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Nanotechnology in aquaculture: Transforming the future of food security

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ABSTRACT

In the face of growing global challenges in food security and increasing demand for sustainable protein sources, the aquaculture industry is undergoing a transformative shift through the integration of nanotechnology. This review paper explores the profound role of nanotechnology in aquaculture, addressing critical issues such as efficient feed utilization, disease management, and environmental sustainability. Nanomaterials are used to enhance nutritional content and digestibility of aquafeed, optimize fish growth and health, and improve disease prevention. Nanoparticle-based vaccines and drug delivery systems reduce antibiotic reliance, while nano sensors monitor water quality in real-time. Furthermore, nanotechnology has revolutionized infrastructure design, contributing to smart, self-regulating aquaculture systems. Despite its vast potential, challenges such as ethical considerations and long-term safety must be addressed. This paper highlights nanotechnology's transformative role in aquaculture, underscoring its potential to contribute significantly to global food security through enhanced productivity and sustainability.

1. Introduction to nanotechnology

The global demand for seafood has surged in recent years, driven by population growth and increasing awareness of the health benefits associated with consuming fish and other aquatic organisms (Golden et al., 2021). About more than 49 % of the world's fish consumption is provided by aquaculture production. Although the production rate of aquaculture has halved in the last two decades compared to previous decades (1980s and 1990s), it is still the fastest producing sector in any of the other animal origin food-producing sectors. At present, about half of the world's annual fish consumption is provided by aquaculture production (FAO, 2018). Given the increasing demand for fish consumption on the one hand and the unchanged capture production (since the 1990s) on the other hand, it is expected that the share of aquaculture will be much higher in the coming years (Oddsson, 2020). However, traditional aquaculture practices face numerous challenges, including environmental degradation, disease outbreaks, and resource inefficiencies, which threaten the industry's sustainability (Naylor et al., 2023). To address these challenges, researchers are turning to cutting-edge technologies, particularly nanotechnology, to revolutionize the aquaculture industry and ensure sustainable food production for future generations (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). Nanotechnology involves the manipulation of matter at the atomic or molecular scale, typically involving structures between 1 and 100 nm. and holds immense promise for transforming various aspects of aquaculture, from improving feed efficiency to enhancing disease management and water quality (Khursheed et al., 2023). One of the most significant applications of nanotechnology in aquaculture lies in the development of nano-enabled feed additives and supplements. These nano-sized particles are often encapsulated within biocompatible materials that can enhance the delivery of essential nutrients, vitamins and minerals to aquatic organisms, thereby promoting their growth, immune response and overall health (Kumar et al., 2022). In particular, nanotechnology offers innovative solutions for enhancing feed efficiency, improving water quality, promoting fish health, and managing diseases (Fajardo et al., 2022a; Fajardo et al., 2022b). For instance, nanomaterial-based water treatment systems have been devised to efficiently remove pollutants, pathogens and excess nutrients from aquaculture effluents, reducing the risk of eutrophication and contamination of natural water bodies (Ibrahim et al., 2016; Yaqoob et al., 2020).

Additionally, nanosensors and monitoring devices enable real-time detection of water quality parameters, allowing for timely interventions to maintain optimal conditions for aquatic species (Lu et al.,

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2016). Moreover, nanotechnology plays a crucial role in revolutionizing disease management strategies in aquaculture (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). By utilizing nanoparticles with antimicrobial properties, researchers aim to develop novel therapeutics capable of combating infectious diseases that pose significant threats to fish and shellfish populations (Wang et al., 2017). Nanoparticle-based vaccines also hold immense potential for enhancing the immune response of aquatic organisms and reducing the prevalence of diseases, thus minimizing the reliance on antibiotics and chemical treatments (Pati et al., 2018). The integration of nanotechnology into aquaculture practices not only enhances productivity and sustainability but also addresses broader challenges related to global food security and resource conservation. With the world's population projected to reach nearly ten billion by 2050, the demand for nutritious and environmentally sustainable food sources will continue to escalate (Mrabet, 2023). Moreover, other branches of nanotechnology like green nanotechnology utilizes biological pathways for nanoparticle production, offering advantages in sectors like pharmaceuticals and bioengineering Vijayaram, Ghafarifarsani, Vuppala, et al., 2024; Vijayaram, Razafindralambo, Ghafarifarsani, et al., 2024; Vijayaram, Razafindralambo, Sun, et al., 2024). By leveraging nanotechnology, the aquaculture industry can meet this demand while minimizing its ecological footprint and preserving fragile aquatic ecosystems.

Despite the promising potential of nanotechnology in aquaculture, its widespread adoption faces several challenges and concerns (Kolupula et al., 2024). Ethical considerations, particularly regarding the potential environmental impact and unforeseen consequences of nanomaterials, require thorough investigation and regulatory oversight. Moreover, key aspects such as long-term safety, cost-effectiveness, and the scalability of nanotechnology-driven aquaculture practices remain areas for further research and discussion. In conclusion, nanotechnology marks a significant paradigm shift in aquaculture, offering transformative opportunities to improve the efficiency, sustainability, and resilience of global food production systems. By leveraging the innovative capabilities of nanomaterials and advanced engineering solutions, the aquaculture industry can address the pressing challenges of the 21st century, ultimately ensuring a more secure and sustainable future for food security across generations.

2. Classification of nanoparticles

Nanoparticles encompass a diverse array of engineered or naturally occurring substances characterized by their unique properties at the nanoscale (1–100 nm). These materials can be broadly classified into several categories based on their composition and origin, each exhibiting distinct functionalities relevant to aquaculture applications (Baig et al., 2021) (Fig. 1). Nanoparticles are commonly categorized into organic, inorganic, and carbon-based types.

2.1. Organic nanoparticles

Organic nanoparticles (ONPs) are derived from organic molecules, generally measuring around 100 nm in size (Ealia & Saravanakumar, 2017). Key examples include ferritin, micelles, dendrimers, and liposomes. Notably, micelles and liposomes serve as heat- and light-sensitive nano capsules, and ONPs are valued in drug delivery applications for being both biodegradable and nontoxic. In aquatic systems, micelles and liposomes function as nanoscale carriers, effectively encapsulating and safeguarding bioactive compounds, which enhances their stability and delivery. Micelles, for example, have been used in fish feed to increase the bioavailability of nutrients, supporting more efficient nutrient uptake (Puri et al., 2009). Additionally, dendrimers are branched macromolecules designed to deliver drugs or vaccines directly to target cells and are gaining attention as valuable tools in managing diseases within aquaculture (Tayel et al., 2019).

2.2. Inorganic nanoparticles

Inorganic nanoparticles consist primarily of metals, metal oxides, and silica. These nanoparticles play crucial roles in various applications within aquaculture.

2.2.1. Metal based nanoparticles

Metal-based nanoparticles (MNPs) are nanoscale particles composed of metals like silver, gold, iron, and copper, showcasing unique physical, chemical, and optical properties due to their minute size and high surface area-to-volume ratio (Nascimento et al., 2018). These properties make MNPs highly suitable for diverse applications, including catalysis, sensing, imaging, and drug delivery. Silver nanoparticles (AgNPs),

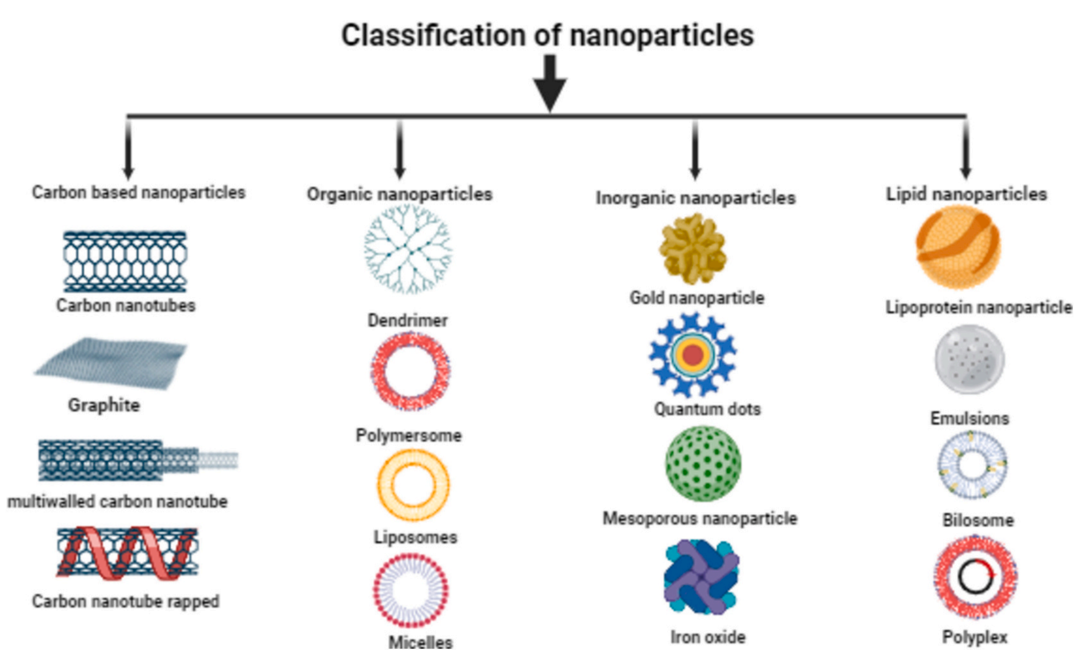

Fig. 1. Diagrammatic representation of the various nanoparticle forms resulting from distinct formulation methods.

known for their strong antimicrobial properties, have been successfully used to combat bacterial infections in fish, contributing to improved health (Wang et al., 2017). Zinc oxide nanoparticles (ZnO NPs) are also valuable in aquaculture, enhancing fish growth, reproductive performance, and immune responses (Ashouri et al., 2015). Quantum dots (QDs), recognized for their distinct optical characteristics (Choi, 2017; Vázquez-González & Carrillo-Carrion, 2014), are proposed as sensors for detecting heavy metals in aquaculture environments (Alexpandi et al., 2020). For example, silver nanoparticles (nAg) have shown efficacy in treating fungal infections in rainbow trout eggs by inhibiting fungal growth (Johari et al., 2015). Zinc oxide nanoparticles (nZnO) demonstrated antibacterial properties by compromising bacterial cell membrane integrity, reducing cell surface hydrophobicity, and downregulating genes related to oxidative stress resistance (Pati et al., 2014). Additionally, research by (Kalita & Baruah, 2020) highlighted that nanoparticles like nTiO2 and nAg helped reduce bacterial accumulation in estuarine waters.

2.2.2. Metal oxide-based nanoparticles

Metal oxide-based nanoparticles are nanoscale particles composed of metal and oxygen atoms. They possess unique properties based on their composition and structure, making them valuable in applications such as catalysis, sensing, and environmental remediation (Nair et al., 2022). These nanoparticles can be synthesized using various methods, and their properties can be tailored for specific applications. However, their potential toxicity and environmental impact require careful assessment. Titanium dioxide nanoparticles (TiO2) is utilized in water treatment processes to remove pollutants and improve water quality in aquaculture systems (Nascimento et al., 2018). Iron oxide nanoparticles have been shown to support growth and immunity in various fish species, offering dual benefits for health management and environmental remediation (Duncan, 2011). The use of titanium photo electrolysis was used in environmental applications including sterilization and disinfection. Under ultraviolet irradiation conditions, TiO_2 NPs produce highly active hydroxyl (OH^-), superoxide ion (−O·), and peroxyl radical ($O_2{}^-$) having high oxidation capacity. Free radicals change cell membrane structure, leading to their apoptosis, thus sterilizing and disinfecting (Cin, 2021).

2.3. Carbon based nanoparticles

Carbon-based nanoparticles (CNPs), such as carbon nanotubes, graphene oxide, fullerenes, and carbon dots, are gaining traction in aquaculture due to their diverse applications and compatibility with biological systems. Known for their potent antimicrobial and antioxidant properties, they help maintain water quality and mitigate pathogen presence (Verma, Rani, et al., 2020; Verma, Thakur, et al., 2020). Among these, fullerenes and carbon nanotubes stand out as key carbon-based nanoparticles (Ealia & Saravanakumar, 2017). Fullerenes, characterized by their hollow, spherical carbon structure, have captured commercial interest due to their distinct features, including electrical conductivity and structural resilience (Georgakilas et al., 2015). Additionally, CNPs serve as efficient carriers for delivering drugs, nutrients, and vaccines, enabling controlled release that boosts treatment efficacy and minimizes dosing needs (Giri et al., 2021). Their pollutant-adsorbing capability makes them highly suitable for water purification, critical for maintaining healthy aquatic systems (Foo et al., 2024). CNPs also enhance nutrient delivery and growth in fish, leading to improved growth rates and feed conversion efficiency (Moges et al., 2020). Furthermore, the optical and electrical properties of CNPs make them ideal for use in sensors, facilitating real-time monitoring of essential water quality indicators (Shafi et al., 2024).

2.4. Lipid based nanoparticles

Lipid-based nanoparticles (NPs) are increasingly valuable in biomedical applications due to their distinct properties. These spherical NPs, typically 10 to 1000 nm in diameter, feature a solid lipid core surrounded by a matrix of lipophilic molecules (Khan et al., 2019) and are stabilized by surfactants or emulsifiers. Lipid nanotechnology is dedicated to the design and synthesis of these NPs, with applications in fields like drug delivery and RNA release for cancer treatments. Research underscores the effectiveness of lipid NPs in targeted drug delivery (Puri et al., 2009). Solid lipid nanoparticles (SLNs), in particular, are capable of encapsulating lipophilic drugs, offering a controlled release system that boosts the therapeutic impact in treating fish diseases (McClements & Rao, 2011). Additionally, nanoliposomes are effective in delivering essential fatty acids, vitamins, and immunostimulants to fish, enhancing their health and growth (Hoseini-Ghahfarokhi et al., 2020). According to (Zhang et al., 2023), lipid carriers for mRNA delivery encompass eight types, including liposomes (LPs), liposome-like nanoparticles (LLPs), solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), lipid-polymer hybrid nanoparticles (LPNs), nano emulsions, exosomes, and lipoprotein particles (LPTs). Among colloidal carriers, SLNs stand out for their enhanced safety, stability, and controlled drug release and can be scaled up following industrial guidelines (Trapani et al., 2022).

3. Applications of nanotechnology in aquaculture sector

Nanotechnology offers innovative solutions to various challenges faced by the aquaculture industry, leading to improved productivity, efficiency, and sustainability (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). By leveraging nanomaterials and nanodevices, aquaculture can enhance feed efficiency, disease management, water quality monitoring, and environmental sustainability (Fajardo et al., 2022a, 2022b). These advancements can significantly contribute to meeting the growing global demand for high-quality seafood, thereby enhancing food security for communities worldwide (Fig. 2).

3.1. Role of nanoparticles in fish growth and reproduction

Nanoparticles have emerged as a promising tool in enhancing fish growth and reproduction in aquaculture, offering innovative solutions to improve productivity and sustainability (Fajardo et al., 2022a, 2022b). The role of nanoparticles in these processes is multifaceted, involving improvements in feed efficiency, nutrient absorption and reproductive performance. This section explores the mechanisms and effects of nanoparticles on fish growth and reproduction, citing relevant research studies to support these findings. Nanoparticles have been shown to enhance feed efficiency and nutrient utilization in fish. For example, titanium dioxide nanoparticles (TiO_2 NPs) have been used as feed additives to improve growth performance in various fish species. (Mohapatra et al., 2021) reported that TiO_2 NPs supplementation in fish diets resulted in improved growth rates, feed conversion ratios and nutrient absorption efficiency. Similarly, zinc oxide nanoparticles (ZnO NPs) have been shown to enhance the growth performance of common carp (*Cyprinus carpio*) by improving nutrient digestibility and absorption (Hoseini-Ghahfarokhi et al., 2020).

Nanoparticles have also shown potential in enhancing fish reproductive performance. Silver nanoparticles (AgNPs), for instance, have been demonstrated to improve sperm quality and increase egg production in fish. (Ahmad, 2022) found that AgNPs supplementation in the diet of zebrafish (*Danio rerio*) resulted in increased sperm motility and viability, leading to higher fertilization rates and increased egg production. Additionally, ZnO NPs have been used to enhance the reproductive performance of fish by improving gonadal development and sperm quality (Suresh et al., 2018). The mechanisms underlying the effects of nanoparticles on fish growth and reproduction are not fully understood but are thought to involve their unique physicochemical properties. Nanoparticles have a high surface area to volume ratio, which allows them to interact more efficiently with biological systems.

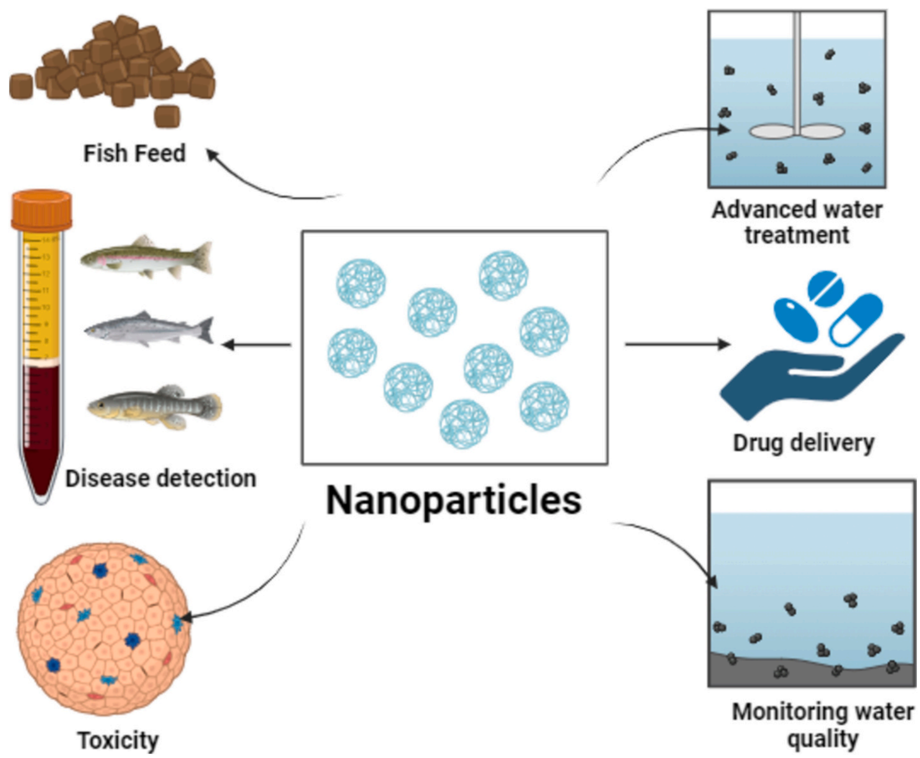

Fig. 2. Diverse applications of nanoparticles across various areas of aquaculture.

Additionally, nanoparticles can penetrate biological barriers, such as cell membranes, and deliver bioactive compounds directly to target tissues, enhancing their efficacy. The findings of (Izadpanah et al., 2022) indicated that providing *Acanthopagrus arabicus* with a PP-based diet enriched with 1–4 mg of n.Se per kg can enhance the reproductive success of female broodfish, as well as increase the length gain and survival rate of their larvae. Furthermore, (Saffari et al., 2021) reported that supplementing plant protein-based diets for female *Acanthopagrus arabicus* with 2 to 4 mg N-Se per kg significantly enhances reproductive performance. The diet with 4 mg N-Se increased relative fecundity and fertilization rates, while the control and 2 mg N-Se diets showed higher hatchability. Notably, larvae from the 2 mg N-Se diet exhibited the best length gain and survival rates at three days post-hatch. These results indicate that nano-selenium supplementation can optimize reproductive outcomes and larval viability in *A. arabicus*, making it a valuable strategy in aquaculture. In addition to this supplementation of plant-protein diets with 2–4 mg nano-Se/Kg enhanced antioxidant status and reproductive efficiency in *A. arabicus* females, while also improving the capacity for antioxidants in the offspring, hence reducing embryonic abnormalities and mortality rates in the offspring. A favourable link was seen between dietary selenium level, glutathione peroxidase activity, and total antioxidant capacity in the eggs, resulting in a reduction of malondialdehyde and therefore an enhancement (Saffari et al., 2022).

Despite their potential benefits, the use of nanoparticles in aquaculture raises safety and environmental concerns. Studies have shown that nanoparticles can accumulate in fish tissues and organs, potentially leading to toxicity issues. Therefore, it is essential to conduct comprehensive risk assessments to ensure the safe use of nanoparticles in aquaculture practices. In conclusion, nanoparticles offer promising opportunities to enhance fish growth and reproduction in aquaculture. Their ability to improve feed efficiency, nutrient absorption, and reproductive performance can contribute significantly to the sustainability and productivity of aquaculture systems. However, further research is needed to fully understand the mechanisms of action and potential risks associated with nanoparticle use in aquaculture.

3.2. Role of nanoparticles in immunity and stress response

Nanomaterials have shown promising applications in enhancing immunity and stress response in fish, offering an innovative approach for sustainable aquaculture (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). Due to their unique properties, such as high bioavailability and targeted nutrient delivery, nanoparticles like zinc oxide, silver, chitosan, and selenium can effectively enhance immune responses and reduce oxidative stress in fish (Aly et al., 2023; Kumar et al., 2023; Rezaei et al., 2024). Studies have demonstrated that zinc oxide nanoparticles can elevate immune markers like immunoglobulin and lysozyme, increasing disease resistance against common pathogens (Awad et al., 2019). Dietary supplements rich in antioxidants are crucial in reducing the risk of peroxidative damage in aquatic animals. Research indicates that nano-selenium (nano-Se) and dietary coenzyme Q10 (CoQ10) supplementation notably enhance immunological and antioxidant responses. Additionally, nano-selenium has been shown to improve stress resilience and endurance in rainbow trout (Aramli et al., 2023). According to (Rezaei et al., 2024), incorporating nano-selenium at a concentration of 3 mg/kg in fish meal-free, plant-based diets boosts growth, feed efficiency, antioxidant immunity, stress resilience, and recovery after stress in juvenile carp (*Cyprinus carpio*). Research on various fish species has demonstrated that nutritional nano-selenium (NNSe) can alleviate both biotic and abiotic stress by neutralizing harmful free radicals, enhancing immune function, maintaining liver tissue integrity, and modulating the expression of heat-shock protein (HSP) genes. Additionally, NNSe significantly reduced cortisol and lactate levels in *A. arabicus* after acute confinement stress. A dosage of 2 mg/kg of nano-selenium is also recommended to boost antioxidant activity in Sobaity juveniles (*Sparidentex hasta*). Furthermore, NNSe aids in the recovery of stressed fish by lowering plasma glucose levels (Abdollahi-Mousavi et al., 2024a; Abdollahi-Mousavi et al., 2024b). (Naderi et al., 2017) found that prolonged exposure to a high stocking density (80 kg/m^3) can significantly impact humoral immune parameters, such as lysozyme and complement activity, as well as the antioxidant system in the liver of rainbow trout. Additionally, recovery from stress induces a shift from aerobic to anaerobic energy production in the liver cells of recuperating fish (*Oncorhynchus mykiss*) (Naderi et al., 2018). Furthermore, nanomaterials enable targeted delivery of essential nutrients and bioactive compounds, improving nutrient absorption and overall health (Jafari & McClements, 2017). These properties of nanomaterials reduce the need for antibiotics, contributing to sustainable practices by limiting chemical residues in aquatic ecosystems and lowering the risk of antibiotic resistance (Munir et al., 2020). As a result, nanotechnology holds great potential in promoting fish welfare and environmental sustainability in the aquaculture industry.

3.3. Role of nanoparticles in aquatic feed

In order to meet the growing demand for seafood worldwide, aquaculture must overcome a number of obstacles, such as preserving the nutritional value and health of farmed fish while reducing its negative environmental effects. The use of nanoparticles to fish diet is one creative solution to these problems (Fajardo et al., 2022a, 2022b). Furthermore, between 5 % and 15 % of the feed remains uneaten by fish, significantly impacting the quality of water in fish farming by contributing to issues such as low oxygen levels and elevated ammonia concentrations (Ghafarifarsani et al., 2022). The incorporation of nanoparticles in aquafeeds enhances nutrient absorption and digestion, resulting in improved feed efficiency and reduced waste (Vijayaram, Ghafarifarsani, Vuppala, et al., 2024; Vijayaram, Razafindralambo, Ghafarifarsani, et al., 2024; Vijayaram, Razafindralambo, Sun, et al., 2024). The nutritional supplementation of nano-Selenium at 3 mg/kg enables the complete substitution of fishmeal with plant-based elements in diets for common carp, without adverse impacts on growth performance and well-being metrics (Sharif-Kanani et al., 2024). In addition to this (Saremi et al., 2024) reported that the combined effect of Se-NPs and vitamin C enhances growth and health in common carp. Diets supplemented with 500 mg of vitamin C and 0.5–1 mg of Se-NPs per kg (VC500SeNPs0.5 and VC500SeNPs1) significantly boosted growth rates, while those containing 1000 mg of vitamin C and 1 mg of Se-NPs per kg (VC1000SeNPs1) or 500 mg of vitamin C and 1 mg of Se-NPs per kg (VC500SeNPs1) improved the overall well-being of the fish.

This not only benefits fish growth and health but also helps maintain better water quality, creating a more sustainable aquaculture environment. Nanoparticles have the potential to improve the overall health and performance of farmed fish as well as the nutritional value of feed (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). Nanoparticles can be employed to more effectively encapsulate and supply vital nutrients, vitamins, minerals, and even medications to aquatic species in the setting of fish feed (Khan et al., 2020). One of the primary advantages of using nanoparticles in fish feed is their ability to enhance nutrient absorption (Ogunkalu, 2019; Zhou et al., 2009). Nutrients that have been nano-encapsulated have more surface area and can interact with the fish's digestive enzymes more effectively. By which fish can absorb these nutrients more efficiently, enabling faster growth and requiring less feed (Pateiro et al., 2021). As a result, the bioavailability of critical nutrients gets increased. Based on their capacity to increase the amount of nutrients taken across the digestive tract, nanoparticles have the potential to boost fish development (Fajardo et al., 2022a, 2022b; Rather et al., 2011). In this context, researchers have also started to identify natural feed additives that act as growth promoters and immunostimulants, which can improve resistance to various infectious diseases (Ghafarifarsani et al., 2021).The impacts of various nanoparticles on the growth performance of various fish species have been the subject of several studies. As per the study, crucian carp, *Carassius auratus gibelio* diets treated with nano-selenium can increase the muscle selenium content, antioxidant status, relative gain rate and final weight of the fish (Zhou et al., 2009). Additionally, nanoparticles can be used to strengthen the defences of farmed fish. When selenium nanoparticles are added to feed, a significant improvement can be shown, enhancing the antioxidant defense system and growth (Ashouri et al., 2015). *Lactobacillus casei* and iron nanoparticles added to the diet of rainbow trout as a probiotic significantly improved growth metrics (Shah & Mraz, 2020). Another study by (Ashouri et al., 2015) demonstrated that feeding *Cyprinus carpio* dietary nano-selenium improved growth parameters and other biochemical parameters when compared to the control group. Moreover, the effects of nano zinc oxide (ZnO) have been compared to Zn O and $ZnSO_4$ as dietary zinc supplements in basal feed to see how they affect the growth and haematological parameters of grass carp, *Ctepharyngodon idella* (Faiz et al., 2015). They found that fish fed levels 1 and 2 of ZnO supplemented diets had the highest percentage weight gain, specific growth rate and feed conversion ratio. They recommended that the ideal dietary supplementation amount of ZnO for *C. idella* be 30 mg/kg feed. Young carp and sturgeon fish were fed iron nanoparticles, and improvements ranged between 30 % and 24 % (Asad et al., 2024). Their research showed that adding separate selenium from different sources (nano selenium and seleno methionine) to the basal diet can improve antioxidant status, final weight, relative weight rate and selenium concentration on crucian carp, *Carassius auratus gibelio* muscle (Saffari et al., 2017). According to (Ashouri et al., 2015), adding 1 mg of nano-Selenium (Se) per kg of feed significantly improved the antioxidant defense system and growth performance of *Cyprinus carpio*, as compared to the control groups. Dietary feed supplemented with iron nanoparticles is utilized to increase Nile tilapia, *Oreochromis niloticus* fish growth and feed efficiency compared to the control (Elabd et al., 2022). Similar to this, feeding selenium nanoparticles at the rate of 5 mg Se/kg and magnesium nanoparticles (base diet +500 mg Nano mg/kg diet) to fish improves their growth performances compared to the control group (Ilham & Fotedar, 2017; Longbaf Dezfouli et al., 2019). These nanoparticles can be added to fish feed to help lower the risk of bacterial and fungal infections, thereby improving the health of the fish as a whole. The use of nanoparticles in fish feed can help aquaculture be more environmentally sustainable. As a result, improved nutrient absorption leads to reduced feed wastage, resulting in lower nutrient runoff into nearby water bodies. However, excess nutrients can damage aquatic ecosystems and produce water pollution, therefore doing this can lessen their negative effects on the environment.

In short, nanoparticles in aquatic feed can improve food security by enhancing nutrient absorption, boosting immune responses and improving growth rates in farmed fish. They can also help reduce the environmental impact of aquaculture by improving feed efficiency and reducing waste. Overall, nanoparticles offer a promising avenue for enhancing the productivity and sustainability of aquaculture, contributing to global food security. However, more study is required to address security issues, improve the use of nanoparticles in fish feed and guarantee financial viability (Samanta et al., 2022).

3.4. Role of nanoparticles in food processing

Nanoparticles play a significant role in food processing, offering innovative solutions for enhancing food quality, safety and shelf-life (Sridhar et al., 2021). These tiny particles, typically ranging from 1 to 100 nano meters in size, can be engineered to have specific properties that benefit various aspects of food production and preservation. One important application of nanoparticles in food processing is in packaging materials. Nanocomposites can be used to create packaging that is stronger, more flexible, and more resistant to gases such as oxygen and carbon dioxide, thus extending the shelf life of packaged foods (Youssef & El-Sayed, 2018). Extending product shelf life is a primary objective of the food industry, since it helps to maintain food quality and freshness. At the moment, food processing divisions can benefit greatly from several developments brought about by nanotechnology. These advancements aim to extend product shelf life by stopping gas passage across packaging, while also providing information about potentially spoiled components (Sagar et al., 2022). Nanoparticles also have antimicrobial properties, which can be utilized to develop food packaging that inhibits the growth of bacteria and other pathogens, further enhancing food safety (Zhu et al., 2014). Moreover, ice that has been impregnated with nanoparticles can be employed in a variety of applications related to food packaging. On the surface of the flathead grey mullet (*Mugil cephalus*), for instance, it has been observed that the incorporation of silver nanoparticles, isolated from the midrib of bananas, into nano-ice reduces the number of microbes and even inhibits the development of Acinetobacter species (Daniel et al., 2016). More attention is being paid to the use of organically generated silver nanoparticles in seafood preservation than to chemical manufacture (Huang et al., 2018). Fish, prawns and oysters are a few more species that have been utilized in the creation of the nanoparticles. Furthermore, nanoparticles are being explored for their potential in food safety and quality control. They can be used in sensors to detect contaminants or pathogens in food products, ensuring they meet regulatory standards (Ramasamy et al., 2016).

3.5. Role of nanoparticles in nanofilms and nano-biosensors

Nanoparticles play a crucial role in the development of nanofilms and nano-biosensors for various applications in aquaculture, including water quality monitoring, disease detection, and drug delivery systems. Nanofilms, which are thin layers of material containing nanoparticles, have unique properties that make them ideal for use in aquaculture. These films can be applied to surfaces to provide antimicrobial properties, improve water quality, and reduce fouling on aquaculture equipment and structures (Handy et al., 2023). Additionally, nanofilms can be used to create barrier coatings for packaging materials, extending the shelf life of seafood products (Aranaz et al., 2016). Nano-biosensors are another important application of nanoparticles in aquaculture. These sensors can detect and quantify various analytes, such as pathogens, toxins, and environmental pollutants, in aquaculture systems (Zhao et al., 2018). Nano-biosensors offer high sensitivity, specificity, and rapid detection capabilities, making them valuable tools for monitoring water quality and ensuring the health of aquaculture species (Zhu et al., 2014). Nanoparticles are increasingly being utilized in aquaculture for their diverse applications in enhancing productivity, sustainability, and environmental monitoring. In the context of nanofilms, nanoparticles like silver, copper, and zinc oxide are commonly incorporated into films to impart antimicrobial properties. These films can be used in aquaculture facilities to reduce the growth of harmful bacteria and improve the overall health of fish and other aquatic organisms (Wang et al., 2022). Nano-biosensors, on the other hand, offer real-time monitoring capabilities for various parameters critical to aquaculture, such as pH, dissolved oxygen, ammonia, and nitrite levels. These sensors, typically made with nanomaterials like carbon nanotubes, graphene, or metal nanoparticles, provide rapid and sensitive detection, enabling prompt actions to maintain optimal conditions for aquaculture operations (Mani et al., 2021). Nanotechnology-based biosensors offer a valuable tool for microbial management. Scientists at NASA in the United States have created a highly sensitive biosensor utilizing carbon nanotubes. This biosensor is capable of detecting minute quantities of microorganisms, including bacteria, viruses, parasites and heavy metals in water and food sources (Ali et al., 2020). Nano colloidal silver, another remarkable product of nanotechnology, acts as a catalyst and can effectively target a broad spectrum of microorganisms, including bacteria, fungi, parasites, and viruses, by disrupting the enzymes crucial for their metabolic processes (Selvaraj et al., 2014). Zinc nanoparticles serve as effective surface coatings against biofilms due to their strong photocatalytic and antimicrobial properties. In the food industry, biofilms pose contamination risks, but zinc nanoparticle coatings help prevent biofilm formation, supporting food safety and hygiene (Akbarian et al., 2022). Additionally, advanced tracking nano-sensors like "Smart fish" can be equipped with sensors and locators, transmitting health and location data to a central computer. This technology has the potential to manage both cage systems and individual fish effectively (Dei et al., 2023).

3.6. Role of nanoparticles in Nano emulsion and Nanoliposomes

Because of its incredibly small droplet size (less than 100 nm), nano emulsion have exceptional stability and physiochemical characteristics (Otoni et al., 2016). Because of these dimensions, lipophilic solutions have better activity because there is more surface area per unit mass (Marhamati et al., 2021). The next frontier in the creation of edible films is represented by nano-emulsions. Alginate films with essential oil-loaded nano-emulsions have been produced to enhance water dispersion and inhibit essential oil degradation (Acevedo-Fani et al., 2015). The antimicrobial activity of an edible composite film created by nano-emulsified cinnamaldehyde, as well as the antibacterial characteristic of manufactured films and thyme essential oil, which has been shown to inhibit *E. coli* growth, have all been reported (Otoni et al., 2014). It is currently known that essential oils have improved and superior antibacterial properties to surfactant nano-metric micelles. (Valencia-Sullca et al., 2016) has demonstrated how essential oils can be enclosed in lecithin nano-liposomes. In addition to this, the incorporation of eugenol into lecithin nano-liposomes allows the films to maintain around 40–50 % of the included eugenol, as opposed to only 1–2 % when same molecule was incorporated through a direct emulsification technique (Hussain et al., 2019).

Moreover, liposomes are synthetically created nanostructures made of lipid bilayers that possess an inherent ability to function as carriers of medications, vaccinations, and other substances. It is non-toxic, biodegradable, immune-stimulating, and the FDA has granted licenses for a number of nano-liposomal products. Furthermore, it is a highly effective delivery system with the ability to easily pass through membranes and manage the targeted release of hydrophobic and hydrophilic chemicals. Fish oil and seafood are good sources of omega-3 fatty acids that can be effectively delivered and protected when added to food through the use of nano-liposome-encapsulated oil (Feizollahi et al., 2018). Nutraceuticals can now be delivered via the dermal route thanks to nano liposomal delivery of essential vitamins like folic acid (Sarkar et al., 2022a, 2022b). Carp (*Cyprinus carpio*) showed a successful vaccination against *Aeromonas salmonicida* antigen encapsulated in liposomes (Radhakrishnan et al., 2023). Using liposome-encapsulated immunostimulant cocktail, a non-specific vaccination nanocarrier was administered to several fish species. According to (Ruyra et al., 2013) liposomal lipopolysaccharide (LPS)-dsRNA cock tail was seen penetrating into the plasma membranes of zebrafish and liver hepatocytes of trout, inducing inflammatory substances and antiviral reactions. (Hasan et al., 2018) reported that encapsulating curcumin into liposomes, which were synthesized from natural sources (*salmon lecithin*), produced positive outcomes when investigated under primary cortical neurons culture.

3.7. Role of nanoparticles in monitoring water quality and in treating pollutants in water

The role of nanoparticles in monitoring water quality can improve food security by ensuring that the water used in aquaculture is safe and clean, which is essential for the health and growth of farmed fish (Fajardo et al., 2022a, 2022b). Nanoparticles can also be used to treat pollutants in water, such as heavy metals and organic contaminants, which can contaminate fish and other aquatic organisms. By removing these pollutants, nanoparticles can help ensure the safety and quality of the fish produced, thus contributing to food security. A global priority is ensuring access to clean and safe water, and successful water quality monitoring is essential to attaining this objective (Mishra et al., 2021). Nanotechnology has recently offered creative methods for utilizing nanoparticles to monitor water quality (Gehrke et al., 2015; Hairom et al., 2021).

Nanoparticles can be engineered to act as extremely sensitive sensors for determining the quality of water. These nanoparticles may be programmed to respond to particular contaminants, such as infections, heavy metals, or organic pollutants (Aguilar-Pérez et al., 2020). (Hairom et al., 2021) conducted a study focusing on the application of nanotechnology to detect and treat surface water contamination, aiming to ensure environmental sustainability. Their research offers valuable insights and opportunities for further exploration of nanotechnology's potential in enhancing surface water treatment methods. It is simple to identify and measure the impurities when these nanoparticles interact with the target substance since they change in attributes like color, fluorescence or conductivity (Prosposito et al., 2020). The capacity of nanoparticles to deliver quick and real-time findings is one of the major benefits of using them for water quality monitoring (Nagar & Pradeep, 2020). Traditional water quality monitoring techniques frequently entail time-consuming laboratory analysis, which can impede decision-making in an emergency. Instantaneous feedback from nanoparticle-based sensors enables swift reaction to possible risks to water quality (Jan et al., 2021).

In a single measurement, nanoparticle-based sensors can collect information on variables including pH, turbidity, dissolved oxygen and the presence of certain contaminants, enabling a more thorough evaluation of water quality (Demetillo et al., 2019). Nanoparticle-based sensors can be integrated into remote monitoring systems, enabling continuous and real-time data collection from diverse water sources. This capability is particularly valuable in remote or hard-to-access locations where regular on-site monitoring may be challenging (Miller et al., 2023). In addition to this, remote monitoring guarantees early detection of problems with water quality and allows for prompt intervention (Lakshmikantha et al., 2021). Long-term cost-effectiveness is a possibility for the use of nanoparticles in water quality monitoring. Nanoparticle-based sensors are frequently less expensive to maintain and use consumables than conventional monitoring techniques, despite having greater initial research and setup expenses. Additionally, by quickly resolving water quality issues, their real-time capabilities can save time and resources (Javaid et al., 2021). Additionally, nanoparticles are revolutionizing the field of water quality monitoring by offering rapid, sensitive and multi-parameter analysis capabilities. Their real-time monitoring potential and cost-effectiveness make them a valuable tool for ensuring clean and safe water sources (Tovar-Lopez, 2023). However, to address security issues, enhance sensor performance and provide standardized protocols, continual research and development is required. Nanoparticle-based water quality monitoring has a lot of potential to conserve our water resources and ensure public health with further innovation.

3.8. Role of nanoparticles in fish health management through disease diagnosis

Disease outbreaks are a serious hazard to the aquaculture sector, as they can result in financial losses and environmental issues (Maldonado-Miranda et al., 2022). Therefore, maintaining good health is essential for protecting fish species from pathogen contamination and recuperation (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). Through innovative techniques and the reformation of traditional technologies, nanoparticles (NPs) have emerged as valuable tools in fish health management, offering innovative solutions for disease diagnosis and treatment (Kaul et al., 2018). Their unique properties, such as small size, high surface area-to-volume ratio, and tenable surface chemistry, make them ideal candidates for various applications in aquaculture. Nanoparticles can be functionalized with specific ligands or antibodies to detect pathogens or biomarkers associated with fish diseases. For example, gold nanoparticles have been used in biosensors to detect fish viruses with high sensitivity and specificity (Huang et al., 2018). These nanoparticle-based biosensors enable rapid and accurate diagnosis of fish diseases, facilitating timely intervention and treatment. For instance, gold nanoparticles capped with immunoglobulin G (IgG) are employed to visualize pathogenic organisms such as *Staphylococcus aureus* and *S. pyogenes*. IgG has the capability to selectively attach to the antigenic epitopes of these bacteria, making IgG-capped gold nanoparticles a precise labelling tool for these microorganisms (Zhu et al., 2014). By utilizing biodegradable nanoparticle carriers like chitosan and poly-lactide-*co*-glycolide acid (PLGA) in combination with DNA vaccines, it is possible to provide substantial protection to fish and shellfish against not only bacterial but also individual viral diseases. The appropriate dietary amounts of silver nanoparticles could increase aquatic organism survival, zootechnical efficiency, and metabolic rank, as well as decrease stress from both abiotic and biotic sources (Khursheed et al., 2023). Furthermore, mass vaccination of fish populations can be accomplished using a nano delivery system with the potential to trigger effective immune responses (Danhier et al., 2012). Herbal and probiotic blends are emerging as innovative diseases control and treatments in aquaculture, offering potential alternatives to conventional chemicals, antibiotics, and vaccines, with added support from advancements in nanotechnology (Vijayaram, Ghafarifarsani, Vuppala, et al., 2024; Vijayaram, Razafindralambo, Ghafarifarsani, et al., 2024; Vijayaram, Razafindralambo, Sun, et al., 2024).

Nanoparticles also play a crucial role in disease treatment in aquaculture. Nanoparticle-based drug delivery systems can improve the efficacy of therapeutics by enhancing their stability, bioavailability, and targeted delivery to infected tissues. For instance, silver nanoparticles have shown antimicrobial properties and have been used to treat bacterial infections in fish (Rajendran et al., 2015). Similarly, nanoparticles loaded with antimicrobial peptides or vaccines can enhance the immune response in fish, reducing the incidence and severity of infections. Silver nanoparticles (AgNPs) possess potent bactericidal properties against both gram-positive bacteria like *Staphylococcus aureus* and *Streptococcus pyogenes*, as well as gram-negative bacteria like *E. coli* and *Proteus vulgaris*. Positively charged AgNPs are drawn to the negatively charged cell walls of these bacteria, thanks to the presence of teichoic acids or lipopolysaccharides (LPS), through electrostatic attraction. They penetrate the cell wall and subsequently interact with the negatively charged cell membrane, which contains carboxyl, phosphate, and amino groups (Abbaszadegan et al., 2015). This interaction damages the cell membrane, leading to the leakage of cellular contents and the eventual demise of the pathogen. Furthermore, once inside the bacterial cell, AgNPs release Ag^{+} ions that can interact with biomolecules such as DNA, enzymes, proteins, and lipids, resulting in DNA damage, lipid peroxidation and the inactivation of enzymes and proteins (Yunan Qing et al., 2018).

Oncorhynchus mykiss challenged with *A. salmonicida* and exposed to silver nanoparticles for a brief period of time (100 g L^{-1} h^{-1}) did not experience any mortality or clinical indications compared to controls (challenged but not exposed to AgNPs) (Shaalan et al., 2016a, 2016b). According to (Kaittanis et al., 2010) nanoparticles can be engineered to interact with particular biomarkers linked to fish disorders, such as viruses, bacteria, and parasites. They are extremely sensitive to molecular interactions due to their high surface area to volume ratio and distinctive characteristics. Nanosensors are also effective and easy solutions to identify pathogens. Various nanosensors can be utilized to efficiently identify significant aquaculture viruses, such as salmonid alpha, betanoda and aquabirna (Sarkar et al., 2022a, 2022b). This makes it possible to detect even very small quantities of disease related biomolecules, resulting in earlier and more accurate disease diagnosis (Thwala et al., 2023). The White Spot Syndrome Virus (WSSV) strain in shrimp has been targeted using an antibody-based, extremely sensitive immunodiagnostics procedure that attaches nanoscale gold with alkaline phosphatase (ALP) attached secondary antibody titre (Thiruppathiraja et al., 2011). Currently, graphene oxide (GO) is applied as a template in designing electrochemical biosensors as it possesses a unique chemical constitution and biocompatibility. The United States Department of Agriculture (USDA) is in the final stages of testing a system for mass fish vaccination using ultrasound. Nano capsules containing short DNA strands are introduced into fishponds, where they are absorbed into the fish cells. Ultrasound is then employed to rupture the capsules, releasing the DNA and prompting an immune response in the fish. This technology has already been successfully tested on rainbow trout by clear spring foods, a major aquaculture company in the United States that produces approximately one-third of all domestically farmed trout. Importantly, this nanoscale device can detect and treat infections well before any symptoms become apparent at a macro scale (Tayel et al., 2019).

3.9. Role of nanoparticles in nanomedicine

Nanoparticles provide significant benefits across multiple scientific disciplines, especially in the field of medicine. In recent years, their application in disease diagnosis and treatment has surged, largely due to the advancement of stimuli-responsive nano systems that can react to internal or external stimuli (Farjadian et al., 2022). Moreover, the physical stimuli-responsive therapeutic and diagnostic systems present distinct advantages over conventional medicine delivery, such as controlled, stimuli-sensitive release, high medicine loading capacity, lower toxicity, enhanced therapeutic synergy, and superior biocompatibility. However, the design and optimization of nanocarriers for these systems are complex, often requiring empirical approaches tailored to specific diseases, medicine properties, and nanocarrier characteristics (Farjadian et al., 2022). In addition, nanogels are significantly important in regenerative medicine, wound healing and tissue engineering (Farjadian et al., 2024).

Nanomedicine provides various opportunities to enhance fish health by leveraging the inherent properties of different types of nanoparticles. In aquaculture, nanoparticles with antimicrobial and prophylactic properties, such as nano-silver and zinc oxide nanoparticles, are already deployed to mitigate bacterial burdens (Siddiqi et al., 2018). Additionally, ongoing research is exploring the potential of nanoparticles like copper oxide and titanium dioxide for improving fish medications through their antibacterial characteristics. Graphene an emerging nanomaterial known for its affordability, renewability, and commercial viability offers further promise in this context, specifically, oxidized grapheme, which readily dissolves in water and is easily to treatable (Brisebois & Siaj, 2020). Graphene oxide (GO), alone or in combination with metal/metal oxide and polymeric nanoparticles, has demonstrated inhibitory effects on significant aquatic pathogens such as *S. aureus*, *P. aeruginosa*, *E. coli*, and *Vibrio harveyi*. The interaction between GO and these nanoparticles leads to cell membrane damage followed by lysis after mechanical enfolding (Kumar et al., 2019).

3.10. Role of nanoparticles in drug and gene delivery

Aquatic infections are a major concern for the aquaculture sector since they can result in adverse aquatic environmental loss. For farmed fish to remain healthy while using less pesticides and antibiotics, efficient drug delivery methods are essential (Bondad-Reantaso et al., 2023). With increased precision, fewer side effects and better treatment outcomes, nanoparticles have shown promise as a medicine delivery method for fish (Patra et al., 2018). Novel qualities such as sustained release, control over the size, shape, dispersity, and surface charge of targeted materials, location-specific, multi-route delivery procedures, and controlled degradability of the nanocarrier are attributed to drug delivery by nanotechnology (Patra et al., 2018). Enhancing the bioavailability of therapeutic chemicals is one of the main benefits of employing nanoparticles in fish medication delivery (Wu et al., 2020). Nanoparticles can encapsulate drugs, protecting them from degradation and facilitating their controlled release within the fish's body. This ensures that a higher proportion of the drug reaches the target tissues, leading to more effective treatments (Shaalan et al., 2016a, 2016b). The risk of medication exposure to healthy tissues is reduced when medications are delivered by nanoparticles exclusively to the organs or tissues that are in need of treatment. However, nanogels offer significant benefits when utilized as "smart" materials capable of sensing environmental changes. Research has shown that responsive hydrogels are transforming drug delivery systems and revealing new advantages for clinical applications (Farjadian et al., 2024).

Targeted drug delivery reduces the risk of side effects and maximizes the therapeutic effects, leading to faster recovery times for fish (De Jong & Borm, 2008). Reduced environmental effect may result from the controlled release characteristics of nanoparticles used in medicine delivery. The risk of drug leftovers contaminating water bodies and harming non-target organisms is reduced by nanoparticle-based drug delivery systems by reducing the amount of medication delivered into the aquatic environment (Gupta et al., 2020). Nanoparticle-based drug delivery systems have the potential to revolutionize disease management in aquaculture. They enable precise dosing; ensuring that the right amount of medication is administered to each fish. This reduces the risk of under-dosing or over-dosing, which can lead to treatment failure or the development of drug-resistant pathogens (Shaalan et al., 2016a, 2016b).

Gene delivery is another promising technology with the potential to address genetic disorders by introducing a specific gene into a cell. This approach offers an alternative to traditional methods like drugs or surgery and can involve the replacement or deactivation of a mutated gene or the introduction of a new gene to combat a disease (as described by the Genetics Home Reference from the NIH, US National Library of Medicine (Silva et al., 2011). However, a significant challenge in successful gene therapy remains the development of an effective and safe delivery system. Non-viral delivery systems have gained increasing attention as alternatives to viral vectors due to their ability to be produced in large quantities while ensuring safety and stability. Some techniques involve the formation of DNA complexes using various carriers, including lipids, proteins, peptides, or polymers. Additionally, these complexes can be equipped with ligands that target cell-surface receptors on the desired cells and facilitate the intracellular transport of DNA to the cell nucleus (Ali et al., 2021).

Positive outcomes have been found in the creation of complexes between chitosan and DNA. Chitosan has shown the potential to enhance gene transfer efficiency and when combined with appropriate ligands, the DNA-chitosan complex appears to achieve more efficient gene delivery through receptor-mediated endocytosis (Cao et al., 2019). As a refined by-product of the shrimp business, chitosan has gained recognition as a popular polymer-based nano-carrier. Chitosan nanoparticles with a DNA construct that attached the VP28 gene of the white spot syndrome virus were given orally to black tiger shrimp (*Penaeus monodon*). A noteworthy survival rate was seen in the WSSV-challenged shrimp, in contrast to the control group's 100 % mortality rate (Rajeshkumar et al., 2009). Furthermore, experiments involving chitosan incubation with cells have demonstrated minimal cytotoxicity. These findings suggest that chitosan can provide similar effectiveness to other synthetic vectors but without the associated toxicity, making it a viable candidate for in vivo gene delivery. Researchers have also developed hybrid lipid-polymer nanoparticles for delivering siRNA, and recent studies have indicated improved cancer treatment outcomes with co-delivery strategies (Dizaj et al., 2014). In a recent publication, chitosan-dextran sulphate and silica nanoparticles were used to create an effective carrier vehicle that delivered dsRNA into *Penaeus monodon* post-larvae and silenced the *Monodon baculovirus* (MBV) structural gene, p74. Following successful gene silencing in *P. monodon*, this carrier system demonstrated a noteworthy survival rate of 86.63 % (Kirthi et al., 2023).

3.11. Role of nanoparticles for advanced toxicity assessment in fish

Diverse pollutants and toxins pose a persistent threat to aquatic ecosystems and can have a negative impact on fish and other aquatic animals (Amoatey & Baawain, 2019). Understanding and reducing the impact of these pollutants requires accurate and sensitive toxicity assessment methodologies. With their distinctive qualities and adaptability, nanoparticles are becoming more and more important in toxicity tests in fish (Savage et al., 2019). Nanoparticles are particularly sensitive detectors, because they can be functionalized to interact with certain pollutants or biomarkers of toxicity. Even minute amounts of pollutants in water, sediments, or fish tissues can be found using the high surface area-to-volume ratio of nanoparticles (Khan et al., 2019). This increased sensitivity enables the early identification of harmful chemicals before their concentrations threaten fish populations significantly. According to (Shaw et al., 2016), traditional toxicity assessments frequently rely on laborious laboratory analyses that may not offer up-to-date data on changes in water quality or fish health. Real-time monitoring capabilities provided by nanoparticle-based sensors can help researchers and aquaculturists react quickly to harmful events or changes in water quality. This rapid response can minimize the impact of contaminants on fish and aquatic ecosystems (Hairom et al., 2021). To detect certain contaminants, such as heavy metals, pesticides, or organic pollutants, nanoparticles can be specially designed. For the purpose of locating and reducing pollution sources, this targeted detection helps to more accurately determine the kind and source of toxicity (Yadav et al., 2021). Nanoparticles can be utilized to create multiplexed assays, which evaluate the toxicity of several compounds at once. This capacity is crucial since pollutant combinations are frequently seen in aquatic environments (Sanchis et al., 2018). The toxicological status of fish populations and their habitats can be thoroughly assessed using multiplexed assays (Segner et al., 2022). The environmental impact of testing can be reduced with nanoparticle-based toxicity assessments. These assays aid in resource conservation and waste reduction by requiring less chemicals and sample material. This is especially crucial for aquatic management strategies that are sustainable.

When it comes to assessing fish toxicity, nanoparticles are proven to be useful since they provide increased sensitivity, real-time monitoring, focused detection, and multiplexed analysis. For understanding and reducing the effects of pollutants on fish populations and aquatic ecosystems, their application shows considerable promise (Nasr-Eldahan et al., 2021a; Nasr-Eldahan et al., 2021b). To achieve widespread use, it is essential to overcome issues with standardization, safety, regulatory approval and cost-effectiveness. Nanoparticles have the potential to dramatically increase our capacity to protect fish populations and uphold the health and sustainability of the aquatic environment with more research and proper application.

4. Toxicological effects of nanoparticles in aquaculture

The use of nanoparticles in aquaculture has raised concerns regarding their potential toxicological effects on aquatic organism's results in the emergence of a novel form of waste known as nano wastes, posing significant environmental hazards. Thus, it is critical to look into how NPs build up and have negative impacts on various trophic phases of food chain (Asztemborska et al., 2014). (Fig. 3) shows the ecological toxicity range of nanomaterials in aquatic environments. Nanoparticles can enter aquatic environments through various routes, such as wastewater from nanomaterial production facilities or the use of nanoparticle-containing products in aquaculture. Once in the water, nanoparticles can interact with aquatic organisms, including fish, crustaceans and mollusks, leading to potential adverse effects on their health and the aquatic ecosystem as a whole. One of the main concerns regarding the toxicological effects of nanoparticles in aquaculture is their ability to bio accumulate in aquatic organisms. Nanoparticles can be taken up by fish through gills, ingestion, or skin absorption, and once inside the organism, they can accumulate in various tissues and organs (Scown et al., 2010). This bioaccumulation can lead to long-term exposure of aquatic organisms to nanoparticles, increasing the risk of adverse effects.

Several studies have investigated the toxicological effects of nanoparticles on fish in aquaculture (Table 1). For example, silver nanoparticles, which are commonly used for their antimicrobial properties, have been shown to induce oxidative stress, DNA damage, and changes in gene expression in fish (Ahamed et al., 2010; Griffitt et al., 2008). Similarly, titanium dioxide nanoparticles have been found to cause oxidative stress, inflammation, and changes in behavior in fish. According to (Scown et al., 2010), AgNPs smaller than 10 nm caused significant harm to the kidneys and gills of rainbow trout compared to larger AgNPs exceeding 35 nm in size. (Johari et al., 2013) found that the toxicity of AgNPs decreased as rainbow trout progressed from the eleuthero stage of embryo development to the larval and juvenile stages, resulting in lower mortality rates. The study also revealed that during the initial ninety-six hours of exposure, even at low concentrations such as 0.25, 0.71, and 2.16 mg/L, AgNPs were lethal to eleuthero eggs, larvae, and juveniles, respectively. Additionally, a three-hour exposure of juveniles to AgNPs led to a decrease in chloride and potassium concentrations and an increase in adrenaline and cholinesterase concentrations. The freshwater fish *Mystus gulio's* liver, muscles, and gills lost protein and carbohydrates after being exposed to Ag NPs for 15 days. On the other hand, these tissues had higher lipid content. (Abirami & Sudharameshwari, 2017) suggest that the decline in energy content could be attributed to increased glucose utilization under stress, the reduction in protein to heightened protein utilization under stressful

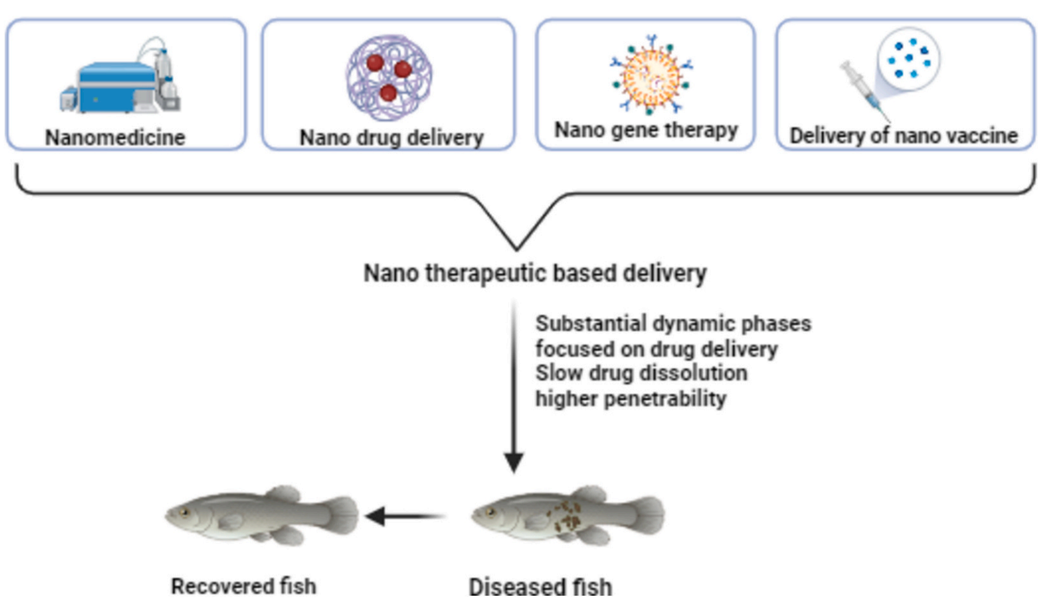

Fig. 3. Emerging applications of nanotechnology in nanomedicine.

Table 1
Impact of nanoparticles on fish species.

Types of nanoparticles	Fish species	Concentration	Effect	References
AgNPs	*Catfish, Rhamdia quelen*	0.03, 0.3, and 3 mg g^{-1}	Injuries in the kidneys and liver, as well as steatosis and vascular congestion was observed.	(López-Barrera et al., 2021)
	Cyprinus carpio	0.03, 0.06, 0.09 mg/L	Most of the sections under study experienced alteration and damage at 0.09 mg/L.	(Kakakhel et al., 2021)
	Clarias garepinus	10 and 100 mg/L (10 nm and 100 nm)	Significant damage was observed in the liver that improves after the recovery time, particularly for 10 nm at 100 mg/L.	(Naguib et al., 2020)
	Oreochromis niloticus and Tilapia zillii	**2 and 4 mg/L**	Elevated concentrations of silver nanoparticles, such as 4 mg/L, negatively affect the antioxidant system in the brain.	(Afifi et al., 2016)
	Rainbow trout	**0.1,0.2,0.4 mg/L**	**It was reported that the development slowed, MHC and MCV values dropped, hepatic enzyme levels rose, and plasma indices changed.**	(Khursheed et al., 2023)
	Common Molly	**0,5,15,25,35,45,60 mg/L**	**The HCT, WBC, and RBC values drastically dropped, and the reproductive physiology changed.**	(Khursheed et al., 2023)
ZnO NPs	***Cyprinus carpio*** L	–	ZnO NPs may have an impact on liver and renal function.	(Chupani et al., 2018)
	Oreochromis mossambicus	20 ppb	Modification in histopathology, morphology and haematological parameters.	(Nascimento et al., 2018)
	Carassius auratus	0.5, 1, and 1.5 mg/L	Significant histological changes in the organs of the liver, kidneys, and gills as well as oxidative stress.	(Ghafarifarsani et al., 2023)
	Oreochromis niloticus	**1 mg/L and 2 mg/L**	Antioxidant enzyme, mRNA expression was dramatically reduced.	(Abdelazim et al., 2018)
	Cyprinus carpio	0.382, 0.573 and 1.146 mg/L	**changes to the gill structure, as well as liver and muscle cell dysfunction.**	(Rajkumar et al., 2022)
Cu NPs	*Danio rerio*	0,25,0.5,1,2,4,8 mg/L	According to the particulate size of the copper suspensions under examination, various anomalies were seen in the structure and behavior of the zebrafish embryos.	(Hua et al., 2016)
	Rutilusrutilus caspicus	**0.1 to 0.5 mgL^{-1}**	**Hepatocellular and renal histological alterations observed. The study's findings demonstrated that copper nanoparticles could kill fish and harm the tissues of the Caspian roach, *Rutillus rutillus caspicus*.**	(Aghamirkarimi et al., 2017)
	Oncorhynchus mykiss	**–**	**Damaged gill paving cells and filaments; the species of fish tested varied in their susceptibility to these effects.**	(Song et al., 2015)
CuO-NPs	*Oreochromis niloticus*	10 mg/L, 20 mg/L, and 50 mg/L. (68.92 ± 3.49 nm)	**Histological impairment of the hepatopancreatic tissues, distal kidneys, and gills.**	(Abdel-Latif et al., 2021)
TiO_2 NPs	*(Oreochromis mossambicus)*	0, 0.5 mg/L, 1.0 mg/L, and 1.5 mg/L.	TiO_2-NPs induced DNA damage.	(Shahzad et al., 2022)
	Prochilodus lineatus	**1 mg/L to 50 mg/L**	Ti accumulates in the brain, liver, and muscles and suppressed the activity of ACHE in the muscles.	(Carmo et al., 2019)
Al2O3-NPs	***Tilapia zillii*** and ***Oreochromis niloticus***	**120 to 180 mgL^{-1}**	**The brain's system for antioxidants is negatively impacted by Ag-NPs at greater concentrations, such as 4 mg/L.**	(Afifi et al., 2016)
As NPs	*Labeo rohita*	1 mg/L, 10 mg/L, and 20 mg/L	Injury to the urinary tract, liver, and lungs was reported.	(Raza et al., 2021)
CdTeQD/CdS	*Oncorhynchus mykiss*	Increasing concentrations system.	CdS/CdTe QD toxicity depended on both concentration and size. Greater than smaller nanoparticles, bulky CdS/CdTe QD masses (25 nm < size <100 nm) decreased the phagocytosis.	(Bruneau et al., 2013)
CdS-NPs	*Channa punctatus*	50 mg/L	Loss of mucous, pillar, and epithelium cells; the micro ridges and microbridges disintegrate, particularly after 30 days.	(Verma, Rani, et al., 2020; Verma, Thakur, et al., 2020)
SiO2-NPs	*(Oreochromis niloticus)*	20, 40, and 100 mg/L	liver and kidney damage.	(Rahman et al., 2022)

circumstances, and the rise in lipids to inappropriate lipid utilization by the tissues.

In fish species like *Mystus gulio,* silver nanoparticles (AgNPs) have been linked to detrimental effects on the main gills lamellae and resulting in problems including tissue necrosis, hypertrophy, and fusing of the main membranes (Abirami & Sudharameshwari, 2017). AgNPs have also been found to decrease the pace at which aquatic organisms feed (Raissy & Ansari, 2011). Furthermore, it was reported that silver nanoparticles (AgNPs) can influence the haematological, serum metabolite, and enzymatic levels in (*Oncorhynchus mykiss*). Additionally, exposure to AgNPs triggers a widespread oxidative stress response in these fish (Mirghaed et al., 2018). Moreover, they may impede the development of micro crustaceans and phytoplankton, which are vital parts of the aquatic food chain and aid in their purification of tainted aquaculture systems (Pham, 2019). Furthermore, AgNPs have the capacity to increase oxidative metabolism in aquatic species' tissues, which causes cypla-2 expression in the gills (Scown et al., 2010). (Hedayati et al., 2022) demonstrated that exposure to iron oxide nanoparticles (IoNPs) resulted in increased levels of cortisol, glutathione S-transferase, and malondialdehyde, along with significant liver damage in fish, characterized by hyperemia, hepatocyte vacuolation, and necrosis. However, incorporating *Lactobacillus casei* into the diet offered protective effects, mitigating the adverse impacts of IoNPs on the common carp's physiological functions.

Moreover, it has been reported that Mozambique tilapias may experience abnormalities in their liver, brain, and gill functioning when exposed to copper nanoparticles (NPs), a major water pollutant. According to (Al Ghais et al., 2019), this detrimental effect also affects the organism's growth and rate of development, which eventually leads to higher death rates. Zinc oxide nanoparticles (ZnO NPs) are harmful to *Oreochromis niloticus*, compromising their antioxidant defense systems; however, vitamin E has been shown to provide protective effects against this toxicity (Farsani et al., 2017). Additionally, research has been done on the toxicity of nickel nanoparticles and are harmful to a variety of aquatic species, including fish, planktonic crustaceans, and algae. (Sadeghi & Peery, 2018) studied that fish size was reduced and toxicity was enhanced when the impacts of silver and selenium nanoparticles on *Tenualosa illish* larvae, fry, juveniles, and fingerlings. Some reports are on the detrimental effects of different iron-containing nanoparticles on Japanese medaka fish due to the growing usage of nanoparticle zerovalent iron-mediated oxidation processes for wastewater treatment. As per there results, Japanese medaka mortality rates were higher during their developmental stages than they were throughout their adult stages due to issues resulting from nanoparticle toxicity (Chen et al., 2013). It was reported that green-synthesized zinc nanoparticles, even at higher concentrations, exhibit lower toxicity compared to their chemical counterparts and can serve as effective nutrient supplements for aquatic animals (Ghafarifarsani et al., 2024). (Mahboub et al., 2022) evaluated the effects of Allium hirtifolium extract (AHE) on enhancing the antioxidant responses of common carp (*Cyprinus carpio*) exposed to foodborne zinc oxide nanoparticles (ZnO-NPs). Results indicated that AHE significantly improved blood indices, stress biomarkers, and antioxidant parameters, while also reducing oxidative stress markers. These findings suggest that AHE supplementation offers notable protective benefits against the toxic effects of ZnO-NPs in common carp. Some scientists have gone deeper to investigate ways to reduce the toxicity of nanoparticles in response to their significant value in treating aquaculture effluents. Unfortunately, it has been found that even plant-mediated nanoparticles which are thought to be more ecologically benign than chemically synthesized ones have harmful impacts on aquatic ecosystem membranes (Abirami & Sudharameshwari, 2017). Moreover, silver nanoparticles synthesized using a metronidazolium-based ionic liquid with citrate as a reducing agent show promise as an antibacterial component in wound dressings, offering enhanced efficacy against both aerobic and anaerobic bacteria (Farjadian et al., 2020). Nevertheless, numerous approaches have been identified to mitigate the toxicity associated with nanoparticles. One such finding reveals that elevating the salinity of the ambient surroundings diminishes the toxicity of silver nanoparticles by promoting the formation of carbonate pellets within fish intestines. This process contributes to the decontamination of pollutants (Kalbassi et al., 2011). In addition to direct effects on fish health, nanoparticles can also impact the aquatic ecosystem by affecting other organisms. (Navarro et al., 2015) found that copper nanoparticles, commonly used in aquaculture as an antifungal agent, can be toxic to phytoplankton, which plays a crucial role in the aquatic food chain. To minimize the potential toxicological effects of nanoparticles in aquaculture, it is essential to understand their fate and behavior in aquatic environments. Factors such as nanoparticle size, shape, surface coating, and concentration can influence their toxicity (Jovanović & Palić, 2012). Additionally, the development of environmentally friendly nanomaterials and sustainable aquaculture practices can help reduce the risk of nanoparticle contamination in aquatic environments.

4.1. Toxicological effects of nanoparticles in human beings

The toxicological effects on aquatic life and potential human health risks raise significant concerns (Tortella et al., 2020). Nanoparticles can enter aquaculture systems through industrial waste, agricultural runoffs, and direct applications, leading to bioaccumulation in fish and other seafood, which humans ultimately consume (Saravanakumar et al., 2022). Studies show that exposure to NPs in aquatic species results in oxidative stress, cellular damage, inflammation, endocrine disruption, and reproductive impairment, with metals like silver and copper nanoparticles demonstrating pronounced toxicity. These toxic effects are exacerbated by the nanoparticles small size and ability to penetrate cellular barriers, increasing the risk of DNA damage and genotoxicity (Brohi et al., 2017; Malhotra et al., 2020; Tortella et al., 2020). In humans, dietary exposure to contaminated seafood can lead to cytotoxic, genotoxic, and potentially carcinogenic effects (Marques et al., 2011; Vignardi et al., 2015). Research has linked prolonged NP exposure to respiratory, neurological, and reproductive health risks, particularly through biomagnification in the food chain (Karimi et al., 2018). As a result, current regulatory frameworks in the U.S. and Europe are reevaluating the safety standards and risk assessment protocols for NPs in aquaculture to mitigate these impacts (Maldonado-Simán et al., 2018). Despite existing guidelines, more comprehensive studies are essential to fully understand nanoparticles long-term effects and to establish stricter regulations to protect both environmental and human health.

5. Mechanism of nanoparticle accumulation in aquatic organisms

In living organisms, toxicity often stems from an overabundance of reactive oxygen species (ROS), which are typically managed by the antioxidant defense system under normal conditions (Bashri et al., 2018). Nanoparticles (NPs) can mimic other toxic substances by generating ROS at elevated concentrations, inducing oxidative stress in affected organisms (Fig. 4). Studies have documented significant ROS production even with small quantities of CuO or ZnO NPs in cells (Chang et al., 2012). NPs can directly provoke ROS production upon contact with organelles within exposed cells, particularly within mitochondria, where disruptions in the electron transport chain which leads to superoxide radical generation (Zhang & Gutterman, 2007). Due to their large surface area, NPs can readily interact with biomolecules, endowing CuO or ZnO NPs with high electronic density (Pisanic et al., 2009).

Research on metallic and metal oxide NPs indicates that oxygen is often essential for ROS generation in AgNPs and nano-zero valent iron, while TiO_2 and ZnO NPs require illumination for ROS generation (Yang et al., 2013). AgNPs are likely toxic to microbes due to the release of silver ions and the production of ROS (Zhang et al., 2016). This excess superoxide oxide (O_2^-) leads to ROS accumulation and oxidative stress (Bashri et al., 2018). The superoxide radical (O_2^-) can be converted to hydrogen peroxide by superoxide dismutase, ultimately resulting in Fenton's reaction, where transition metals convert hydrogen peroxide to highly toxic hydroxyl radicals (Yamakoshi et al., 2003). These ROS can interact with biomolecules, oxidizing lipids and proteins and disrupting biological systems (Xia et al., 2008; Xiong et al., 2011). Studies on metal oxide-induced oxidative stress in zebrafish have shown damage to biomolecules in the absence of light (Yang et al., 2009). Oxidative stress is common mechanism underlying NP-induced cell damage, validated in numerous studies on NP toxicity (Pulskamp et al., 2007; Yang et al., 2009). In addition to harmful substances, an imbalance occurs when ROS generation surpasses its elimination, leading to an oxidative burst. This imbalance triggers the release of intracellular calcium ions (Ca_2^+), disrupting mitochondria and eventually causing cell apoptosis (Xia et al., 2008). Heightened ROS production from nanoparticles can also disrupt DNA integrity and hinder protein synthesis (Yang et al., 2009). (Singh et al., 2009) noted that increased ROS levels induced by NPs within lysosomes could contribute to DNA point mutations.

5.1. Countries advancing nanotechnology in aquaculture

Nanotechnology holds immense promise for advancing aquaculture systems, offering pathways to reduce costs, increase efficiency, and lower environmental impact, all crucial for sustaining the food demands of over 7 billion people. China has taken a leading role in rapidly developing and applying nanotechnology in the agri-food sector, using additives to enhance feed efficiency and incorporating nanosilver for its antimicrobial properties (Prasad et al., 2017). By 2020, the economic influence of the nanotechnology sector was projected to reach at least $3 trillion, employing approximately 6 million people (He et al., 2019). The global market for nanotechnology in food has been forecasted to grow over 24 % annually from 2019 to 2023, largely driven by innovations in nutraceuticals, with a projected value of $112.48 billion (Technavio., 2019). Currently, the U.S. leads in the nanofood sector, followed by China, Japan, and the European Union (Chaudhry et al., 2017; Thiruvengadam et al., 2018). With the largest funding support worldwide, the U.S. invests $3.7 billion through its National Nanotechnology Initiative (NNI), fueling advancements in this area (Meghani et al., 2020; Thiruvengadam et al., 2018). Major companies such as AQUANOVA (Germany), BASF (Germany), NanoPack (Belgium), and PEN (USA) are prominent in this industry. Globally, countries are investing heavily in nanotechnology to make aquaculture more productive and

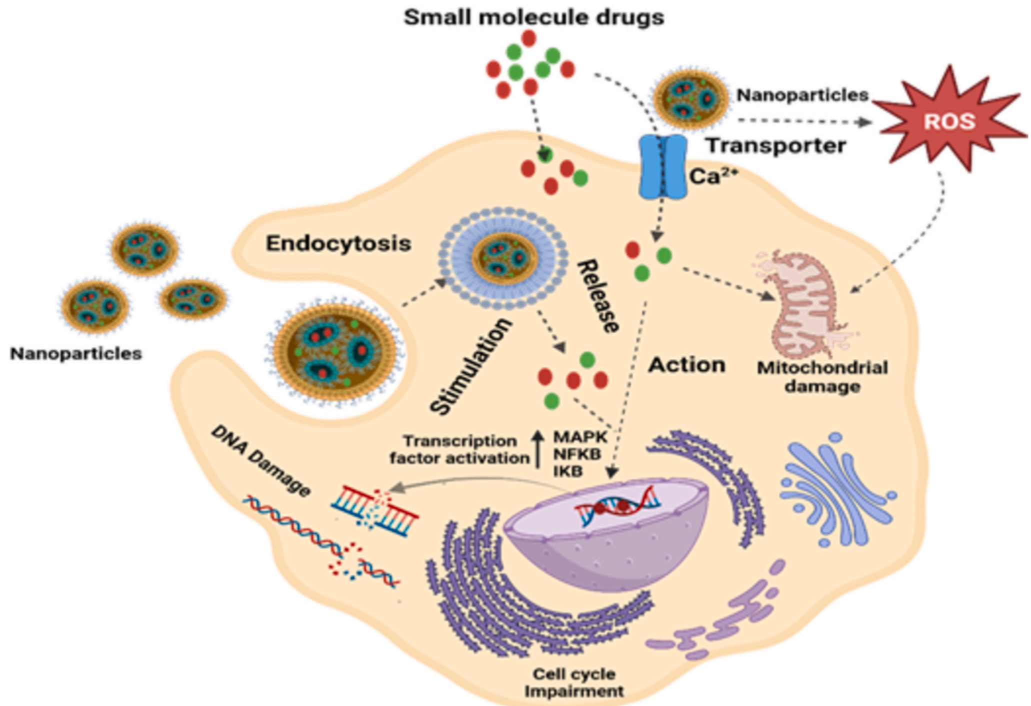

Fig. 4. Systematic mechanism illustrating how nanoparticles get accumulated.

sustainable, using various nanotech solutions to boost efficiency and resilience. The United States leads in research applications like nanoparticles for drug delivery and disease management in aquaculture (Fajardo et al., 2022a, 2022b). Countries such as India, Brazil, and South Africa have also significantly invested in nanotechnology for agriculture and food systems over the past decade (Gruere et al., 2011). India focuses on nanoparticle use for vaccine delivery and water quality monitoring (Narsale et al., 2024), while Brazil explores nanotechnology in feed additives and pathogen detection (Pereira et al., 2022). Japan has introduced nano-coatings in fish farming for improved nutrient absorption (Anilakumar, 2021), and the EU supports nanotechnology-driven sustainability efforts through funded projects, emphasizing safe nanomaterial practices (Furxhi et al., 2023). This broad international engagement underscores the importance of collaborative frameworks to safely integrate nanotechnology into aquaculture practices. Partnerships between the public and private sectors, alongside collaborations between developed and developing nations, can be instrumental in achieving the core objectives of aquaculture, ultimately delivering shared and global benefits (Joffre et al., 2017).

6. Future prospects

Emerging developments in the fields of nanotoxicology and fish health constitute critical areas of inquiry, particularly as nanotechnology advances and nanoparticles find progressively widespread applications in diverse sectors. One salient trend involves the adoption of multi-omics methodologies, encompassing genomics, transcriptomics, proteomics and metabolomics to gain a comprehensive grasp of how nanoparticles impact fish at the molecular and cellular tiers. These methodologies yield valuable insights into the mechanisms underpinning nanoparticle toxicity and facilitate the elucidation of their repercussions on fish well-being (Nguyen et al., 2020). Concurrently, nanotoxicology is broadening its purview to encompass nano-ecotoxicology, which centres on scrutinizing the ecological ramifications of nanoparticle exposure within aquatic milieus. Researchers delve into the destiny and migration of nanoparticles, their accrual within fish organisms, and the ensuing repercussions on aquatic ecosystems and food chains. This all-encompassing approach enhances our comprehension of the more extensive environmental consequences associated with nanoparticles (Khan et al., 2015). Moreover, personalized fish toxicology is gaining momentum, recognizing the potential for individual variability in fish responses to nanoparticles. Factors such as genetics, age, and gender may engender disparate reactions among fish within a population. This approach customizes toxicity assessments to accommodate the gamut of susceptibilities among fish, rendering more precise risk evaluations (Kasper et al., 2022).

Interactions between nanoparticles and microplastics constitute another burgeoning field of interest. Researchers are investigating how microplastics may impact the behavior and toxicological effects of nanoparticles within aquatic organisms. Profound comprehension of these interactions proves pivotal in evaluating the cumulative impact of these particulate pollutants on fish health and aquatic ecosystems (Kalbassi et al., 2011). Lastly, a noteworthy trend involves the development of “green” or environmentally friendly nanoparticles. These nanoparticles are meticulously designed to curtail their ecological footprint while upholding their functionality. The thrust behind green nanoparticles lies in their aspiration to diminish the environmental impact of nanomaterials and, in turn, to contribute to the protection of fish health and the overall well-being of aquatic environments (Hao et al., 2018). The emerging trends in nanotoxicology and fish health encompass multi-omics methodologies, the expansion of nano-ecotoxicology, personalized toxicological investigations, exploration of interactions between nanoparticles and microplastics, and the formulation of eco-friendly nanoparticles. These trends mirror the evolving landscape of research endeavours aimed at comprehending and mitigating the potential risks posed by nanoparticles to fish and aquatic ecosystems.

7. Conclusion

This review demonstrates that nanotechnology holds immense potential for transforming the aquaculture sector. Through the use of nanomaterials, aquafeed efficiency can be improved, water quality monitored in real-time, and fish health managed through advanced drug delivery systems and vaccines. The adoption of these technologies could significantly enhance productivity and sustainability in aquaculture. However, challenges such as the potential toxicological effects of nanoparticles on aquatic ecosystems and human health, as well as the cost and scalability of these technologies, must be addressed through rigorous research and regulation. Future research should focus on the long-term environmental impacts, further development of eco-friendly nanomaterials, and cost-effective production methods. With careful consideration of these factors, nanotechnology could provide a sustainable solution to global food security challenges.

Recommendations for the aquaculture industry include the adoption of nanoparticle-based feed additives to improve nutrient uptake and reduce waste, as well as the use of nanosensors for precise water quality management. Future research should explore the integration of biodegradable and environmentally safe nanomaterials to mitigate potential ecological risks. Collaborative efforts between researchers and industry leaders are also needed to scale up these technologies and make them economically viable.

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CRediT authorship contribution statement

Saba Khursheed Khan: Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Joydeep Dutta:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Ishtiyaq Ahmad:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Mohd Ashraf Rather:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Conceptualization.

Declaration of 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.

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