchus mykiss*). Fish Shellfish Immunol. **98**, 210–217 (2020). https://doi.org/10.1016/j.fsi.2020.01.016

Khosravi-Katuli, K., Prato, E., Lofrano, G., et al.: Effects of nanoparticles in species of aquaculture interest. Environ. Sci. Pollut. Res. **24**, 17326–17346 (2017). https://doi.org/10.1007/s11356-017-9360-3

Khurana, A., Tekula, S., Saifi, M.A., Venkatesh, P., Godugu, C.: Therapeutic applications of selenium nanoparticles. Biomed. Pharmacother. **111**, 802–812 (2019)

Kim, T., Hyeon, T.: Applications of inorganic nanoparticles as therapeutic agents. Nanotechnology. **25**(1), 012001 (2013)

Kookaram, K., Mojazi Amiri, B., Dorkoosh, F.A., Nematollahi, M.A., Mortazavian, E., Abed, E.A.: Effect of oral administration of GnRHa + nanoparticles of chitosan in oogenesis acceleration of goldfish *Carassius auratus*. Fish. Physiol. Biochem. **47**(2), 477–486 (2021)

Kumar, S.R., Ahmed, V.I., Parameswaran, V., et al.: Potential use of chitosan nanoparticles for oral delivery of DNA vaccine in Asian sea bass (*Lates calcarifer*) to protect from *Vibrio (Listonella) Anguillarum*. Shellfish Immunol. **25**(1–2), 47–56 (2008). Fish

Kumar, P., Huo, P., Zhang, R., Liu, B.: Antibacterial properties of graphene-based nanomaterials. Nanomaterials **9**, 737 (2019). https://doi.org/10.3390/nano9050737

Kumaran, S., Perianaika Anahas, A.M., Prasannabalaji, N., et al.: Chitin derivatives of NAG and Chitosan nanoparticles from marine disposal yards and their use for economically feasible fish feed development. Chemosphere. **281**, 130746 (2021). https://doi.org/10.1016/j.chemosphere.2021.130746

Kuppusamy, P., Yusoff, M.M., Maniam, G.P., Govindan, N.: Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications: an updated report. Saudi Pharm. J. **24**, 473–484 (2016). https://doi.org/10.1016/j.jsps.2014.11.013

Kurniawan, T.A., Sillanpää, M.E.T., Sillanpää, M.: Nanoadsorbents for remediation of aquatic environment: local and practical solutions for global water pollution problems. Crit. Rev. Environ. Sci. Technol. **42**, 1233–1295 (2012). https://doi.org/10.1080/10643389.2011.556553

Kwok, K.W., Leung, K.M., Flahaut, E., et al.: Chronic toxicity of double-walled carbon nanotubes to three marine organisms: influence of different dispersion methods. Nanomedicine **5**, 951–961 (2010)

Lacave, J.M., Fanjul, Á., Bilbao, E., et al.: Acute toxicity, bioaccumulation and effects of dietary transfer of silver from brine shrimp exposed to PVP/PEI-coated silver nanoparticles to zebrafish. Comp. Biochem. Physiol. C: Toxicol. Pharmacol. **199**, 69–80 (2017). https://doi.org/10.1016/j.cbpc.2017.03.008

Li, Y., Zhou, H., Zhu, G., et al.: High efficient multifunctional Ag_3PO_4 loaded hydroxyapatite nanowires for water treatment. J. Hazard. Mater. **299**, 379–387 (2015). https://doi.org/10.1016/j.jhazmat.2015.06.032

Li, J., Schiavo, S., Rametta, G., et al.: Comparative toxicity of nano ZnO and bulk ZnO towards marine algae *Tetraselmis Suecica* and *Phaeodactylum tricornutum*. Environ. Sci. Pollut. Res. **24**, 6543–6553 (2017). https://doi.org/10.1007/s11356-016-8343-0

Liu, D., Li, Z., Zhu, Y., et al.: Recycled chitosan nanofibril as an effective Cu(II), pb(II) and cd(II) ionic chelating agent: Adsorption and desorption performance. Carbohydr. Polym. **111**, 469–476 (2014). https://doi.org/10.1016/j.carbpol.2014.04.018

Liu, L., Gong, Y.-X., Liu, G.-L., et al.: Protective immunity of grass carp immunized with DNA vaccine against *Aeromonas hydrophila* by using carbon nanotubes as a carrier molecule. Fish Shellfish Immunol. **55**, 516–522 (2016). https://doi.org/10.1016/j.fsi.2016.06.026

Luis, A.I.S., Campos, E.V.R., de Oliveira, J.L., Fraceto, L.F.: Trends in aquaculture sciences: From now to use of nanotechnology for disease control. Reviews in Aquaculture. **11**, 119–132 (2017). https://doi.org/10.1111/raq.12229

Luis, A.I.S., Campos, E.V.R., Oliveira, J.L., et al.: Ecotoxicity evaluation of polymeric nanoparticles loaded with ascorbic acid for fish nutrition in aquaculture. J. Nanobiotechnol. (2021). https://doi.org/10.1186/s12951-021-00910-8

Maggioni, D., Tatulli, G., Montalbetti, E., et al.: From DNA barcoding to nanoparticle-based colorimetric testing: a new frontier in cephalopod authentication. Appl. Nanosci. **10**, 1053–1060 (2020). https://doi.org/10.1007/s13204-020-01249-6

Mahboob, S., Al-Balawi, H.F.A., Al-Misned, F., et al.: Erratum to: tissue metal distribution and risk assessment for important fish species from Saudi Arabia. Bull. Environ Contam. Toxicol. **93**, 256–256 (2014). https://doi.org/10.1007/s00128-014-1301-y

Mahdave Jehanabad, J., Rastiannasab, A., Ghaedi, A., Mahmodi, R., Salahi Ardakani, M.M.: Effect of different levels of selenium nanoparticles on some reproductive indices in rainbow trout (*Oncorhynchus mykiss*). Aquat. Physiol. Biotechnol. **7**(3), 113–132 (2019)

Martinez-Vargas, S., Martínez, A.I., Hernández-Beteta, E.E., et al.: Arsenic adsorption on cobalt and manganese ferrite nanoparticles. J. Mater. Sci. **52**, 6205–6215 (2017). https://doi.org/10.1007/s10853-017-0852-9

Marzuki, N., Bakar, F., Salleh, A., et al.: Electrochemical biosensor immobilization of formaldehyde dehydrogenase with Nafion for determination of formaldehyde from indian mackerel (*Rastrelliger kanagurta*) Fish. Curr. Anal. Chem. **8**, 534–542 (2012). https://doi.org/10.2174/157341112803216843

Masimen, M.A.A., Harun, N.A., Maulidiani, M., Ismail, W.I.W.: Overcoming methicillin-resistance *Staphylococcus aureus* (MRSA) using antimicrobial peptides-silver nanoparticles. Antibiotics **11**, 951 (2022). https://doi.org/10.3390/antibiotics11070951

Matranga, V., Corsi, I.: Toxic effects of engineered nanoparticles in the marine environment: model organisms and molecular approaches. Mar. Environ. Res. **76**, 32–40 (2012)

Matteucci, F., Giannantonio, R., Calabi, F., et al.: Deployment and exploitation of nanotechnology nanomaterials and nanomedicine. AIP Conference Proceedings. (2018). https://doi.org/10.1063/1.5047755

Mattsson, K., Johnson, E.V., Malmendal, A., Linse, S., Hansson, L.A., Cedervall, T.: Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. Sci. Rep. **7**(1), 1–7 (2017)

Mirza, Z., Karim, S.: Nanoparticles-based drug delivery and gene therapy for breast cancer: recent advancements and future challenges. Sem. Cancer Biol. **69**, 226–237 (2021). https://doi.org/10.1016/j.semcancer.2019.10.020

Mongillo, J.F.: Nanotechnology. Greenwood Press, Westport (2007)

Muller, R.H., Keck, C.M.: Challenges and solutions for the delivery of biotech drugs–a review of drug nanocrystal technology and lipid nanoparticles. J. Biotechnol. **113**(1–3), 151–170 (2004)

Murali, M., Suganthi, P., Athif, P., et al.: Histological alterations in the hepatic tissues of Al_2O_3 nanoparticles exposed freshwater

fish *Oreochromis mossambicus*. J. Trace Elem. Med. Biol. **44**, 125–131 (2017). https://doi.org/10.1016/j.jtemb.2017.07.001
Muralisankar, T., Saravana Bhavan, P., Radhakrishnan, S., et al.: The effect of copper nanoparticles supplementation on freshwater prawn *Macrobrachium rosenbergii* post larvae. J. Trace Elem. Med. Biol. **34**, 39–49 (2016). https://doi.org/10.1016/j.jtemb.2015.12.003
Murata, J., Ohya, Y., Ouchi, T.: Design of quaternary chitosan conjugate having antennary galactose residues as a gene delivery tool. Carbohydr. Polym. **32**, 105–109 (1997). https://doi.org/10.1016/s0144-8617(96)00154-3
Naiel, M.A.E., Ismael, N.E.M., Abd El-hameed, S.A.A., Amer, M.S.: The antioxidative and immunity roles of chitosan nanoparticle and vitamin C-supplemented diets against imidacloprid toxicity on *Oreochromis niloticus*. Aquaculture. **523**, 735219 (2020). https://doi.org/10.1016/j.aquaculture.2020.735219
Nasr-Eldahan, S., Nabil-Adam, A., Shreadah, M.A., et al.: A review article on nanotechnology in aquaculture sustainability as a novel tool in fish disease control. Aquacult. Int. **29**, 1459–1480 (2021). https://doi.org/10.1007/s10499-021-00677-7
National Nanotechnology Initiative [NNI]:. http://www.nano.gov. Accessed 19 November 2022
Nguyen, N.Y., An, B.N., Le, M.V., Hoang, H.A.: Antibacterial activity of copper nanoparticles-chitosan composite against *Vibrio parahaemolyticus*. Biocontrol Sci. **25**, 159–165 (2020). https://doi.org/10.4265/bio.25.159
Niu, J., Liu, Y.J., Lin, H.Z., et al.: Effects of dietary chitosan on growth, survival and stress tolerance of postlarval shrimp, *Litopenaeus vannamei*. Aquacult. Nutr. **17**, e406–e412 (2011). https://doi.org/10.1111/j.1365-2095.2010.00775.x
Ogunkalu, O.A.: Utilization of nanotechnology in aquaculture and seafood sectors. Eurasian J. Food Sci. Technol. **3**(1), 26–33 (2019)
Oliveira Lima, K., Barreto Pinilla, C.M., Alemán, A., et al.: Characterization, bioactivity and application of chitosan-based nanoparticles in a food emulsion model. Polymers **13**, 3331 (2021). https://doi.org/10.3390/polym13193331
Oliveri Conti, G., Copat, C., Wang, Z., et al.: Determination of illegal antimicrobials in aquaculture feed and fish: An ELISA study. Food Control. **50**, 937–941 (2015). https://doi.org/10.1016/j.foodcont.2014.10.050
Ozogul, Y., Yuvka, İ., Ucar, Y., et al.: Evaluation of effects of nanoemulsion based on herb essential oils (rosemary, laurel, thyme and sage) on sensory, chemical and microbiological quality of rainbow trout (*Oncorhynchus mykiss*) fillets during ice storage. LWT. **75**, 677–684 (2017). https://doi.org/10.1016/j.lwt.2016.10.009
Pati, K., Chowdhury, S., Dora, K.C., et al.: Effects of zinc oxide nano particle on fortified tilapia mince during refrigerated storage (4 ± 1°C). J. Food Sci. Technol. **59**, 3976–3988 (2022). https://doi.org/10.1007/s13197-022-05433-0
Pei, L., Huang, Y., Li, C., et al.: Detection of triphenylmethane drugs in Fish muscle by surface-enhanced Raman Spectroscopy coupled with Au-Ag Core-Shell nanoparticles. J. Nanomaterials **2014**, 1–8 (2014). https://doi.org/10.1155/2014/730915
Pelgrift, R.Y., Friedman, A.J.: Nanotechnology as a therapeutic tool to combat microbial resistance. Adv. Drug Deliv. Rev. **65**(13–14), 1803–1815 (2013)
Pérez-Sánchez, T., Mora-Sánchez, B., Balcázar, J.L.: Biological approaches for disease control in aquaculture: advantages, limitations and challenges. Trends Microbiol. **26**, 896–903 (2018). https://doi.org/10.1016/j.tim.2018.05.002
Perreault, F., de Faria, A.F., Nejati, S., Elimelech, M.: Antimicrobial properties of graphene oxide nanosheets: why size matters. ACS Nano **9**, 7226–7236 (2015). https://doi.org/10.1021/acsnano.5b02067
Pumchan, A., Sae-Ueng, U., Prasittichai, C., et al.: A novel efficient piscine oral nano-vaccine delivery system: modified halloysite nanotubes (HNTs) preventing streptococcosis disease in Tilapia (*Oreochromis* Sp.). Vaccines **10**, 1180 (2022). https://doi.org/10.3390/vaccines10081180
Qin, F., Shi, M., Yuan, H., et al.: Dietary nano-selenium relieves hypoxia stress and, improves immunity and disease resistance in the Chinese mitten crab (*Eriocheir sinensis*). Fish Shellfish Immunol. **54**, 481–488 (2016)
Rajeshkumar, S., Venkatesan, C., Sarathi, M., et al.: Oral delivery of DNA construct using chitosan nanoparticles to protect the shrimp from white spot syndrome virus (WSSV). Fish Shellfish Immunol. **26**(3), 429–437 (2009)
Rajkumar, K.S., Kanipandian, N., Thirumurugan, R.: Toxicity assessment on haemotology, biochemical and histopathological alterations of silver nanoparticles-exposed freshwater fish *Labeo rohita*. Appl. Nanosci. **6**, 19–29 (2016)
Ramesh Kumar, D., Elumalai, R., Raichur, A.M., et al.: Development of antiviral gene therapy for monodon baculovirus using dsRNA loaded chitosan-dextran sulfate nanocapsule delivery system in *Penaeus monodon* post-larvae. Antiviral Res. **131**, 124–130 (2016)
Ramya, V.L., Sharma, R., Gireesh-Babu, P., et al.: Development of chitosan conjugated DNA vaccine against nodavirus in *Macrobrachium rosenbergii* (De Man, 1879). J. Fish Dis. **37**(9), 815–824 (2014)
Rather, M.A., Sharma, R., Aklakur, M., et al.: Nanotechnology: a novel tool for aquaculture and fisheries development. a prospective mini-review. Fisheries Aquac. J. **16**(1–5), 3 (2011)
Rather, M.A., Bhat, I.A., Gireesh-Babu, P., Chaudhari, A., Sundaray, J.K., Sharma, R.: Molecular characterization of kisspeptin gene and effect of nano–encapsulted kisspeptin-10 on reproductive maturation in *Catla catla*. Domest. Anim. Endocrinol. **56**, 36–47 (2016a)
Rather, M.A., Bhat, I.A., Sharma, N., Sharma, R., Chaudhari, A., Sundaray, J.K.: Molecular characterization, tissue distribution of follicle-stimulating hormone (FSH) beta subunit and effect of kisspeptin-10 on reproductive hormonal profile of *Catla catla* (Hamilton, 1822). Aquacult. Res. **47**(7), 2089–2100 (2016b)
Rather, M.A., Bhat, I.A., Sharma, N., Sharma, R.: Molecular and cellular toxicology of nanomaterials with related to aquatic organisms. Cell. Mol. Toxicol. Nanopart. **263**, 284 (2018)
Rather, M.A., Agarwal, D., Kumar, S., Sundaray, J.K.: Nanobiotechnology: prospects and applications in aquaculture. Adv Fisheries Biotechnol (2021). https://doi.org/10.1007/978-981-16-3215-0_14
Razmara, P., Pyle, G.G.: Recovery of rainbow trout olfactory function following exposure to copper nanoparticles and copper ions. Aquat. Toxicol. **245**, 106109 (2022). https://doi.org/10.1016/j.aquatox.2022.106109
Rivas-Aravena, A., Fuentes, Y., Cartagena, J., et al.: Development of a nanoparticle-based oral vaccine for Atlantic salmon against ISAV using an alphavirus replicon as adjuvant. Fish Shellfish Immunol. **45**, 157–166 (2015). https://doi.org/10.1016/j.fsi.2015.03.033
Rocha, T.L., Gomes, T., Sousa, V.S., et al.: Ecotoxicological impact of engineered nanomaterials in bivalve mollusks: An overview. Mar. Environ. Res. **111**, 74–88 (2015)
Roy, M.: DNA-chitosan nanospheres: transfection efficacy and cellular uptake. In Proc. Int'l. Symp. Control. Rel. Bioact. Mater 24:673–674. (1997)
Saha, R., Bhat, I.A., Charan, R., et al.: Ameliorative effect of chitosan conjugated 17α-methyltestosterone on testicular development in *Clarias batrachus*. Anim. Reprod. Sci. **193**, 245–254 (2018)

Sahdev, P., Ochyl, L.J., Moon, J.J.: Biomaterials for nanoparticle vaccine delivery systems. Pharm. Res. **31**, 2563–2582 (2014). https://doi.org/10.1007/s11095-014-1419-y

Sakhare, K., Prasasvi, K.R., Palani, S.G.: Plant and bacteria mediated green synthesis of silver nanoparticles. Green. Functionalized Nanomater. Environ. Appl. (2022). https://doi.org/10.1016/b978-0-12-823137-1.00006-3

Sarkar, B., Mahanty, A., Gupta, S.K., et al.: Nanotechnology: a next-generation tool for sustainable aquaculture. Aquaculture **546**, 737330 (2022). https://doi.org/10.1016/j.aquaculture.2021.737330

Satgurunathan, T., Bhavan, P.S., Joy, R.D.S.: Green synthesis of chromium nanoparticles and their effects on the growth of the Prawn *Macrobrachium rosenbergii* Post-larvae. Biol. Trace Elem. Res. **187**, 543–552 (2018). https://doi.org/10.1007/s12011-018-1407-x

Satgurunathan, T., Bhavan, P.S., Kalpana, R., et al.: Influence of Garlic (*Allium sativum*) clove-based selenium nanoparticles on status of nutritional, biochemical, enzymological, and gene expressions in the freshwater Prawn *Macrobrachium rosenbergii*. Biol. Trace Elem. Res. **1879**, 2036–2057 (2022). https://doi.org/10.1007/s12011-022-03300-9

Sekhon, B.S.: Nanotechnology in agri-food production: an overview. Nanatechnol. Sci. Appl. **31**, 53 (2014)

Selvaraj, B., Subramanian, K., Gopal, S., Renuga, P.S.: Nanotechnology as a novel tool for aquaculture industry: a review. World J. Pharmac. Sci. 1089–1096. (2014). https://wjpsonline.com/index.php/wjps/article/view/nanotechnology-aquaculture-industry-review

Senturk, A.: Nanotechnology as a food perspective. J. Nanomater. Mol. Nanatechnol. (2013). https://doi.org/10.4172/2324-8777.1000125

Shaalan, M., Saleh, M., El-Mahdy, M., El-Matbouli, M.: Recent progress in applications of nanoparticles in fish medicine: a review. Nanomed. Nanotechnol. Biol. Med. **12**, 701–710 (2016). https://doi.org/10.1016/j.nano.2015.11.005

Shaalan, M., Sellyei, B., El-Matbouli, M., Sz´ekely, C.: Efficacy of silver nanoparticles to control flavobacteriosis caused by *Flavobacterium johnsoniae* in common carp *Cyprinus carpio*. Dis. Aquat. Org. **137**, 175–183 (2020)

Shah, B.R., Mraz, J.: Advances in nanotechnology for sustainable aquaculture and fisheries. Rev. Aquac. **12**, 925–942 (2019). https://doi.org/10.1111/raq.12356

Shah, S.N.A., Shah, Z., Hussain, M., Khan, M.: Hazardous effects of titanium dioxide nanoparticles in ecosystem. Bioinorg. Chem. Appl. **2017**, 1–12 (2017). https://doi.org/10.1155/2017/4101735

Shahbazi, M.A., Santos, H.A.: Revolutionary impact of nanovaccines on immunotherapy. New. Horizons in Translational Medicine. **2**(2), 44–50 (2015)

Sharawy, Z.Z., Ashour, M., Labena, A., et al.: Effects of dietary *Arthrospira platensis* nanoparticles on growth performance, feed utilization, and growth-related gene expression of Pacific white shrimp, *Litopenaeus vannamei*. Aquaculture. **551**, 737905 (2022). https://doi.org/10.1016/j.aquaculture.2022.737905

Sharma, R., Rather, M.A., Vijaykumar Leela, R., et al.: Preliminary observations on effect of nano-conjugated pheromones on *Clarias batrachus* (Linnaeus, 1758). Aquac. Res. **45**(8), 1415–1420 (2014)

Sherif, A.H., Gouda, M., Darwish, S., Abdelmohsin, A.: Prevalence of antibiotic-resistant bacteria in freshwater fish farms. Aquac. Res. **52**, 2036–2047 (2020). https://doi.org/10.1111/are.15052

Shirazi, M.A., Shariati, F., Ramezanpour, Z.: Toxic effect of aluminum oxide nanoparticles on green Micro-Algae *Dunaliella salina*. Int. J. Environ. Res. **9**, 2 (2015)

Siddiqi, K.S., Husen, A., Rao, R.A.K.: A review on biosynthesis of silver nanoparticles and their biocidal properties. J. Nanobiotechnol. (2018). https://doi.org/10.1186/s12951-018-0334-5

Soltani, M., Ghodratnema, M., Ahari, H., et al.: The inhibitory effect of silvernanoparticles on the bacterial fish pathogens, *Streptococcus iniae*, *Lactococcus garvieae*, *Yersinia ruckeri*, *Aeromonas hydrophila*. Iran. J Vet Med. **3**, 137–142 (2009)

Srinivasan, V., Bhavan, P.S., Rajkumar, G., et al.: Dietary supplementation of magnesium oxide (MgO) nanoparticles for better survival and growth of the freshwater prawn *Macrobrachium rosenbergii* post-larvae. Biol. Trace Elem. Res. **177**, 196–208 (2016)

Srivastava, S., Sinha, R., Roy, D.: Toxicological effects of malachite green. Aquat. Toxicol. **66**(3), 319–329 (2004)

Subramanian, P.: Lipid-based Nanocarrier System for the effective delivery of Nutraceuticals. Molecules. **26**, 5510 (2021). https://doi.org/10.3390/molecules26185510

Sun, J., Liu, Z., Quan, J., et al.: Protective effects of different concentrations of selenium nanoparticles on rainbow trout (*Oncorhynchus mykiss*) primary hepatocytes under heat stress. Ecotoxicol. Environ. Saf. **230**, 113121 (2022). https://doi.org/10.1016/j.ecoenv.2021.113121

Swain, P., Nayak, S.K., Sasmal, A., et al.: Antimicrobial activity of metal based nanoparticles against microbes associated with diseases in aquaculture. World J. Microbiol. Biotechnol. **30**, 2491–2502 (2014). https://doi.org/10.1007/s11274-014-1674-4

Swain, P., Das, R., Das, A., et al.: Effects of dietary zinc oxide and selenium nanoparticles on growth performance, immune responses and enzyme activity in rohu, *Labeo rohita*(Hamilton). Aquac. Nutr. **25**, 486–494 (2018). https://doi.org/10.1111/anu.12874

Tavabe, K.R., Kuchaksaraei, B.S., Javanmardi, S.: Effects of ZnO nanoparticles on the Giant freshwater prawn (*Macrobrachium rosenbergii*, De Man, 1879): Reproductive performance, larvae development, CHH concentrations and anti-oxidative enzymes activity. Anim. Reprod. Sci. **221**, 106603 (2020). https://doi.org/10.1016/j.anireprosci.2020.106603

Technavio: Food Nanotechnology Market by Application and Geography - Forecast and Analysis 2021–2025. Accessed on 3 September 2023. (2022)

Teles, M., Reyes-López, F.E., Balasch, J.C., et al.: Toxicogenomics of gold nanoparticles in a marine fish: linkage to classical biomarkers. Front. Mar. Sci. (2019). https://doi.org/10.3389/fmars.2019.00147

Teymouri, Z., Shekarchizadeh, H.: A colorimetric indicator based on copper nanoparticles for volatile sulfur compounds to monitor fish spoilage in intelligent packaging. Food Packaging Shelf Life **33**, 100884 (2022). https://doi.org/10.1016/j.fpsl.2022.100884

Tong, T., Wilke, C.M., Wu, J., et al.: Combined toxicity of nano-ZnO and nano-TiO_2: From single to multi nanomaterial systems. Environ. Sci. Technol. **49**, 8113–8123 (2015)

Toniazzo, T., Berbel, I.F., Cho, S., et al.: β-carotene-loaded liposome dispersions stabilized with xanthan and guar gums: Physico-chemical stability and feasibility of application in yogurt. LWT - Food Science and Technology. **59**, 1265–1273 (2014). https://doi.org/10.1016/j.lwt.2014.05.021

Ubbink, J., Krüger, J.: Physical approaches for the delivery of active ingredients in foods. Trends Food Sci. Technol. **17**, 244–254 (2006). https://doi.org/10.1016/j.tifs.2006.01.007

Uddin, R., Wahid, M.I., Jasmeen, T., Huda, N.H., Sutradhar, K.B.: Detection of formalin in fish samples collected from Dhaka City, Bangladesh. Stamford J. Pharma Sci. **4**, 49–52 (2011)

Valentini, P., Galimberti, A., Mezzasalma, V., et al.: DNA barcoding meets nanotechnology: Development of a Universal Colorimetric Test for Food Authentication. Angew. Chem. **129**, 8206–8210 (2017). https://doi.org/10.1002/ange.201702120

Veisi, S., Johari, S.A., Tyler, C.R., et al.: Antioxidant properties of dietary supplements of free and nanoencapsulated silymarin and their ameliorative effects on silver nanoparticles induced oxidative stress in Nile tilapia (*Oreochromis niloticus*). Environ. Sci. Pollut. Res. **28**, 26055–26063 (2021). https://doi.org/10.1007/s11356-021-12568-8

Vendramini, T.H.A., Takiya, C.S., Silva, T.H., et al.: Effects of a blend of essential oils, chitosan or monensin on nutrient intake and digestibility of lactating dairy cows. Anim. Feed Sci. Technol. **214**, 12–21 (2016)

Vibhute, P., Jaabir, M., Sivakamavalli, J.: Applications of nanoparticles in aquaculture. Nanotechnological approaches to the Advancement of innovations in aquaculture 127–155. (2023). https://doi.org/10.1007/978-3-031-15519-2_8

Vijayaram, S., Tsigkou, K., Zuorro, A., et al.: Inorganic nanoparticles for use in aquaculture. Reviews in Aquaculture. **15**, 1600–1617 (2023). https://doi.org/10.1111/raq.12803

Vimal, S., Taju, G., Nambi, K.S.N., et al.: Synthesis and characterization of CS/TPP nanoparticles for oral delivery of gene in fish. Aquaculture. **358–359**, 14–22 (2012). https://doi.org/10.1016/j.aquaculture.2012.06.012

Völker, C., Kämpken, I., Boedicker, C., et al.: Toxicity of silver nanoparticles and ionic silver: comparison of adverse effects and potential toxicity mechanisms in the freshwater clam *Sphaerium corneum*. Nanotoxicology **9**(6), 677–685 (2015)

Wang, Y., Li, J.: Effects of Chitosan nanoparticles on survival, growth and meat quality of tilapia, *Oreochromis niloticus*. Nanotoxicology. **5**(3), 425–431 (2011)

Wang, Y., Liu, L., Zhou, J., et al.: Effect of Chitosan nanoparticle coatings on the quality changes of postharvest Whiteleg Shrimp, *Litopenaeus vannamei*, during Storage at 4 °C. Food Bioprocess Technol. **8**, 907–915 (2014). https://doi.org/10.1007/s11947-014-1458-8

Wang, Y., Sun, Y., Dai, H., et al.: A colorimetric biosensor using Fe_3O_4 nanoparticles for highly sensitive and selective detection of tetracyclines. Sens. Actuators B. **236**, 621–626 (2016). https://doi.org/10.1016/j.snb.2016.06.029

Wisdom, K.S., Bhat, I.A., Kumar, P., et al.: Fabrication of chitosan nanoparticles loaded with aromatase inhibitors for the advancement of gonadal development in *Clarias Magur* (Hamilton, 1822). Aquaculture. **497**, 125–133 (2018)

Wu, Y., Rashidpour, A., Almajano, M.P., Meton, I.: Chitosan-based drug delivery system: Applications in fish biotechnology. Polymers **12**(5), 1177 (2020)

Xiao, B., Wang, X., Yang, J., et al.: Bioaccumulation kinetics and tissue distribution of silver nanoparticles in zebrafish: The mechanisms and influence of natural organic matter. Ecotoxicol. Environ. Saf. **194**, 110454 (2020). https://doi.org/10.1016/j.ecoenv.2020.110454

Xu, W., Huang, K., Jin, W., Luo, D., Liu, H., Li, Y., et al.: Catalytic and anti-bacterial properties of biosynthesized silver nanoparticles using native inulin. RSC Adv. **8**, 28746–28752 (2018)

Yang, J., Zhang, Q., Chang, H., Cheng, Y.: Surface-engineered dendrimers in gene delivery. Chem. Rev. **115**(11), 5274–5300 (2015)

Yhee, J.Y., Son, S., Kim, N., Choi, K., Kwon, I.C.: Theranostic applications of organic nanoparticles for cancer treatment. MRS Bull. **39**(3), 239–249 (2014)

Yin, B., Tang, S., Sun, J., et al.: Vitamin C and sodium bicarbonate enhance the antioxidant ability of H_9C_2 cells and induce HSPs to relieve heat stress. Cell. Stress Chaperones. **23**, 735–748 (2018). https://doi.org/10.1007/s12192-018-0885-2

Yu, W., Huang, Y., Pei, L., et al.: Magnetic Fe_3O_4/Ag hybrid nanoparticles as surface-enhanced Raman Scattering substrate for trace analysis of furazolidone in fish feeds. J. Nanomater. **2014**, 1–8 (2014). https://doi.org/10.1155/2014/796575

Zhang, C., Zheng, Y.-Y., Gong, Y.-M., et al.: Evaluation of immune response and protection against spring viremia of carp virus induced by a single-walled carbon nanotubes-based immersion DNA vaccine. Virology. **537**, 216–225 (2019). https://doi.org/10.1016/j.virol.2019.09.002

Zhu, X., Tian, S., Cai, Z.: Toxicity assessment of iron oxide nanoparticles in zebrafish (*Danio rerio*) Early Life stages. PLoS One **7**, e46286 (2012). https://doi.org/10.1371/journal.pone.0046286

Zhu, X., Teng, J., Xu, E.G., et al.: Toxicokinetics and toxicodynamics of plastic and metallic nanoparticles: a comparative study in shrimp. Environ. Pollut. **312**, 120069 (2022). https://doi.org/10.1016/j.envpol.2022.120069