Aquaculture International (2024) 32:6449–6486
https://doi.org/10.1007/s10499-024-01473-9

REVIEW

Recent advancements of nanotechnology in fish aquaculture: an updated mechanistic insight from disease management, growth to toxicity

Muhammad Sharjeel[1] · Shaukat Ali[1] · Muhammad Summer[1] · Shehzeen Noor[1] · Laiba Nazakat[1]

Received: 17 February 2024 / Accepted: 16 March 2024 / Published online: 1 April 2024

Abstract
Nanotechnology is an emerging branch of science that incorporates the nanomaterials recognized as nanoparticles ranging from 1–100 nm in size. This technology is being used in the food industry, pharmaceutical industry, agricultural industry, medical treatments, environmental science, biological research, and aquaculture industry. Increasing disease susceptibility, pathogenic emergence and divergence, less efficient vaccines, probiotics, and ineffective antibiotics forced us to seek an alternative approach to tackle these challenges. Nanotechnology can change our views, perceptions, and perspectives, as it has provided us with a necessary tool to address these challenges. This technology has revolutionized aspects of providing solutions to many hazardous issues like disease control, nutrient delivery, water purification, vaccines, and drug delivery in aquaculture using nanoparticles. Several nanoparticles have been used as growth promoters, e.g., zinc, iron, and selenium nanoparticles. Many of them have antibacterial properties, e.g., silver and copper nanoparticles. Besides that, these nanoparticles have few toxicological effects, when they are used without proper knowledge and lead to unrealistic results. Therefore, there should be complete information and standard observation regarding their administration (e.g., time, dosage, exposure, and concentration), and certain parameters (temperature, pH, and salinity) should also noted before their use in aquaculture. This review aims to critically analyze and thoroughly discuss the meta-role of various nanoparticles regarding disease control, drug delivery, water treatment, nutrition, and growth performance as well as their toxicological impacts in fish aquaculture.

Keywords Nanotechnology · Diseases · Growth · Mode · Toxicity

Handling Editor: Brian Austin

✉ Shaukat Ali
dr.shaukatali@gcu.edu.pk

✉ Muhammad Summer
muhammad.summer@gcu.edu.pk

[1] Medical Toxicology and Biochemistry Laboratory, Department of Zoology, Government College University, Lahore 54000, Pakistan

Introduction

The world's population is increasing with each passing day and could reach approximately nine billion in 2050 (Kumar et al. 2023; United Nations 2022). Due to such an escalating population, food security has become a major issue worldwide (Daniel et al. 2022). As a result, there is an increase in food demand as the population is growing (Korican et al. 2022). The available resources for protein-based food are meat, cereal, beans, and dairy products (FAO STAT 2022; Fanzo et al. 2013). In this regard, livestock plays a crucial role in providing a protein-rich diet in the form of beef and mutton.

However, excessive consumption of meat and meat products could also lead to health problems like obesity and cardiovascular disorders, and the issues mainly arose due to the high proportion of lipids in the meat (Gonzalez et al. 2020). Moreover, the intensification of livestock requires a lot of care, time, shelter, and much more (Michalk et al. 2019; Benton et al. 2018; Rivera-Ferre et al. 2016; Fraser 2005). Meanwhile, they used to be a reason for the transmission of diseases from animals to humans, as more than 60% of pathogens are zoonotic in origin (Rahman et al. 2020).

At the same time, preferences for chicken meat became highly demanding, regardless of its price and impact on human life (Jayaraman et al. 2013). Its intensive growth method has several hazardous impacts on humans and the environment, e.g., poultry waste, litter, and manure (Grzinic et al. 2023). On the other hand, the nutritional quality of crops is being threatened due to climatic changes and pest outbreaks (Zhu et al. 2022).

Therefore, hunger and malnutrition have become a great challenge in the world. Keeping that in view, the current pace of development does not seem to eradicate hunger by 2050 (Ramani 2023). In this regard, we need some alternative approaches to overcome malnutrition and food demand. Aquaculture is a field that can provide an essential component of protein. It is the farming of aquatic organisms such as fishes, shrimps, mollusks, crustaceans, and aquatic plants. It has become the fastest food-producing sector in the world (FAO 2018, 2020; Ritchie and Roser 2017; FAO 2016a, b). Its production is expected to reach approximately 140 Mt by 2050 (Waite et al. 2014; Sysoenko and Kerimova 2019).

It has become a promising field across the world that provides economic benefits and conserves food security, worldwide (Golden et al. 2021; Editorial 2021; Gui et al. 2018; Han et al. 2018; FAO 2020; Valenti et al. 2018). In aquaculture, fish is a major component that is an essential source of nutrients and micronutrients, which could play a vital role in human nutrition and food security.

Moreover, it is the source of health-promoting omega-3 and essential minerals like zinc, iron, calcium, phosphorus, iodine, and vitamins (Hicks et al. 2019; Golden et al. 2016; Thilsted et al. 2016). Freshwater fishes such as *Labeo rohita*, *Catla catla*, and Chinese major carps are important sources of nutrients and escalation in protein, which are solely obtained from aquaculture (Youn et al. 2014; Halpern et al. 2019).

A unique flesh quality, rapid growth performance, and short reproductive cycle make them strongly adaptable to the environment (Bai JunJie and Li ShengJie 2019). In comparison with other animal-based protein sources, it is cheaper and easily available everywhere, and its production in aquaculture is an efficient way to yield high-quality proteins for mankind (Ali et al. 2021; Khalil et al. 2021; Maulu et al. 2021).

Furthermore, adding fish to a regular diet could reduce the risk of life-threatening diseases by 6 to 14% as compared to a standard flesh-based diet and also reduce type II diabetes by 25%, cardiovascular disorder by 20%, and cancer effectively being reduced by a rate of 12% (Bezbaruah and Deka 2021; Zhao et al. 2016; Tilman and Clark 2014). In an era of severe malnutrition, fishes provide nutrients to fight against malnutrition (Hicks et al. 2019).

However, there are great challenges to fish in the aquatic environment, most importantly pathogens such as bacteria, viruses, toxins, and pesticides which can impair their immunity and cause diseases that affect the livelihood of farmers and damage food security (Parlapani et al. 2023; Leung and Bates 2013; Rymuszka and Siwicki 2004). In fish aquaculture, the most common solutions are the use of antibiotics, disinfectants, and pesticides for the treatment of diseases. Antibiotics have been used for so many years to fight against pathogens (Salma et al. 2022; Cabello 2006; Rico and Van den Brink 2014). However, uncontrolled and unnecessary use of antibiotics causes bacterial resistance, and pathogens are no longer sensitive to them. Meanwhile, extreme uses have led to the resistance of bacterial, fungal, and viral strains (Mondal and Thomas 2022; FDA, 2020; Zaman et al. 2017; Arestrup 2005; Hajipour et al. 2012; Pelgrift and Friedman 2013; Cabello 2006). Furthermore, several studies have shown that antibiotics accumulate in the aquatic environment leading to residue buildup in water and sediment with unpleasant effects on fish (Lulijwa and Kajobe 2018; Chen et al. 2018). Therefore, there is a need for alternative methods for proficient detection of disease-causing pathogens and their control (Nasr-Eldahan et al. 2021; Ninawe et al. 2016).

In that instance, there is an emerging field of science known as nanotechnology which synthesizes nanomaterial called nanoparticles, and their size ranges from 1 to 100 nm (Ghelani and Faisal 2022; Dubchak et al. 2010). Nanoparticles have wide applications in the field of aquaculture. With the characteristics of being antibacterial and anti-fungal, particles are designed in such a way that they are attracted by diseased cells, allowing them to direct treatment of the defective cells (Matatkova et al. 2022; Leela and Vivekanandan 2008). It could lead to the development of new technologies for the management of medications and production of vaccines, promising the defense of fish against pathogenic microbes (Nasr-Eldahan et al. 2021).

An alternate strategy for controlling disease outbreaks has become possible through the antibacterial properties of metal nanoparticles (NPs), such as silver NPs, gold NPs, and zinc oxide NPs, against numerous fish diseases (Saleh et al. 2016). Silver nanoparticles are considered to be a potent antimicrobial agent that effectively fights against bacteria (Bruna et al. 2021). Broad-spectrum antibacterial properties, potent sterilization, ease of preparation, minimal environmental impact, and resistance to drug resistance are some of the benefits of using silver nanoparticles. It was extensively employed in many different products as an antimicrobial material (Hu et al. 2019).

Fish diseases

A major factor in fish mortality, particularly in juvenile fish, is disease. Fish diseases can be classified as either pathogenic or non-pathogenic based on how contagious they are. The other one is connected to inadequate water quality, starvation, etc. Gas bubble diseases are a representation of non-infectious diseases because of extensive aeration, nutritional illnesses brought on by a lack of specific nutrients (such as vitamins and minerals), diseases brought on by industrial and agricultural pollutants, and neo-plastics and genetic abnormalities an abnormal growth to various organs that causes the organ to lose their structure and function (El-Sayed Ali et al. 2014a, b, 2017; Idowu et al. 2017).

Another kind of disease, called a pathogenic disease, is extremely lethal since its fish-to-fish spread which results in high fatality rates. Infectious diseases can be classified as fungal, parasitic, or bacterial (the most common types are *Aeromonas hydrophila*, *Vibrio* spp., *Streptococcus* spp., and *Pseudomonas* spp.). Fish have both non-specific and specific defenses against illness. The body has an adaptation of immune responses that recognizes certain pathogens and responds to them (Chaplin 2010).

Disease treatment in fish

Antibiotics

Antibiotics can be synthetic or natural substances that are being used as antibacterial drugs to either stop the growth or kill bacteria (Schar et al. 2020; Patel et al. 2019; Okoye et al. 2022; Lozano et al. 2017; Lulijwa et al. 2020). In aquaculture, the most commonly used antibiotics are sulfadiazine, forfenicol, and oxytetracycline (Lulijwa et al. 2020; Sun et al. 2020).

Antibiotics, known as agents that inhibit bacterial growth, are defined as synthetic substances that can either eradicate or impede the growth of pathogenic microorganisms (Romero et al. 2012). Both artificial and natural resources may be their sources, but they need to be non-toxic to the host to utilize as a chemotherapeutic substance to treat bacterial diseases. Because there are so many bacterial diseases in aquaculture, the use of antibiotics is expanding (Defoirdt et al. 2007).

Mixing the antibiotic drug with aquaculture feed is the most popular method of administering antibiotics in aquaculture. Different paths include injectable and pond sprinkling as methods of administering antibiotics (Liu et al. 2017). Farmers use antibiotics unintentionally without knowing the real, precise causes of fish disease (Rahman et al. 2021). When using antibiotics in excessive amounts, there are a lot of drawbacks such as when antibiotics are added to feed, it settles in the water, and fish can ingest it, which increases biological transport in hydrocarbons. In aquaculture, antibiotics are frequently used, but not all bacteria respond to them; in fact, some bacteria that were initially susceptible to an antibiotic eventually develop resistance to it (Mondal and Thomas 2022). Animal and human sources are the entry points for antibiotic-resistant bacteria into aquatic environments. Water-based microorganisms that contain these bacteria can inherit their genes for resistance (Kraemer et al. 2019).

The persistence of antibiotic buildup in the aquatic environments resulted in the emergence of antimicrobial resistance genes (Richardson and Kimura 2019; Saima et al. 2020; Liu et al. 2021). The widespread use of antibiotics in both medical treatments for humans and animals, along with their numerous other uses, has made them one of the most significant categories of emerging contaminants endurance over time in the environment (Sodhi et al. 2021; Okoye et al. 2022).

Research has confirmed that fish do not effectively metabolize antibiotics (Sun et al. 2020). Almost 75% of the antibiotics that are given to fish are thought to be excreted into the environment, ultimately (Burridge et al. 2010). Additionally, several studies have demonstrated that antibiotics build up in aquatic environments, causing residue to accumulate in water and sediment and having an unpleasant effect on fish (Lulijwa and Kajobe 2018; Chen et al. 2018).

Antibiotic remains in aquatic products have the potential to be directly harmful to consumer health on a systemic level influencing the intricate microflora that live in the human digestive system, possibly having negative effects. These chemical treatments come with a hefty price tag, intense stimulation, poor efficacy, and a host of negative side effects (Monteiro et al. 2018; Burridge et al. 2010).

Fisheries-related antibiotic-resistant bacteria

For many years, antibiotics have been used for the treatment of bacterial diseases. However, antibiotic-resistant bacteria can arise as a result of the uncontrolled and excessive use of antibiotics (Mondal and Thomas 2022). An investigation into the use of antibiotics in fish farms across 25 countries was carried out. It was discovered that the most commonly used antibiotic in fish farming is tetracycline. The emergence of bacteria resistant to antibiotics and the overuse of antibiotics in aquaculture are closely related. There is a rise in the number of resistant bacteria, including those that are methicillin-resistant. There have been reports of *Staphylococcus aureus* and its multiple drug-resistant varieties (Tusevljak et al. 2013; Atyah et al. 2010).

Several *Aeromonas hydrophila* isolates from tilapia in culture exhibited resistance to broad-spectrum antibiotics, including erythromycin, streptomycin, and tetracycline (Son et al. 1997). Many bacteria were found to be resistant to antibiotics like *Photobacterium damselae*, *Aeromonas salmonicida*, *Yersinia ruckeri*, *Pfiesteria piscicida*, *Vibrio*, *Listeria*, *Pseudomonas*, and *Edwardsiella* (Sørum 2008; Swain et al. 2014). A number of studies also identified enterococci-resistant antibiotics found in the sediments fish farm which highlights the risk that these types of bacteria can spread infections to humans as well.

Consequently, the existence of these bacteria in fish farms is a significant issue of public health concern (Di Cesare et al. 2012). Antibiotics are typically given to every species of the population in aquaculture, including healthy, sick, and carrier individuals. Antibiotics are thus frequently overused and misused in aquaculture across many nations (Santos and Ramos 2018).

Furthermore, overuse of antibiotics in aquaculture may hasten the development of resistance in the cultured fish and aquaculture environment. Moreover, eating fish that have been antibiotic-treated may harm people's health (Limbu et al. 2021). Antibiotic use in aquaculture has the potential to contaminate farmed organisms and culture environments in a variety of ways, with feed being one of the most crucial sources of contamination (Li et al. 2021).

Probiotics

Probiotics are one or more beneficial microorganisms that can withstand the bile and acid in the digestive tract and have a positive impact on the host (Kothari et al. 2019).

The two most powerful probiotic bacteria are thought to be found in the digestive tract, *L. acidophilus* and *B. subtilis*, which were isolated from grass carp and silver carp (Irianto and Austin 2002). When used as a growth promoter to enhance the growth of cultured fishes in aquaculture, these probiotics have positive effects like enhanced growth, improvement of nutrient digestion improvement of water quality, and resilience to stress (Aydın and Çek-Yalnız 2019). Fig. 1 modified from Chauhan and Singh illustrates the improved growth in fish.

Despite their many positive aspects, probiotics have the following drawbacks. Histamine is a chemical of the immune system that typically secretes when it detects any threat, and certain strains have the ability to raise histamine levels. When produced in large quantities, it increases blood flow in the affected area resulting in redness and swelling (Branco et al. 2018).

An increase in probiotic bacteria in the body can be toxic to the bacteria and result in the failure of organs. They also penetrate the intestinal mucosa and reach vital organs via the bloodstream, where they cause localized or systemic infections (Kothari et al. 2019). In aquaculture, many bacterial diseases cannot be treated with antimicrobials only; therefore, another treatment is being used known as a vaccine (Dadar et al. 2016).

Vaccines

Vaccines can be classified as genetically modified, DNA recombinant, vector synthetic peptide, killed, attenuated, or sub-united vaccines. Immunization lowers the need for medications, e.g., antibiotics in aquaculture, and lessens the likelihood of medication resistance (Plant and Lapatra 2011). Through immune system activation, vaccination is the most crucial and most effective method for the prevention and management of fish-related infectious diseases (Sahdev et al. 2014; Mohd-Aris et al. 2019).

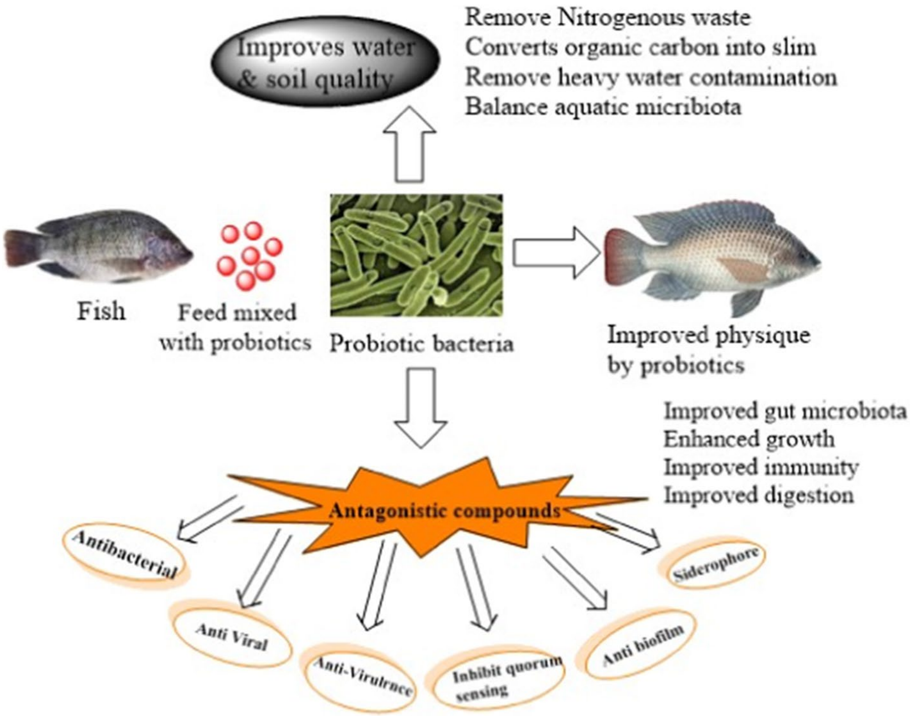

Fig. 1 Applications of probiotics in aquaculture and improved fish growth

In aquaculture, vaccinations have proven to be an essential defensive mechanism against microbes, shielding hosts from infections caused by pathogens (Shah and Mraz 2020a, b). Vaccination has been essential to the success of fish farming and is crucial to large-scale commercial aquaculture (FAO 2018). Fish vaccinations have emerged as a well-recognized, economical means of preventing several pathogenic infections in the aquaculture industry for many years (Assefa and Abunna 2018).

However, due to their short half-lives, the majority of administered vaccines are stored and preserved in suspension form at low temperatures and are typically injected into blood systems. These obstructions have decreased the likelihood that vaccines would be widely useful, especially in some fin and shellfish. An approaching mass immunization technique in aquaculture is called nanovaccine through nanotechnology (Assefa and Abunna 2018).

Aquaculture and nanotechnology

Nanotechnology

Nanotechnology is a newly developing branch of science that produces nanomaterials, or nanoparticles, whose size ranges from 1–100 nm (Ghelani and Faisal 2022: Matteucci et al. 2018; Dubchak et al. 2010). Because of their antibacterial and anti-fungal properties, nano-particulates are highly useful in the aquaculture industry. Their unique design attracts diseased cells, enabling the treatment of those cells directly (Matatkova et al. 2022).

Effective drug delivery, vaccine development, and fish nutrition are all impacted by nanotechnology as mentioned in Fig. 2 modified from Shah and Mraz's (2020a, b) work.

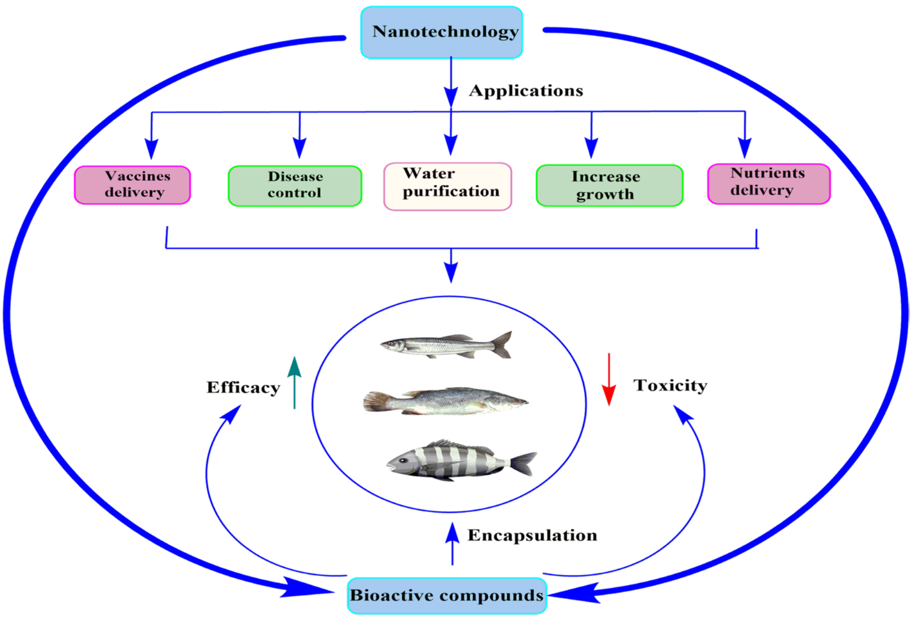

Fig. 2 Applications of nanotechnology in aquaculture

Using biological and nanotechnology together materials draws more attention to innovative nanoparticles that are produced effectively and affordably (Malhotra et al. 2020; Malhotra et al. 2020; Kakakhel et al. 2021).

It might lead to the creation of novel technologies for the control of medications and the creation of vaccines, protecting fisheries resources from pathogenic microbes (Nasr-Eldahan et al. 2021). Following are some of the methods that are being used in fisheries and aquaculture to overcome disease burden.

Nanotechnology and disease management

Silver nanoparticles

All forms of silver have historically been used either independently or in combination with other technologies as an antimicrobial agent. Silver NPs are demonstrated as nanomaterials that have all of their dimensions falling between 1 and 100 nm.

Compared to silver bulk, these have illustrated higher surface area-to-volume ratio, greater capacity, and capability. This material shows distinctive catalytic, electrical, and optical qualities, which have prompted research and product development for targeted medication delivery, diagnosis, detection, and imaging (Yaqoob et al. 2020; Silva et al. 2017) (Fig. 3).

These NPs have shown very strong antibacterial action against various strains of gram-positive and gram-negative bacteria (Cavassin et al. 2015). Silver nanoparticles have potential antibacterial qualities against a variety of microorganisms, such as bacteria, fungi, and viruses (Rathi Sre et al. 2015).

These are known to be effective antimicrobial agents against multi-drug-resistant bacteria, including vancomycin- and methicillin-resistant bacteria *Staphylococcus aureus*, ampicillin-resistant species *Escherichia coli*, and erythromycin-resistant

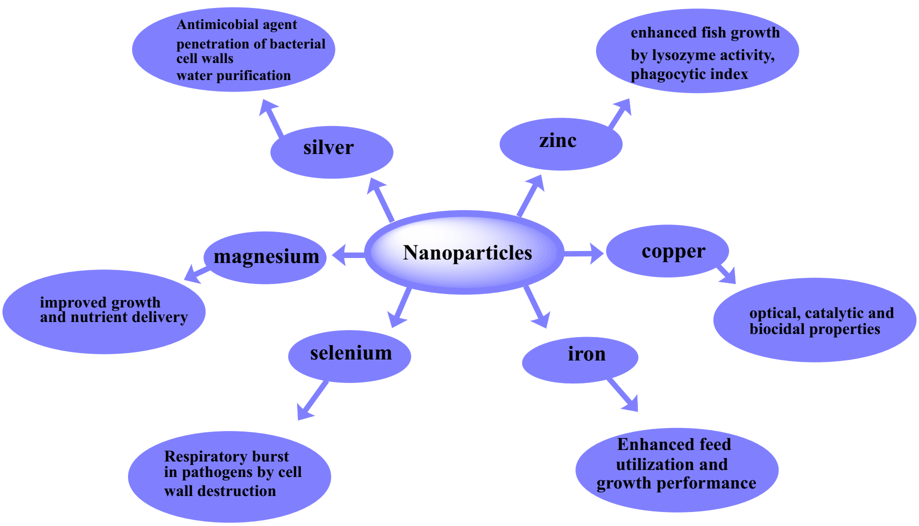

Fig. 3 Different types of nanoparticles and their function

species *Streptococcus pyogens* (Bose and Chatterjee 2016). Due to a specific action, these nanoparticles begin to perform their functions at the cellular and molecular level once it has reached their target location (Aydın and Barbas 2020).

According to a number of studies, microbe cellular machinery primarily aids in the assembly of the most stable AgNPs. Silver cations are responsible for the bactericidal activity of AgNPs because they have the ability to bind with the thiol group on bacterial proteins in a specific way, disrupt their physiological activities, and cause their necrobiosis. AgNPs use a Trojan horse mechanism to kill bacteria. First, they bind to the cell surface, which changes penetration and impairs respiration. Next, they penetrate the cell barrier and release metallic silver ions into the cell (Burdușel et al. 2018). Because of their tiny size, which makes them easy to penetrate microbial cell walls, they are also being used in the food industry for packaging to prevent pathogens from destroying food products (Siddiqi et al. 2018).

Now, silver is widely being used as an antibacterial, antiviral, antimycotic, and chemotherapeutic agent in a variety of pharmaceutical fields (Vadlapudi and Amanchy 2017). Silver is also useful in textile, cosmetic, medical, and even household appliances. Whether in combined, ionic, colloidal, or the form of nanoparticle, silver can function as a medication. It has also shown promise in the treatment of several diseases, such as inflammation, cancer, and malaria, primarily in the uterine region (Venkatesan et al. 2016).

Antibacterial activity

AgNPs have an effective antibacterial assay that occurs after reactive oxygen species (ROS) are present and Ag ions disperse. The deactivation of a bacterial cell protein and genetic material results in bacterial death (Singh et al. 2020). There are three ways in which silver influences microorganisms. One technique is the penetration of bacterial cell walls by silver cations, which then react with peptidoglycans (Sim et al. 2018).

The second mechanism by which silver nanoparticles exhibit antibacterial activity is oxidative stress, which is brought on by the particles' binding to a bacterial cell and subsequent release of ions (Tang and Zheng 2018).

Membrane permeability may be considerably impacted by the binding of silver nanoparticles to membrane proteins. Cell contents may seep out as a result, moving uncontrollably across the cytoplasmic membrane. AgNPs that attach to membrane proteins can alter phosphate ion uptake and release, which can interfere with energy production and the respiratory chain. When AgNPs enter the cell, they may attach themselves to intracellular components like DNA, lipids, and proteins, which inhibit transcription (Tang and Zheng 2018).

They cause damage to protein synthesis and harm DNA (Mathur et al. 2018). Reactive oxygen species have the potential to significantly influence DNA modification and disruption of cell membranes. The constant release of silver ions by AgNPs is thought to be the mechanism by which microorganisms are destroyed (Yin et al. 2020). Consequently, AgNP bactericidal activity results from their action on the bacterial cell, which causes cell death as demonstrated in Fig. 4 modified from Bury et al.'s (1999), Morones et al.'s (2005), and Summer et al.'s (2024) work.

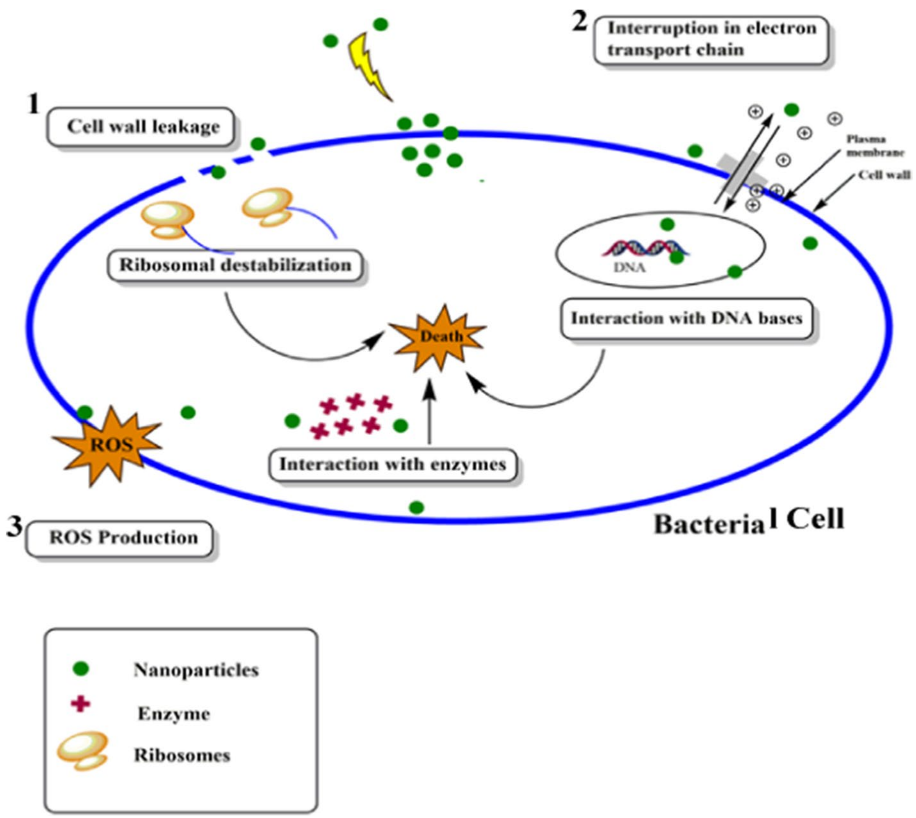

Fig. 4 Mechanism of silver nanoparticles in bacterial cell disruption

Copper nanoparticles

Copper nanoparticles have important optical and catalytic qualities, high surface area-to-volume ratio, and biocidal characteristics among their many other physical and chemical characteristics (Dutta et al. 2018; Borda et al. 2018; Levchenko and Reisfeld 2017; Kruk et al. 2015). For many fish species, copper is a crucial micro-nutrient and bioactive trace metal in aquatic environments (Zitoun 2019).

Besides, broad-spectrum antibacterial activity is demonstrated by copper (Ingle et al. 2014; Lemire et al. 2013). Copper's high surface-to-volume ratio at the nano-scale makes it toxic and has stronger antibacterial properties than its bulk counterpart (Ermini and Voliani 2021; Salah et al. 2021; Sankar et al. 2014).

It is also stated that many harmful microorganisms were destroyed on surfaces with no less than 55–70% copper. About 300 copper-containing amalgams were chosen by the US Environmental Protection Agency (EPA) to be used as antimicrobial operators, effectively combating the growth of microorganisms that cause serious diseases.

According to research, the mechanism of copper nanoparticles against a variety of pathogens is due to the antibacterial effect that damages bacterial cell membranes, cytoplasmic elements, and intracellular enzymes, disrupts proteins and ions from the cells, and prevents the bacteria from growing (Vincent et al. 2016). Therefore, CuNPs and their complexes are highly recommended in nanomedicine as an antibacterial, antiviral, and anti-fouling agent (Ermini and Voliani 2021).

Copper NPs were discovered to have a variety of harmful effects on bacterial cells, including the production of ROS (reactive oxygen species), protein oxidation, lipid peroxidation, and DNA damage (Chatterjee et al. 2014). Another way that CuNPs react against bacteria is by reducing copper through a Fenton-like process that generates reactive oxygen species (ROS) and causes enzymatic- and non-enzymatic-mediated oxidative damage, resulting in cell death (Salah et al. 2021). CuNPs have been shown in numerous investigations to be able to diffuse or endocytose across cell membranes and accumulate in intracellular compartments like the nucleus and mitochondria (Wang et al. 2015; Srikanth et al. 2016).

Zinc nanoparticles

ZnNPs also demonstrated strong antibacterial activity against pathogenic bacteria and were efficient in lowering bacterial load in fish vital tissues, e.g., skin, intestine, and muscles (El-Saadony et al. 2021). Fish with diets high in zinc have immunity from infectious pathogens, and zinc prevents fish from becoming infected with bacteria because it is essential for antibacterial activity (Kumar et al. 2019). A mechanism of bacterial cell disruption by zinc nanoparticles is mentioned in Fig. 5 (Gao et al. 2019a, b; Mohd Yusof et al. 2020).

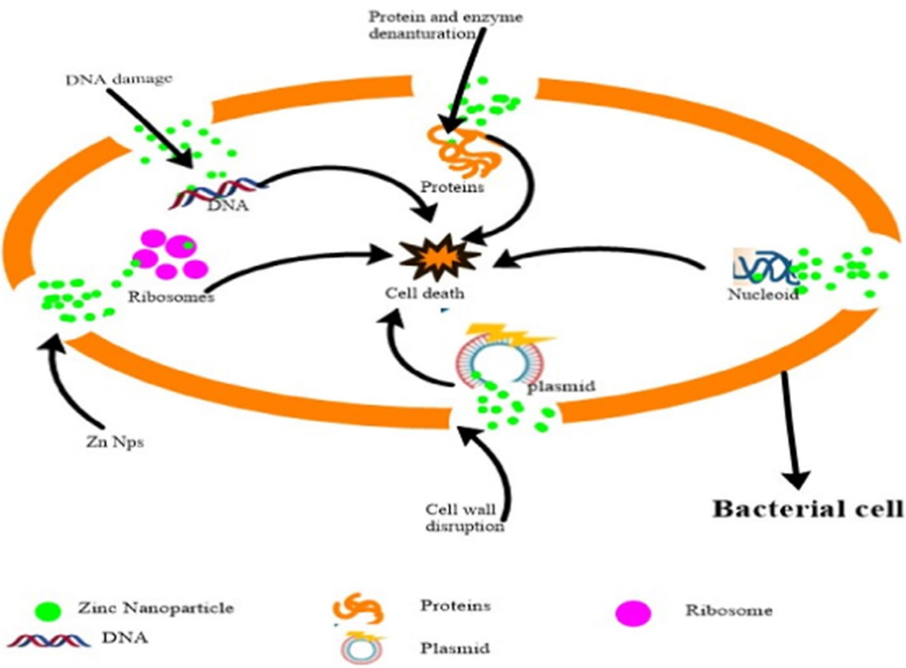

Fig. 5 Mechanism of antibacterial potential of Zinc nanoparticles

Nanotechnology and pond water treatment

Pond water treatment via *AgNPs*

Water contaminated with pollutants is constantly being added to aquaculture and other water bodies (Patel et al. 2019). The most common method for enhancing water quality for a long time was to regularly replace the freshwater in ponds with new fresh water. Nonetheless, the daily water volume required for small- to medium-sized aquaculture systems might amount to several hundred cubic meters (Borja 2002). Water pollution and toxicity levels are still difficult to detect and take a long time to process (Altenburger et al. 2019).

In this respect, nanotechnology is playing an important role and provides innovative methods for cleaning and treating water to lower organic compounds, inorganic nutrients, and harmful bacteria disinfection using silver bactericidal nanoparticles that eliminate the pollutants and organic materials by applying membranes constructed with compounds containing nanoparticles in the aquaculture industry. The most significant function of silver nanoparticles is to clean the water in fish habitats and the surroundings (Willson and Halupka 1995; Noriega-Treviño et al. 2012). Applications of nanoparticles in aquaculture include the improvement of water quality, nutrition for aquatic animals, medication delivery, diagnosis, and treatment of diseases (Byrd et al. 2021).

The management of fish health emerged as another difficult issue. The effects of climate change and declining environmental quality have caused a marked increase in pathogens and diseases in aquaculture. There are still many infectious diseases that have no known cures, like fin and gill rot and epizootic disease known as epizootic ulcerative syndrome, and some that even become irreversibly damaged when treated with antibiotics. The outbreak of white spot disease has hampered the profitable success of cultured *Penaeus monodon* (Zhang et al. 2016).

In this regard, observation showed that the highest concentrations of Ag nanoparticles show the highest bactericidal efficiencies against many fish farm bacterial pathogens after 2-h contact time at the dose 0.1, 0.05, and 0.01 mg/L silver nanoparticles which was adequate to inhibit 85.33%, 71.93%, and 62.19% of total bacterial count in fish pond water (Dosoky et al. 2015). Silver nanoparticles with their advanced cleaning system and specialized plates clean every drop of water in all directions that the water moves.

Water quality can be enhanced by silver nanoparticles, and aquaculture practices require larger amounts of water; this source of intense intervention requires a higher quality of water, and the world is getting less and less of it every day. Aquaculture practices have a direct impact on the environment due to their intensive intervention, as they require larger quantities of water, which is becoming increasingly scarce globally.

Furthermore, during the production of the life forms, more waste was produced than was needed for fish food, excretion products, feces, chemical products, and antibiotics. This waste was then released into the environment surrounding these production farms (Vanni and Craig 1997). Many of the discharges are characterized by a high organic load from left-over feeds, pesticides, and human wastes which possibly impact the physico-chemical parameters of the farm water and also add anthropogenic materials (Coldebella et al. 2017).

Additionally, toxic heavy metals in water that pose a major threat to fish life are removed using silver nanoparticles. The heavy metals are bound by these nanoparticles and eliminated in a targeted concentration. Heavy metals and environmental contaminants can be readily eliminated with great concern using an integrated approach by using silver-based nanoparticles. Fish health is, of course, greatly influenced by the quality of the water.

The physio-chemical characteristics of fish farm water play an important role in the production and growth of the fish. Besides, the impact on physico-chemical properties, trace metals, and organic matters such as poly-chlorinated bi-phenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and herbicides are introduced in the aquatic biota (Abbassy 2018).

Standard concerns include removing nitrogen wastes from the water, maintaining water quality for the species' immediate needs (e.g., temperature, salinity, and dissolved oxygen levels), and observing how these parameters interact (Salze and Davis 2015). To remove foreign materials from pond water more effectively than micron-scale filtration, nano-filtration techniques are also recommended (Zodrow et al. 2009).

The production of hybrid nano-composite membranes with nanosilver and polyamide (PA) demonstrated their ability to inhibit microbe growth and bio-fouling. In addition to the salt rejection effect and water flux, *Pseudomonas* sp., to create multifunctional membranes acting as filtration systems in various types of contaminated water, nanosilver composite can be used (Zahid et al. 2018; Lee et al. 2007). Fewtrell showed that nanoparticles directly applied in water could affect the fish culture by bio-accumulation. It is essential to make toxicity acquisitions to regulate their use in the aquaculture industry (Fewtrell 2014).

Therefore, it has been highlighted in an analysis of nanoparticles applied to water treatment to prevent the growth of bacteria and viral pathogens. But there is a need for an evaluation of costs and benefits because the technology might be costly at the time (Pradeep 2009).

Nanotechnology and fish growth

Selenium nanoparticles

Nanotechnology has a lot of potential applications in the seafood and aquaculture industries. Nanoparticles of selenium (Se) are one of the microelements that all organisms of aquaculture use for a variety of functions (Sarkar et al. 2015a, b; Ibrahim et al. 2021). It is highly recommended to introduce Se nanoparticles into the aqua-feed industry in order to improve the production and health of aquatic animals.

Selenium nanoparticles have been extensively examined and have great potential in aquaculture as growth-promoting antioxidants and immuno-stimulant agents (Chris et al. 2018; Dawood 2021; Rathore et al. 2021). Several experimental studies have shown that increased levels of growth hormone were observed in fish species, e.g., *Tor putitora*, when dietary selenium nanoparticles were given. Similarly, a 6-week feeding trial of Asian seabass (*Lates calcarifer*) fed dietary nanoselenium in a dose of 4 mg/kg demonstrated improved growth performance (Longbaf Dezfouli et al. 2019).

It is mentioned that a feed with supplemented nanoselenium can increase weight, antioxidant status, and relative gain rate in fish. Moreover, in crucian carp (*Carassius auratus gibelio*), it can increase glutathione peroxidase and muscle concentrations (Handy et al. 2012; Bhupinder 2014).

Efficient diet supplements of selenium NPs observed an improved crucian carp (*Carassius auratus gibelio*)-like antioxidant stamina weight gain and muscle bio-accumulation over time (Wang et al. 2007; Zhou et al. 2009). Goldfish (*Carassius auratus*) given dietary selenium NPs at 0.6 mg/kg for 9 weeks observed an increased weight, particularly growth, and also IGF-1 gene expressions. Meanwhile, a study found that feeding dietary

Se nanoparticles to a grass carp (*Ctenopharyngodon idella*) at a diet of 0.6–0.9 mg/kg for 10 weeks improved both the growth rate and survival rate (Jahanbakhshi et al. 2021).

Iron nanoparticles

It has been shown that young sturgeon and carp grow more quickly when iron nanoparticles are given. Various nanoparticles can serve as immune modulators and growth promoters when added to a fish diet on a micro-scale. Aquaculture frequently faces anemia because of inadequate iron levels in fish; to address iron deficiency, one potential solution to this problem is to use iron NPs as a supplemented diet (Thangapandiyan and Monika 2020) (Table 1).

Zinc nanoparticles

There is a lack of information about the effects on aquatic organisms, and a vital microelement, zinc particles (ZnNPs), is involved in numerous fish body functions, such as gene regulation, metabolism of proteins, cell membrane integrity, and bone health.

In catfish (*Pangasius hypophthalmus*) under mixed biotic and abiotic stress conditions, zinc NPs induced growth and immune modulation (Kumar et al. 2018a, b; Davis and Gatlin 1996). As an essential micro-nutrient for both organisms and their surroundings, zinc plays a meta-role in numerous biological functions. For proper growth rate and metabolism, fish and all vertebrates need trace minerals like zinc. The primary component of the enzyme tertiary framework is zinc ions.

Zinc is a second essential micro-element and is involved in many body processes, such as energy and protein metabolism, gene regulation, cell membrane integrity, and bone health. In addition, zinc regulates protein synthesis, nucleic acid metabolism, and fish antioxidative enzymes (Yu et al. 2021). It is an essential trace element or micro-nutrient that is required for many biological processes, but the body is unable to store it, so it needs to be consumed continuously.

Zinc is necessary for the development of fish, for metabolic functions, for the health of the digestive system, and for defense against reactive and free radical oxygen species. Physiological concentrations of zinc may benefit species that support immuno-modulation and the integrity of the gut wall (Skalny et al. 2021).

According to studies, a fish deficient in zinc caused their offspring to also lack zinc in the subsequent generation, and these effects on the offspring included decreased activity, altered DNA methyl-transferase regulation, and an increase in mortality. In addition, inadequate zinc levels have a detrimental impact on the growth of fish, and adult fish that are zinc-deficient exhibit a marked reduction in size and fitness (Beaver et al. 2017). Zinc is the most vital mineral to all organisms including fish. It is crucial for transcription factors and the synthesis of proteins, both of which bind zinc and are thought to need it for their processes.

Furthermore, it is essential for the metabolic processes that sustain life, such as the uptake of oxygen, RNA, and DNA by cells, reproduction, preservation of integrity of cell membrane, and free radical sequestration. Aquatic animals' physiological and biological processes are impacted by zinc deficiency, and inadequate zinc leads to physiological and biological disturbances in aquatic organisms.

The best method for overcoming zinc deficiency in aquatic organisms is to supplement with zinc oxide nanoparticles (Thangapandiyan and Monika 2020). Because nanomaterials

Table 1 Different types of Nanoparticles and their role in fish growth

Fish species	NPs	Dose	Duration	Potential effect	Reference
Grey mullet (*Liza ramada*)	Zn	24.61–35.5 mg kg^{-1}	8 weeks	Enhanced villus height, width goblet cells, antioxidative capacity, phagocytic index, phagocytic activity, lysozyme activity, catalase, glutathione peroxidase, and superoxide dismutase Feed conversion ratio and concentration of malondialdehyde	Shukry et al. 2022
Catfish (*Pangasius hypophthalmus*)	Zn	75 days	10 mg/kg	The growth performance was enhanced, and antioxidative stress (catalase, superoxide dismutase, and glutathione-s-transferase) significantly reduced in the Zn-NP-supplemented groups	Kumar et al. 2018a, b
Mahseer (*Tor putitora*)	Se	70 days	0.68 mg kg	A substantial ($P < 0.05$) rise in physiological features such as hemoglobin level, red blood cell count, hematocrit values, and lysozyme activity. Enhanced muscle tissues, tissue total protein content, and blood levels of growth hormone	Khan et al. 2016
Asian seabass (*Lates calcarifer*)	Se	4 mg/kg	6 weeks	Improved immune responses and growth Levels of alanine aminotransferase (ALT) aspartate transaminase (AST) and liver catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPx)	Longbaf Dezfouli et al. 2019
Nile tilapia (*Oreochromis niloticus*)	Se	1–2 mg/kg	4 weeks	Respiratory burst activity, serum lysozyme, antioxidant enzymes, and resistance to bacteria (*Aeromonas sobria*)	Ayoub et al. 2021
Rohu (*Labeo rohita Hamilton*)	Se	0.3 mg/kg	120 days	Respiratory burst, activities of alkaline phosphatase and lactate dehydrogenase growth, SOD, resistance, lysozyme, acetylcholine esterase activity	Swain et al. 2019

Table 1 (continued)

Fish species	NPs	Dose	Duration	Potential effect	Reference
Grass carp (*Ctenopharyngodon idella*)	Zn	4 weeks	30 mg/kg	Improved growth	Faiz et al. 2015
Nile tilapia (*Oreochromis niloticus*)	Se	60 days	1 mg/kg	Hemoglobin, red blood cells, and globulin levels were greater in fish given SeNPs ($P < 0.05$). The maximum levels of lysozyme activity, immunoglobulin, phagocytic activity, and phagocytic index	Ghazi et al. 2021
White leg shrimp (*Litopenaeus vannamei*)	Se	56 days	0.15 mg/kg	Increased growth performance	Karamzadeh et al. 2021
Rainbow trout (*Oncorhynchus mykiss*)	Zn	64 days	63 mg/kg 123 mg/kg inorganic zinc	Major effect on the retention of nutrients Potential for improved feed component use	Meiler and Kumar 2021
Goldfish (*Carassius auratus*)	Se	09 weeks	0.6 mg/kg	Observed an increased weight, particular growth ratio, and IGF-1 gene expressions	Jahanbakhshi et al. 2021
Rohu (*Laboe rohita*)	Zn	8 weeks	7.85 52.93 mg/kg	An increase in growth factors, hematological markers, and somatic indicators Affected the quantity of zinc in tissue and the actions of antioxidants	Musharraf and Khan 2019
Nile tilapia (*Oreochromis niloticus*)	Se	30 days	1 mg/kg	Demonstrated higher development performance as evidenced by isometric growth and increased survivorship (> 95%)	Dawit Moges et al. 2022
Rainbow trout (*Oncorhynchus mykiss*)	Fe	60 days	150 mg/kg	Enhanced feed utilization and growth performance	Evliyaoğlu et al. 2022
Common carp (*Cyprinus carpio*)	Se	8 weeks	0.7 mg/kg	Increased growth, liver SOD, CAT, and GPx activities Activity levels of AST, MDA, lactate dehydrogenase, and alanine transaminase	Saffari et al. 2017
Grass carp (*Ctenopharyngodon idella*)	Se	10 weeks	0.6–0.9 mg/kg	Improved both the growth and survival rate of grass carp	Jahanbakhshi et al. 2021
Nile tilapia (*Oreochromis niloticus*)	Zn	60 days	10 mg/kg	Exhibited higher levels of weight gain, final body weight, and specific growth rate	Ghazi et al. 2021

Table 1 (continued)

Fish species	NPs	Dose	Duration	Potential effect	Reference
Zebrafish (*Danio rerio*)	Zn	30 days	2 mg/kg	Analysis of growth showed that zebrafish were noticeably larger in both length and weight	Fasil et al. 2021
Nile tilapia (*Oreochromis niloticus*)	Zn	60 days	40 mg/kg	Demonstrated notable and substantial gains in feed conversion ratio, specific growth rate, body weight, and total gain rate	Kishawy et al. 2020
African catfish (*Clarias gariepinus*)	Zn	60 days	20–30 mg/kg	Growth performance, immune system, stress-related genes, lysozyme, growth, antioxidant state, IgM, and nitric oxide	Mahboub et al. 2020
European seabass (*Dicentrarchus labrax*)	Se	50 days	1 mg/kg	The European seabass exhibited improved growth rate, feed efficiency, haemato-biochemical indices, immunity, antioxidative responses, and anti-inflammatory effects due to the phagocytic index, phagocytic, and lysozyme activities	Abd El-Kader et al. 2020
Red sea bream (*Pagrus major*)	Se	45 days	1 mg/kg	Significantly improved red sea bream growth and feed efficiency	Dawood et al. 2019
Nile tilapia (*Oreochromis niloticus*)	Se	60 days	1 mg/kg	Immune system function, digestive enzyme activity, and haemato-biochemical parameters all significantly improved	Eissa et al. 2023

have unique, novel qualities, the US FDA has approved them as having features including a large A/V ratio, tiny size, and high superficial activity (Shah and Mraz 2020a, b).

Several challenges that restrict the productivity of fish have been addressed by the usage of nanotechnology. By using nanoparticle supplements, essential nutrients like silver iron, zinc, selenium, and copper can be included in their diet to support healthy growth, reproduction, and overall well-being. Additionally, they are essential for fast disease diagnosis, antimicrobial drug delivery, and nanovaccination, among other applications of fish medicine. Additionally, they significantly contribute to the cleaning and packaging of fish and water, the removal of chemical and biological pollutants, and the provision of high-quality water (Abbas et al. 2021).

Zinc NPs are also used in pharmaceuticals, immunizations, farm water flotation, growth booting products, fertility stimulants, feed additives, protein synthesis, energy consumption, animal growth, and other fields. It also plays a role in strengthening the immune system (Kumar et al. 2021).

In research, adding 30 mg kg^{-1} of ZnONPs to the diet of tilapia (*Orechromess niloticus*) resulted in higher quantities of total protein, lysozyme, survival rate, and total antioxidant capacity, along with increased gene expression of interleukins (Awad et al. 2019). The Nile tilapia experiment compared the effects of ZnO nanoparticles and conventional ZnO added to their diet at the rate of 30 and 60 mg kg^{-1} to a control diet.

According to the studies, a fish that received 60 mg kg^{-1} of ZnONPs demonstrated the highest levels of oxidative enzyme activity and improved intestinal topography. Research showed that ZnONPs at a dosage of 60 mg kg^{-1} enhance the growth, feed consumption, intestinal morphology, enzyme activity, and biomarkers of the oxidative response in Nile tilapia (Ibrahim et al. 2022).

Moreover, male rainbow trout sperm quality and health are significantly impacted by zinc, especially when it comes in nano-form. According to the study, the trout's sperm motility and spermatocyte increased after receiving 40 mg kg^{-1} of ZnONPs over 16 weeks, suggesting a beneficial effect on semen parameters.

According to the passage, nanozinc antioxidant qualities might be to blame for this effect, and compared to other forms of zinc, it might be a more effective way to improve sperm health and quality (Kazemi et al. 2020). The application of NPs in aquaculture systems has made it possible to tackle various challenges that affect fish productivity.

Nanotechnology and vaccines

Nanovaccines

An approaching mass immunization technique in aquaculture is called nanovaccine (Assefa and Abunna 2018). Nanovaccines have induced humoral and cellular immune responses in fishes based on several studies of the detection of the antigen by various methods, and it has been proposed that oral nanovaccines can effectively transport purified antigens or DNA as shown in Fig. 6 proposed by Rajesh Kumar et al. (2008).

Vaccines in the intestine, gills, liver, muscle, heart, blood, spleen, and head kidney have been studied (Rajesh Kumar et al. 2008; Vimal et al. 2012; Li et al. 2013). Fascinatingly, NPs have been shown in multiple studies to target the liver and other organs, and this effect is dependent on many factors (Wang et al. 2019).

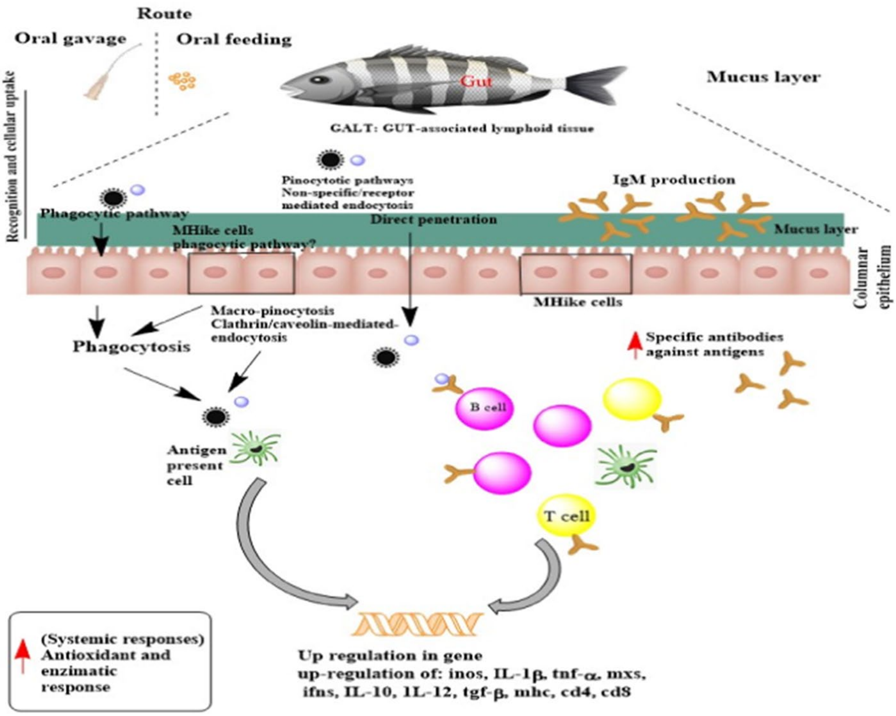

Fig. 6 This pictorial representation elaborates that NPs maintain the stability of the antigen and facilitate its effective uptake by antigen-presenting cells, which proceed to generate adaptive immune responses via complex pathways, that include presenting antigen to lymphocytes, which stimulate clonal growth and strengthen the effector mechanisms of humoral and T-cell responses to fight against the pathogen

It is interesting to point out that some nanovaccines have the ability to alter the integrity of the cell junction during the permeation process. This mechanism may be connected to the positive charges of NPs and is suggested as a beneficial feature to support the delivery of antigen or DNA vaccines (Liu et al. 2016). The US Department of Agriculture exhibited a device that uses ultrasound technology to vaccinate fish in large quantities.

A fish pond is filled with short DNA-loaded nano-capsule strands that attach themselves to fish cells. After that, ultrasonography is used to burst the capsules and release the DNA, which causes an immune reaction. This technology was experimented in rainbow trout and is being sold by Clear Springs Foods in the USA (Mongillo 2007). Similarly, the targeted-oriented release of activated components for vaccination and oral delivery of vaccines will reduce fish aquaculture farming costs (Rivas-Aravena et al. 2015).

Recent times have seen advancements in fish vaccination, and among the advancements are the creation of multivalent vaccines and the immunization of large stocks at once (Plant and Lapatra 2011). In 1942, fish vaccinations against *Aeromonas salmonicida* infection were introduced in Cutthroat. There are vaccines that are injectable and adjuvant to oil, and adjuvants enhance the immune system's response and reduce the need for frequent administration (Gudding and Van Muiswinkel 2013). Practically, all animals used in food production receive vaccinations on a large scale. In aquaculture, it lessens the usage of antibiotics (Plaza-Diaz et al. 2019a, b).

Toxicological impacts of nanoparticles

Iron nanoparticles toxicity

An experimental study on zebrafish (*D. rario*) with doses of 50 and 100 mg/L demonstrated developmental toxicity after 14 h in the embryos which leads to mortality and delayed hatching processes (Hafiz et al. 2018).

Another study demonstrated the long-term effects of 500 mg/L concentration of iron oxide nanoparticles (Fe2O3NPs) on the hematological, iono-regulatory, and physiological parameter of Rohu (*L. rohita*), a decrease in mean cellular hemoglobin concentration (MCHC), mean cellular volume (MCV), mean cellular hemoglobin (MCH), and white blood cell (WBC) levels throughout the research. In fish biology, the interaction of iron oxide nanoparticles also causes changes in ion regulation, which results in hypokalemia (K^+), hyponatremia (Na^+), and hypochloremia (Cl^-). Gill Na^+/K^+-ATPase activity has been found to double. The outcomes constitute an overview of the toxicological effects of iron oxide nanoparticles on *L. rohita* physiology and metabolism for a period of 25 days (Remya et al. 2015).

Similarly, the toxicological effect of FeNps was observed on Catla fish (*C. catla*) with a dose of 2.1 ppm iron nanoparticles in which biochemical analysis in various tissues such as muscle, liver, brain, and kidney showed remarkable variations in sugar, lipid, and protein levels after 96 h. These findings are taken as stress inducers on fish due to heavy metal toxicity and significant changes in metabolism processes like fatty acid and gluconeogenesis synthesis (Ilavazhahan et al. 2015).

Rohu (*Labeo rohita*) have shown changes in behavior upon exposure to iron oxide nanoparticles. A sub-lethal dosage of 300 mg/L for 4 weeks results in changes in behavior patterns such as surface separation, bottom resting, and jerking (Keerthika et al. 2016). Iron oxide nanoparticles with 15 mg/L dosage for 60-day duration also induced chronic histopathological destruction in *Oreochromis mossambicus* (Vidya and Chitra 2019).

In an experimental study, results showed how exposure to iron oxide nanoparticles with 50 mg/L affects *Oreochromis mossambicus*' hematological parameters. It was subjected to three different iron oxide NP concentrations. An increased level of serum glutamic oxaloacetic transaminase (SGOT) and serum glutamic pyruvic transaminase (SGPT) was observed after 48 h and indicates damage to fish liver tissue by accumulation (Karthikeyeni et al. 2013).

In another study on the fish rainbow trout (*Oncorhyn chusmykiss*), the ecological impacts of the iron oxide nanoparticles were analyzed on spermatozoon. An exposure of iron nanoparticles at the range of 100 mg/L had significant ($P<0.05$) decreases in the velocities of spermatozoon after 24 h exposure. Study also reported a decrease in catalase (CAT) and superoxide dismutase (SOD) activities (Özgür et al. 2018).

Silver nanoparticle toxicity

Silver NPs also have some toxicological impacts in a few fish species, e.g., zebrafish (*Danio rerio*) in which modest impacts on the genome were observed after exposure dosage of 1.0 mg/L for 15 days that resulted in embryo changes, delayed hatching, and ultimately mortality (Cambier et al. 2018). Similarly, juvenile fish (*Prochilodus lineatus*) were exposed to 2.5 and 25.0 μgAgNP L^{-1} for 5 and 15 days in order to check silver nanoparticle toxicity. Silver nanoparticles accumulated in tissue (e.g., liver, intestine, and brain). Hematological and morphometric parameters and oxidative stress markers also indicated the accumulation of silver nanoparticles in the fish (Ale et al. 2018).

A few other kinds of research showed that Japanese medaka (*Oryzias latipes*) was exposed to 400 µg/L of silver nanoparticles for 70 days resulting in some damages in the developing organs like the embryos and brain (Wu et al. 2010). Another study showed that an increased concentration of AgNPs leads to bio-accumulation of AgNPs in vital tissues, and hematological parameters have shown a significant alteration in the experimented fish.

A histological consequence caused by chemically produced AgNPs resulted in the damage in the tissues, blood vessels, and primary lamella of *L. rohita* at different dosage levels (25, 50, 100, 500, and 1000 mg kg^{-1}) for 7 days (Rajkumar et al. 2016). Gill impairment in Eurasian Perch larva (*Perca fluviatilis*) at the dose of 386 µg L^{-1} after 24 h was observed due to silver nanoparticle exposure (Bilberg et al. 2010).

A similar study was conducted to analyze the eco-toxicological impacts of AgNPs on blood and reproductive parameters of common molly (*Poecilia sphenops*) and its larvae. Exposure of female species at different concentrations of 0, 5, 15, 25, 35, 45, and 60 mg L^{-1} of AgNPs and larvae were exposed to 0, 3, 5, 10, and 15 mg L^{-1}. A significant decrease was observed in RBC, WBC, hematocrit level, and reproductive parameters when a fish was exposed to a higher concentration of more than 10 mg L^{-1} (Vali et al. 2022).

Meanwhile, juvenile fish pacu (*Piaractus mesopotamicus*) was analyzed for toxicological endpoints such as metal burdens, genotoxicity, and oxidative stress. Fish were exposed to (control) 2.5, 10, and 25 µg AgNPs/L. After 1 day, it was observed that AgNPs accumulated in large amounts in the brain. An increased level of lipid peroxidation was observed in the liver when exposed to 10 µg AgNPs/L (Bacchetta et al. 2017).

Copper nanoparticle toxicity

Copper is a non-biodegradable substance that has the potential to accumulate in the environment and cause hazardous impacts. The accumulation and release of copper have raised concerns globally (Nriagu 1996; Woody and O'Neal 2012) (Fig. 7).

According to a study, common carp (*Cyprinus carpio*) subjected to 20 to 100 µg/L for 7 days to copper NPs showed signs of damaged liver, which manifested cells with pyknotic nuclei (Gupta et al. 2016). The liver and kidney of common carp (*Cyprinus* carpio) had been damaged by exposure to both CuNP\s at 0.25 mg/L and $CuSO_4$ at 25 mg/L for 14 days. However, the damage produced by $CuSO_4$ in common carp was greater than that of CuNPs (Hoseini et al. 2016).

Selenium nanoparticle toxicity

As previously stated, to generate a nutritionally adequate fish feed, the right amount of selenium nanoparticles is needed. However, high amounts and excessive dosages of selenium nanoparticles have the potential to have hazardous effects and to disrupt a variety of physiological and biological functions in fish bodies (El-Sharawy et al. 2021; Mal et al. 2017; Khan et al. 2017). Thus, an excessive amount of Se nanoparticles adversely affected the gill and liver histology along with related metabolic parameters, e.g., LDH, acetylcholine esterase (ACHE), and liver function (ALP, AST, and ALT) with the dose of 5.29 and 3.97 mg/L in *Pangasius hypophthalmus* (Kumar et al. 2018a, b).

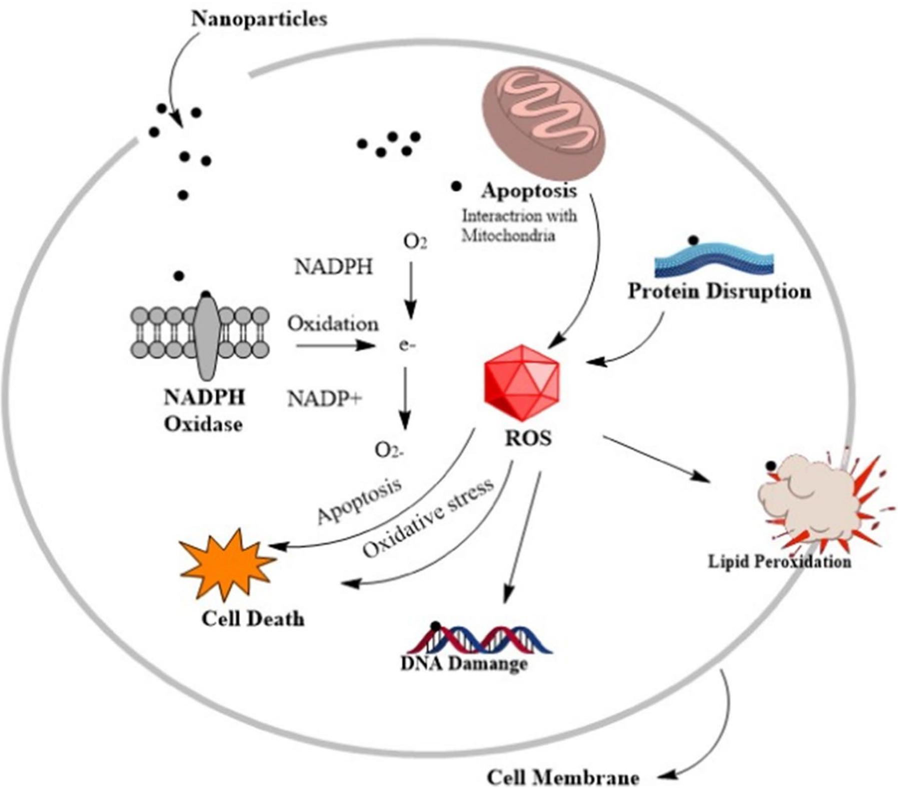

Fig. 7 Nanoparticles internalized in cells through endocytosis. Particles are released into the specific site and generated reactive oxygen species (ROS) by nanoparticles, then attach to the mitochondria and attach to nicotinamide-adenine dinucleotide phosphate (NADPH), and lose electrons. DNA damage and protein disruption leads to cell death

Goldfish (*Carassius auratus*) was exposed to selenium nanoparticle toxicity for a duration of 60 days at 1 mg/kg which showed an increase in spermatocyte and spermatid counts, disruption of DNA in sperm, and higher MDA and GPx levels in seminal plasma (Seyedi et al. 2021) (Table 2).

Conclusion

Nanotechnology is an innovative technology that is gaining attention globally because it has played a vital role in various fields of science and technology through nanoparticles. In the aquaculture industry, it has been used to tackle several challenges like disease management, vaccine delivery, growth factor, water treatment, and nutrient delivery using different nanoparticles like zinc, silver, selenium, iron, and copper. This review is helpful to overcome the various challenges faced by the aquaculture industry. Many researches mentioned above have shown that these nanoparticles have a high potential of being antioxidant and antibacterial.

Table 2 Different types of Nanoparticles and their toxicological impacts

Fish species	NPs	Dose	Duration	Effect	Reference
Common molly (*Poecilia sphenops*)	Ag	60 mg/L^{-1}	62 days	A significant decrease in WBC, RBC, hematocrit level, and reproductive parameters	Vali et al. 2022
Tilapia (O*reochromis mossambicus*)	Fe	15 mg/L	60 Days	Induced chronic histo-pathological destruction	Vidya and Chitra 2019
Rohu (*L. rohita*)	Ag	500 & 1000 mg kg^{-1}	7 days	This leads to bio-accumulation of AgNPs in vital tissues as well as hematological parameters that have shown a significant alteration in the experimented fish. A histological consequence caused by chemically produced AgNPs resulted in the damage in the tissues, blood vessels, and primary lamella of *L. rohita*	Rajkumar et al. 2016
Mozambique tilapia (*Oreochromis mossambicus*)	Fe	50 mg/mL	48 h	An increased level of serum glutamic oxaloacetic transaminase (SGOT) and serum glutamic pyruvic transaminase (SGPT) after 48 h indicates damage to fish liver tissue by its accumulation	Karthikeyeni et al. 2013
Zebrafish (*Danio rerio*)	Ag	1.0 mg/L	15 days	Impacts on the genome were observed after exposure to AgNPs that resulted in embryo changes, delayed hatching, and ultimately mortality	Cambier et al. 2018
Sabalo fish (*Prochilodus lineatus*)	Ag	2.5 & 25.0 μg/ L^{-1}	15 days	Hematological and morphometric parameters and oxidative stress markers indicate the accumulation of silver nanoparticles in the fish. It was also accumulated in tissue (e.g., liver, intestine, & brain)	Ale et al. 2018
Rohu (*Labeo rohita*)	Fe	500 mg/L	25 days	A decrease in mean cellular hemoglobin concentration (MCHC), mean cellular volume (MCV), mean cellular hemoglobin (MCH), and white blood cell (WBC) levels, changes in ion regulation, which result in hypokalemia (K^+), hyponatremia (Na^+), and hypochloremia (Cl^-). Gill Na^+/K^+-ATPase activity has been observed	Remya et al. 2015
Japanese medaka (*Oryzias latipes*)	Ag	400 μg/L	70 days	Results in damages in the developing organs like embryos and the brain	Wu et al. 2010

Table 2 (continued)

Fish species	NPs	Dose	Duration	Effect	Reference
Rohu (*Labeo rohita*)	Fe	300 mg/L	4 weeks	Sub-lethal dosages result in changes in behavior patterns such as surface separation, bottom resting, and jerking	Keerthika et al. 2016
Perch larvae (*Perca fluviatilis*)	Ag	386 μg L^{-1}	24 h	Gill impairment in larvae of *Perca fluviatilis* was observed due to silver nanoparticle exposure	Bilberg et al. 2010
Pacu (*Piaractus mesopotamicus*)	Ag	10 & 25 μg/L	24 h	Observed accumulation of silver nanoparticles in large amounts in the brain region. An increased level of lipid peroxidation was also observed in the liver when exposed to 10 μg/L	Bacchetta et al. 2017
Common carp (*Cyprinus carpio*)	Cu	20 to 100 μg/L	7 days	According to a study, subjected copper nanoparticles showed signs of damaged liver, which manifested cells with pyknotic nuclei	Gupta et al. 2016
Catla fish (*Catla catla*)	Fe	2.1 ppm	96 h	Biochemical analysis of various tissues such as the muscle, liver, brain, and kidney showed a remarkable variation in sugar, lipid, and protein levels These findings are taken as stress inducers on fish, because of heavy metal toxicity and significant changes in metabolism processes like fatty acid and gluconeogenesis synthesis	Ilavazhahan et al. 2015
Common carp (*Cyprinus carpio*)	Cu	0.25 mg/L & 25 mg/L	14 days	Liver and kidney have been damaged by exposure to both CuNP\s in *Cyprinus carpio*	Hoseini et al. 2016
Zebrafish (*Danio rerio*)	Se	50 & 100 mg/L	14 h	This demonstrated a developmental toxicity in the embryos which leads to mortality and delayed hatching processes in the zebrafish	Hafiz et al. 2018
Rainbow trout (*Oncorhynchus mykiss*)	Fe	100 mg/L	24 h	Observed ecological impacts of the iron oxide nanoparticles on spermatozoon. Significant ($P < 0.05$) decreases in the velocities of spermatozoon after its exposure. Study also reported decrease in catalase (CAT) and superoxide dismutase (SOD) activities	Özgür et al. 2018

Table 2 (continued)

Fish species	NPs	Dose	Duration	Effect	Reference
Goldfish (*Carassius auratus*)	Se	1 mg kg	60 days	Observed toxicity which results in an increase in spermatocyte and spermatid counts, disruption of DNA in sperm, and higher MDA and GPx levels in seminal plasma	Seyedi et al. 2021
Catfish (*Pangasius hypophthalmus*)	Cu	5.29 & 3.97 mg/L	96 h	Analyzed an excessive amount of selenium nanoparticles that adversely affected the gill and liver histology along with related metabolic parameters, e.g., LDH, acetylcholine esterase (ACHE), and liver function (ALP, AST, and ALT)	Kumar et al. 2018a, b

Several nanoparticles, e.g., zinc, selenium, and iron, have an important role in growth promotion by enhancing protease, metallo-protease activity, digestive tract enzyme function, enzyme activity, and improved intestinal topography. Meanwhile, many of them have played a crucial role in being antibacterial, antiviral, and anti-fungal like silver nanoparticles.

Several researchers have proved that silver nanoparticle shows high antibacterial properties by deactivation of a bacterial cell protein and genetic material which leads to bacterial cell disruption. Therefore, this technology is gaining so much attention in the aquaculture industry.

Apart from this, these nanoparticles have some toxicological impacts that can cause harmful impacts on fish health, while they are used without deep observations, which may lead to undesired consequences. Therefore, it is important to have all relevant information on their mode of administration as this literature review covers including the duration of exposure, dosage, and concentration accessible. According to many researchers mentioned above, it should be applied for a specific time duration to prevent their toxicity, and complete check and balance (e.g., temperature, pH, and salinity) should be enlisted before its use in aquaculture industry.

Author contributions M.S. wrote and edited the manuscript and did the software work.
S.A. edited and evaluated the manuscript.
M.S. edited the manuscript and help in data acquisition regarding mechanism of action.
S.N. proofread and edited the manuscript.
L.N. proofread and edited the manuscript.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Research involving human participants and/or animals This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent This article does not contain any studies with human participants or animals performed by any of the authors.

Competing interests The authors declare no competing interests.

References

Abbas Q, Javed MS, Ahmad A, Siyal SH, Asim I, Luque R, Tighezza AM (2021) ZnO nano-flowers assembled on carbon fiber textile for high-performance supercapacitor electrode. Coatings 11(11):1337. https://doi.org/10.3390/coatings11111337

Abbassy MMS (2018) Water and fish quality of aquaculture pond adjacent to intensive pesticides application agro-system. Fish Aquac J 9(3):1–10. https://link.gale.com/apps/doc/A568009457/AONE. Accessed 7-03-2024

Abd El-Kader MF, El-Bab AFF, Shoukry M, Abdel-Warith AWA, Younis EM, Moustafa EM, ..., Dawood MA (2020) Evaluating the possible feeding strategies of selenium nanoparticles on the growth rate and wellbeing of European seabass (Dicentrarchus labrax). Aquac Rep 18:100539. https://doi.org/10.1016/j.aqrep.2020.100539

Ale A, Rossi AS, Bacchetta C, Gervasio S, de la Torre FR, Cazenave J (2018) Integrative assessment of silver nanoparticles toxicity in Prochilodus lineatus fish. Ecol Indic 93:1190–1198. https://doi.org/10.1016/j.ecolind.2018.06.023

Ali A, El Sherif S, Abd Alla J, Maulu S, Tantawy AA, Soliman MFK et al (2021) Morphometric, histochemical, and ultrastructural analysis of the reproductive system and spermatogenic stages of male blue crab (*Callinectessapidus Rathbun*, 1896). J Mar Sci Eng 9:1105. https://doi.org/10.3390/jmse9101105

Altenburger R, Brack W, Burgess RM, Busch,W, Escher BI, Focks A, ..., Krauss M (2019) Future water quality monitoring: improving the balance between exposure and toxicity assessments of real-world pollutant mixtures. Environ Sci Eur 31(1):1–17. https://doi.org/10.1186/s12302-019-0193-1

Arestrup FM (2005) Veterinary drug usage and antimicrobial resistance in bacteria of animal origin. Basic Clin Pharmacol Toxicol 96(4):271–281

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

Atyah MAS, Zamri-Saad M, Siti-Zahrah (2010) A first report of methicillin resistant Staphylococcus aureus from cage-cultured tilapia (Oreochromis niloticus). Vet Microbiol 144(3):502–504. https://doi.org/10.1016/j.vetmic.2010.02.004

Awad AM, Shaikh SM, Jalab R, Gulied MH, Nasser MS, Benamor A, Adham S (2019) Adsorption of organic pollutants by natural and modified clays: a comprehensive review. Sep Purif Technol 228:115719. https://doi.org/10.1016/j.seppur.2019.115719

Aydın B, Barbas LAL (2020) Sedative and anesthetic properties of essential oils and their active compounds in fish: a review. Aquaculture 520:734999. https://doi.org/10.1016/j.aquaculture.2020.734999

Aydın F, Çek-Yalnız Ş (2019) Effect of probiotics on reproductive performance of fish. Nat Eng Sci 4(2):153–162. https://doi.org/10.28978/nesciences.567113

Ayoub HF, Tohamy EY, Salama HM, Mohamed SS (2021) *Citrullus colocynthis* extract and synthesized selenium nanoparticles enhance non-specific response and resistance against Aeromonas sobria in Nile tilapia (*Oreochromis niloticus*). Aquac Res. https://doi.org/10.1111/are.15366

Bacchetta C, Ale A, Simoniello MF, Gervasio S, Davico C, Rossi AS, ..., Cazenave J (2017) Genotoxicity and oxidative stress in fish after a short-term exposure to silver nanoparticles. Ecol Indic 76:230–239. https://doi.org/10.1016/j.ecolind.2017.01.018

Bai JunJie BJ, Li ShengJie LS (2019) Genetic breeding and molecular marker-assisted selective breeding of largemouth bass. https://www.elsevier.com/books/genetic-breeding-and-molecular-marker-assisted-selective-breeding-of-largemouth-bass/junjie/978-0-12-816473-0

Beaver LM, Nkrumah-Elie YM, Truong L, Barton CL, Knecht AL, Gonnerman GD et al (2017) Adverse effects of parental zinc deficiency on metal homeostasis and embryonic development in a zebrafish model. J Nutri Biochem 43:78–87. https://doi.org/10.1016/j.jnutbio.2017.02.006

Benton TG, Bailey R, Froggatt A, King R, Lee B, Wellesley L (2018) Designing sustainable land use in a 1.5 C world: the complexities of projecting multiple ecosystem services from land. Curr Opin Environ Sustain 31:88–95. https://doi.org/10.1016/j.cosust.2018.01.011

Bezbaruah G, Deka DD (2021) Variation of moisture and protein content in the muscle of three catfishes: a comparative study. Int J Fish Aquat Stud 9(1):223–226. https://doi.org/10.22271/fish.2021.v9.i1c.2406

Bhupinder SS (2014) Nanotechnology in agri-food production: an overview. Nanotechnol Sci Appl 7:31–53. https://doi.org/10.2147/NSA.S39406

Bilberg K, Malte H, Wang T, Baatrup E (2010) Silver nanoparticles and silver nitrate cause respiratory stress in Eurasian perch (Perca fluviatilis). Aquat Toxicol 96(2):159–165. https://doi.org/10.1016/j.aquatox.2009.10.019

Borda FLG, de Oliveira SJR, Lazaro LMSM, Leiróz AJK (2018) Experimental investigation of the tribological behavior of lubricants with additive containing copper nanoparticles. Tribol Int 117:52–58. https://doi.org/10.1016/j.triboint.2017.08.012

Borja A (2002) Los impactos ambientales de la acuiculturayla sostenibilidad de esta actividad. Bol Inst Esp Oceanogr 18(1–4):41–49

Bose D, Chatterjee S (2016) Biogenic synthesis of silver nanoparticles using guava (psidium guajava) leaf extract and its antibacterial activity against Pseudomonas aeruginosa. Appl Nanosci 6(6):895–901. https://doi.org/10.1007/s13204-015-0496-5

Branco ACCC, Yoshikawa FSY, Pietrobon AJ, Sato MN (2018) Role of histamine in modulating the immune response and inflammation. Mediators Inflamm 2018. https://doi.org/10.1155/2018/9524075

Bruna T, Maldonado-Bravo F, Jara P, Caro N (2021) Silver nanoparticles and their antibacterial applications. Int J Mol Sci 22(13):7202. https://doi.org/10.3390/ijms22137202

Burdușel AC, Gherasim O, Grumezescu AM, Mogoanta L, Ficai A, Andronescu E (2018) Biomedical applications of silver nanoparticles: an up-to-date overview. Nanomaterials 8(9):1–25. https://doi.org/10.3390/nano8090681

Burridge L, Weis JS, Cabello F, Pizarro J, Bostick K (2010) Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. Aquaculture 306(1–4):7–23. https://doi.org/10.1016/j.aquaculture.2010.05.020

Bury NR, Galvez F, Wood CM (1999) Effects of chloride, calcium, and dissolved organic carbon on silver toxicity: comparison between rainbow trout and fathead minnows. Environ Toxicol Chem: Int J 18(1):56–62. https://doi.org/10.1002/etc.5620180108

Byrd KA, Thilsted SH, Fiorella KJ (2021) Fish nutrient composition: a review of global data from poorly assessed inland and marine species. Public Health Nutr 24(3):476–486. https://doi.org/10.1017/S1368980020003857

Cabello FC (2006) Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. Environ Microbiol 8:1137–1144

Cambier S, Røgeberg M, Georgantzopoulou A, Serchi T, Karlsson C, Verhaegen S, ..., Gutleb AC (2018) Fate and effects of silver nanoparticles on early life-stage development of zebrafish (Danio rerio) in comparison to silver nitrate. Sci Total Environ 610:972–982. https://doi.org/10.1016/j.scitotenv.2017.08.115

Cavassin ED, de Figueiredo LFP, Otoch JP, Seckler MM, de Oliveira RA, Franco FF, Marangoni VS, Zucolotto V, Levin ASS, Costa SF (2015) Comparison of methods to detect the in vitro activity of silver nanoparticles (AgNP) against multidrug resistant bacteria. J Nanobiotechnol 2015(13):1–16. https://doi.org/10.1186/s12951-015-0120-6

Chaplin DD (2010) Overview of the immune response. J Allergy and Clin Immunol 125(2 Suppl):S3–S23. https://doi.org/10.1016/j.jaci.2009.12.980

Chatterjee AK, Chakraborty R, Basu T (2014) Mechanism of antibacterial activity of copper nanoparticles. Nanotechnology 25(13):135101. https://doi.org/10.1088/0957-4484/25/13/135101

Chen B, Lin L, Fang L et al (2018) Complex pollution of antibiotic resistance genes due to beta-lactam and aminoglycoside use in aquaculture farming. Water Res 134:200–208. https://doi.org/10.1016/j.watres.2018.02.003

Choi JE, Kim S, Ahn JH, Youn P, Kang JS, Park K, ..., Ryu DY (2010) Induction of oxidative stress and apoptosis by silver nanoparticles in the liver of adult zebrafish. Aquat Toxicol 100(2):151–159. https://doi.org/10.1016/j.aquatox.2009.12.012

Chris UO, Singh NB, Agarwal A (2018) Nanoparticles as feed supplement on growth behaviour of cultured catfish (Clarias gariepinus) fingerlings. Mater Today: Proc 5(3):9076–9081. https://doi.org/10.1016/j.matpr.2017.10.023

Coldebella, Boscolo WR, Feiden A (2017) Effluents from fish farming ponds: a view from the perspective of its main components. Sustainability 10(1):3. https://doi.org/10.3390/su10010003

Dadar M, Dhama K, Vakharia VN, Hoseinifar SH, Karthik K, Tiwari R, Khandia R, Munjal A, Salgado-Miranda C, Joshi SK (2016) Advances in aquaculture vaccines against fish pathogens: global status and current trends. Rev Fish Sci Aquac 25(3):184–217. https://doi.org/10.1080/23308249.2016.1261277

Daniel AI, Fadaka AO, Gokul A, Bakare OO, Aina O, Fisher S, ..., Klein A (2022) Biofertilizer: the future of food security and food safety. Microorganisms 10(6):1220. https://doi.org/10.3390/microorganisms10061220

Davis DA, Gatlin DM (1996) Dietary mineral requirements of fish and marine crustaceans. Rev Fish Sci 4:75–99. https://doi.org/10.1080/10641269609388579

Dawit Moges F, Hamdi H, Al-Barty A, Zaid AA, Sundaray M, Parashar SKS, ..., Das B (2022) Effects of selenium nanoparticle on the growth performance and nutritional quality in Nile tilapia, Oreochromis niloticus. PloS one 17(6):e0268348. https://doi.org/10.1371/journal.pone.0268348

Dawood MA (2021) Nutritional immunity of fish intestines: important insights for sustainable aquaculture. Rev Aquac 13(1):642–663

Dawood MA, Koshio S, Zaineldin AI, Van Doan H, Ahmed HA, Elsabagh M, Abdel-Daim MM (2019) An evaluation of dietary selenium nanoparticles for red sea bream (Pagrus major) aquaculture: growth, tissue bioaccumulation, and antioxidative responses. Environ Sci Pollut Res 26:30876–30884. https://doi.org/10.1007/s11356-019-06223-6

Defoirdt T, Boon N, Sorgeloos P, Verstraete W, Bossier P (2007) Alternatives to antibiotics to control bacterial infections: luminescent vibriosis in aquaculture as an example. Trends Biotechnol 25(10):472–479. https://doi.org/10.1016/j.tibtech.2007.08.001

Di Cesare A, Vignaroli C, Luna GM, Pasquaroli S, Biavasco F (2012) Antibiotic-resistant enterococci in seawater and sediments from a coastal fish farm. Microb Drug Resist 18(5):502–9. https://doi.org/10.1089/mdr.2011.0204

Dosoky R, Kotb S, Farghali M (2015) Efficiency of silver nanoparticles against bacterial contaminants isolated from surface and ground water in Egypt. http://bdvets.org/JAVAR/V2I2/b79_pp175-184

Dubchak S, Ogar A, Mietelski JW, Turnau K (2010) Influence of silver and titanium nanoparticles on arbuscular mycorrhiza colonization and accumulation of radiocesium Helianthus anus. Span J Agric Res 8(1):103–108

Dutta D, Phukan A, Dutta DK (2018) Nanoporous montmorillonite clay stabilized copper nanoparticles: efficient and reusable catalyst for oxidation of alcohols. Mol Catal 451:178–185. https://doi.org/10.1016/j.mcat.2017.12.032

Editorial (2021) Harness the world's aquatic 'blue' food systems to help end hunger. Nature 597:303. https://doi.org/10.1038/d41586-021-02476-9

Eissa ESH, Bazina WK, Abd El-Aziz YM, Abd Elghany NA, Tawfik WA, Mossa MI, Khalil HS (2023) Nano-selenium impacts on growth performance, digestive enzymes, antioxidant, immune resistance and histopathological scores of Nile tilapia, Oreochromis niloticus against Aspergillus flavus infection. Aquac Int 1–25. https://doi.org/10.1007/s10499-023-01230-4

El-Saadony MT, Alkhatib FM, Alzahrani SO, Shafi ME, AbdelHamid SE, Taha TF, Aboelenin SM, Soliman MM, Ahmed NH (2021) Impact of mycogenic zinc nanoparticles on performance, behavior, immune response, and microbial load in Oreochromis niloticus. Saudi J Biol Sci 28(8):4592–4604. https://doi.org/10.1016/j.sjbs.2021.04.066

El-Sayed Ali T, Abdel-Aziz SH, El-Sayed AM, Zeid S (2014a) Structural and functional effects of early exposure to 4-nonylphenol on gonadal development of Nile tilapia (Oreochromis niloticus): a-histological alterations in ovaries. Fish Physiol Biochem 40:1509–1519. https://doi.org/10.1007/s10695-014-9944-5

El-Sayed Ali T, Abdel-Aziz SH, El-Sayed AM, Zeid S (2014b) Structural and functional effects of early exposure to 4-nonylphenol on gonadal development of Nile tilapia (Oreochromis niloticus): a-histological alterations in testes. Fish Physiol Biochem 40:1495–1507. https://doi.org/10.1007/s10695-014-9944-5

El-Sayed Ali T, El-Sayed AM, Abdel-Razek Eissa M, Hanafi H (2017) Effects of dietary biogen and sodium butyrate on hematological parameters, immune response and histological characteristics of Nile tilapia (Oreochromis niloticus) fingerlings. Aquac Int 26:139–150. https://doi.org/10.1007/s10499-017-0205-3

El-Sharawy ME, Hamouda M, Soliman AA, Amer AA, El-Zayat AM, Sewilam H, ..., Dawood MA (2021) Selenium nanoparticles are required for the optimum growth behavior, antioxidative capacity, and liver wellbeing of striped catfish (Pangasianodon hypophthalmus). Saudi J Biol Sci 28(12):7241–7247. https://doi.org/10.1016/j.sjbs.2021.08.023

Ermini ML, Voliani V (2021) Antimicrobial nano-agents: the copper age. ACS Nano 15(4):6008–6029. https://doi.org/10.1021/acsnano.0c10756

Eroldoğan OT (2022) Iron supplementation in plant-based aquafeed: efects on growth performance, tissue composition, iron-related serum parameters and gene expression in rainbow trout (Oncorhynchus mykiss). Aquaculture 550:737884. https://doi.org/10.1016/j.aquaculture.2021.737884

Evliyaoğlu E, Kilercioğlu S, Yılmaz HA, Turchini GM, Paolucci M, Clark TD, Demirkale İ, Eroldoğan OT (2022) Iron supplementation in plant-based aquafeed: Effects on growth performance, tissue composition, iron-related serum parameters and gene expression in rainbow trout (Oncorhynchus mykiss). Aquaculture 550

Faiz H, Zuberi A, Nazir S, Rauf M (2015) Zinc oxide, zinc sulfate and zinc oxide nanoparticles as source of dietary zinc: comparative effects on growth and hematological indices of juvenile grass carp (*Ctenopharyngodon idella*). Int J Agricult Biol 17:568–574. https://doi.org/10.17957/IJAB/17.3.14.446

Fanzo J, Hunter D, Borelli T et al (2013) Diversifying food and diets. Taylor & Francis, New York

FAO (2016a) Contributing to food security and nutrition for all (The state of world fisheries and aquaculture). Food and Agriculture Organization of the United Nations, Rome

FAO (2016b) El estado mundial de la pesca y la acuicultura 2016.Contribuci_on a la seguridad alimentaria y la nutrici_on paratodos, Roma, 224 pp

FAO (2017) The future of food and agriculture: trends and challenges (Rome)

FAO (2018) The state of world fisheries and aquaculture 2018 meeting the Sustainable Development Goals (FAO)

FAO (2020) The state of world Fisheries and aquaculture 2020. Sustainability in action.

FAO STAT (2022) Available online: https://www.fao.org/faostat/en/#data (accessed on 28 June 2022)

Fasil DM, Hamdi H, Al-Barty A, Zaid AA, Parashar SKS, Das B (2021) Selenium and zinc oxide multinutrient supplementation enhanced growth performance in zebra fish by modulating oxidative stress and growth-related gene expression. Front Bioeng Biotechnol 9:721717. https://doi.org/10.3389/fbioe.2021.721717

Fewtrell L (2014) Silver: water disinfection and toxicity. Aberystwyth University, Centre for Research into Environment and Health, p 58

Food and Drug Administration (FDA) (2020) Approved drugs for use in seafoods; FDA:, New York. 2020. Available online: https://www.fda.gov/animal-veterinary/aquaculture/approved-aquaculture-drugs (accessed on 1 June 2021)

Fraser DG (2005) Animal welfare and the intensification of animal production: an alternative interpretation vol 2. Food & Agriculture Org

Gao Y, Anand MAV, Ramachandran V, Karthikkumar V, Shalini V (2019a) *Aspergillus niger*, their anti-oxidant, antimicrobial and anticancer activity. J Clust Sci 30:937–946. https://doi.org/10.1007/s10876-019-01551-6

Gao Y, Arokia Vijaya Anand M, Ramachandran V, Karthikkumar V, Shalini V, Vijayalakshmi S, Ernest D (2019b) Biofabrication of zinc oxide nanoparticles from Aspergillus niger, their antioxidant, antimicrobial and anticancer activity. J Clust Sci 30:937–946

Ghazi S, Diab AM, Khalafalla MM, Mohamed RA (2021) Synergistic effects of selenium and zinc oxide-nanoparticles on growth performance, hemato-biochemical profile, immune and oxidative stress responses, and intestinalmorphometry of Nile tilapia (Oreochromis niloticus). Biol Trace Elem Res 1–11. https://doi.org/10.1007/s12011-021-02631-3

Ghelani D, Faisal S (2022) Synthesis and characterization of aluminium oxide nanoparticles. Authorea Preprints. https://doi.org/10.22541/au.166490972.20428974/v1

Golden CD, Allison EH, Cheung WWL, Dey MM, Halpern BS, McCauley DJ, Smith M, Vaitla B, Zeller D, Myers SS (2016) Nutrition: fall in fish catch threatens human health. Nature 534(7607):317–320

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF et al (2021) Aquatic foods to nourish nations. Nature 598:315–320. https://doi.org/10.1038/s41586-021-03917-1

Gonnerman GD, ..., Ho E (2017) Adverse effects of parental zinc deficiency on metal homeostasis and embryonic development in a zebrafish model. J Nutr Biochem 43:78–87. https://doi.org/10.1016/j.jnutbio.2017.02.006

Gonzalez N, Marquès M, Nadal M, Domingo JL (2020) Meat consumption: which are the current global risks? A review of recent (2010–2020) evidences. Food Res Int 137:109341. https://doi.org/10.1016/j.foodres.2020.109341

Griffitt RJ, Hyndman K, Denslow ND, Barber DS (2009) Comparison of molecular and histological changes in zebrafish gills exposed to metallic nanoparticles. Toxicol Sci 107(2):404–415. https://doi.org/10.1093/toxsci/kfn256

Grzinic G, Piotrowicz-Cieślak A, Klimkowicz-Pawlas A, Górny RL, Ławniczek-Wałczyk A, Piechowicz L, ..., Wolska L (2023) Intensive poultry farming: a review of the impact on the environment and human health. Sci Total Environ 858:160014. https://doi.org/10.1016/j.scitotenv.2022.160014

Gudding R, Van Muiswinkel WB (2013) A history of fish vaccination: science-based disease prevention in aquaculture. Fish Shellfish Immunol 35(6):1683–1688. https://doi.org/10.1016/j.fsi.2013.09.031

Gui JF, Tang QS, Li ZJ, Liu JS, De Silva SS (2018) Aquaculture in China: Success stories and modern trends. John Wiley and Sons Ltd, Oxford

Gupta YR, Sellegounder D, Kannan M, Deepa S, Senthilkumaran B, Basavaraju Y (2016) Effect of copper nanoparticles exposure in the physiology of the common carp (Cyprinus carpio): Biochemical, histological and proteomic approaches. Aquac Fish 1:15–23. https://doi.org/10.3390/nano10061126

Hafiz SM, Kulkarni SS, Thakur MK (2018) In-vivo toxicity assessment of biologically synthesized iron oxide nanoparticles in zebrafish (Danio rerio). Biosci Biotechnol Res Asia 15(2):419–425.https://doi.org/10.13005/bbra/2645

Hajipour MJ, Fromm KM, Ashkarran AA, de Aberasturi DJ, deLarramendi IR, Rojo T et al (2012) Antibacterial properties of nanoparticles. Trends Biotechnol 30(10):499–511. https://doi.org/10.1016/j.tibtech.2012.06.004

Halpern BS, Cottrell RS, Blanchard JL, Bouwman L, Froehlich HE, Gephart JA et al (2019) Putting all foods on the same table: achieving sustainable food systems requires full accounting. Proc Natl Acad Sci 116(37):18152–18156. https://doi.org/10.1073/pnas.1913308116

Han D, Shan XJ, Zhang WB, Chen YS, Wang QY, Li ZJ et al (2018) A revisit to fishmeal usage and associated consequences in Chinese aquaculture. Rev Aquac 10:493–507. https://doi.org/10.1111/raq.12183

Handy RD, Cornelis G, Fernandes T, Tsyusko O, Decho A, Sabo-Attwood T et al (2012) Ecotoxicity test methods for engineered nanomaterials: practical experiences and recommendations from the bench. Environ Toxicol Chem 31(1):15–31.https://doi.org/10.1002/etc.706

Hicks CC, Cohen PJ, Graham NAJ, Nash KL, Allison EH, D'Lima C, MacNeil MA (2019) Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574(7776):95–98

Hoseini SM, Hedayati A, Mirghaed AT, Ghelichpour M (2016) Toxic effects of copper sulfate and copper nanoparticles on minerals, enzymes, thyroid hormones and protein fractions of plasma and

histopathology in common carp Cyprinus carpio. Exp Toxicol Pathol 68(9):493–503. https://doi.org/10.1016/j.etp.2016.08.002
Hu S, Yi T, Huang Z, Liu B, Wang J, Yi X, Liu J (2019) Etching silver nanoparticles using DNA. Mater Horiz 6(1):155–159. https://doi.org/10.1039/C8MH01126E
Ibrahim MS, El-gendy GM, Ahmed AI, Elharoun ER, Hassaan MS (2021) Nanoselenium versus bulk selenium as a dietary supplement: effects on growth, feed efficiency, intestinal histology, haemato-biochemical and oxidative stress biomarkers in Nile tilapia (Oreochromis niloticus Linnaeus, 1758) fingerlings. Aquac Res 52(11):5642–5655
Ibrahim MI, Alsafadi D, Alamry KA, Oves M, Alosaimi AM, Hussein MA (2022) A promising antimicrobial bionanocomposite based poly (3-hydroxybutyrate-co-3-hydroxyvalerate) reinforced silver doped zinc oxide nanoparticles. Sci Rep 12(1):14299. https://doi.org/10.1038/s41598-022-17470-y
Idowu TA, Adedeji HA, Sogbesan OA (2017) Fish disease and health management in aquaculture production. Int J Environ Agri Sci 1:2–6
Ilavazhahan M, Tamilselvi R, Sujatha LB (2015) Biochemical alteration in themuscle, liver, kidney and brain of a fresh water fish, Catlacatla (Ham.) exposure of a heavy metal toxicant ferrous sulphate. Biomed Pharmacol J 5(2):261–272. http://biomedpharmajournal.org/?p=2500. Accessed 7-03-2024
Ingle AP, Duran N, Rai M (2014) Bioactivity, mechanism of action, and cytotoxicity of copper-based nanoparticles: a review. Appl Microbiol Biotechnol 98:1001–1009. https://doi.org/10.1007/s00253-013-5422-8
Irianto A, Austin B (2002) Review probiotics in aquaculture. J Fish Dis 1997:633–642. https://doi.org/10.1046/j.1365-2761.2002.00422.x
Jahanbakhshi A, Pourmozaffar S, Adeshina I, Mahmoudi R, Erfanifar E, Ajdari A (2021) Selenium nanoparticle and selenomethionine as feed additives: Effects on growth performance, hepatic enzymes' activity, mucosal immune parameters, liver histology, and appetite-related gene transcript in goldfish (Carassius auratus). Fish Physiol Biochem 47:639–652. https://doi.org/10.1007/s10695-021-00937-6
Jayaraman K, Munira H, Dababrata C, Iranmanesh M (2013) The preference and consumption of chicken lovers with race as a moderator-an empirical study in Malaysia. Int Food Res J 20:165–76
Kakakhel MA, Sajjad W, Wu F, Bibi N, Shah K, Yali Z, Wang W (2021) Green synthesis of silver nanoparticles and their shortcomings, animal blood a potential source for silver nanoparticles: a review. J Hazard Mater Adv 1:100005. https://doi.org/10.1016/j.hazadv.2021.100005
Karamzadeh M, Yahyavi M, Salarzadeh A, Nokhbe Zare D (2021) The effects of different concentrations of selenium and zinc nanoparticles on growth performance, survival and chemical composition of whiteleg shrimp (*Litopenaeus vannamei*). Iran Sci Fish J 29:43–51
Karthikeyeni S, Siva Vijayakumar T, Vasanth S, Arul Ganesh MM, Subramanian P (2013) Biosynthesis of iron oxide nanoparticles and its haematological effects on fresh water fish Oreochromis mossambicus. J Acad Indus Res 10:645–649
Kazemi E, Sourinejad I, Ghaedi A, Johari SA, Ghasemi Z (2020) Effect of different dietary zinc sources (mineral, nanoparticulate, and organic) on quantitative and qualitative semen attributes of rainbow trout (Oncorhynchus mykiss). Aquaculture 515:734529. https://doi.org/10.1016/j.aquaculture.2019.734529
Keerthika V, Ramesh R, Rajan MR (2016) Impact of iron oxide nanoparticles on behavioural changes in fresh water fish Labeo Rohita. Paripex Ind J Res 5(8):158–160
Khalil HS, Momoh T, Al-Kenawy D, Yossa R, Badreldin AM, Roem A et al (2021) Nitrogen retention, nutrient digestibility and growth efficiency of Nile tilapia (*Oreochromis niloticus*) fed dietary lysine and reared in fertilized ponds. Aquac Nutr 00:1–13. https://doi.org/10.1111/anu.13365
Khan KU, Zuberi A, Nazir S, Fernandes JBK, Jamil Z, Sarwar H (2016) Effects of dietary selenium nanoparticles on physiological and biochemical aspects of juvenile Tor putitora. Turk J Zool 40(5):704–712. https://doi.org/10.3906/zoo-1510-5
Khan KU, Zuberi A, Fernandes JBK, Ullah I, Sarwar H (2017) An overview of the ongoing insights in selenium research and its role in fish nutrition and fish health. Fish Physiol Biochem 43:1689–1705. https://doi.org/10.1007/s10695-017-0402-z
Khosravi-Katuli K, Prato E, Lofrano G, Guida M, Vale G, Libralato G (2017) Effects of nanoparticles in species of aquaculture interest. Environ Sci Pollut Res 24:17326–17346. https://doi.org/10.1007/s11356-017-9360-3
Kishawy AT, Roushdy EM, Hassan FA, Mohammed HA, Abdelhakim TM (2020) Comparing the effect of diet supplementation with different zinc sources and levels on growth performance, immune response and antioxidant activity of tilapia, Oreochromis niloticus. Aquac Nutr 26(6):1926–1942
Korican M, Perčić M, Vladimir N, Soldo V, Jovanović I (2022) Environmental and economic assessment of mariculture systems using a high share of renewable energy sources. J Clean Prod 333:130072. https://doi.org/10.1016/j.jclepro.2021.130072

Kothari D, Patel S, Kim SK (2019) Probiotic supplements might not be universally-effective and safe: a review. Biomed Pharmacother 111:537–547. https://doi.org/10.1016/j.biopha.2018.12.104

Kraemer SA, Ramachandran A, Perron GG (2019) Antibiotic pollution in the environment: from microbial ecology to public policy. Microorganisms 7:1–24. https://doi.org/10.3390/microorganisms7060180

Kruk T, Szczepanowicz K, Stefańska J, Socha RP, Warszyński P (2015) Synthesis and antimicrobial activity of monodisperse copper nanoparticles. Colloids Surf B: Biointerfaces 128:17–22. https://doi.org/10.1016/j.colsurfb.2015.02.009

Kumar N, Krishnani KK, Singh NP (2018a) Effect of dietary zinc-nanoparticles on growth performance, anti-oxidative and immunological status of fish reared under multiple stressors. Biol Trace Elem Res 186(1):267–278. https://doi.org/10.1007/s12011-018-1285-2

Kumar N, Krishnani KK, Singh NP (2018b) Comparative study of selenium and selenium nanoparticles with reference to acute toxicity, biochemical attributes, and histopathological response in fish. Environ Sci Pollut Res 25:8914–8927. https://doi.org/10.1007/s11356-017-1165-x

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

Kumar N, Chandan NK, Kumar P (2021) Impact of zinc nanoparticles on aquatic ecosystems: Risks and benefits. In: Zinc_based nanostructures for environmental and agricultural applications. Elsevier, pp 433–456.

Kumar S, Dev I, Kumar N (2023) Forestry and Agroforestry. In: Trajectory of 75 years of Indian Agriculture after Independence. Springer Nature Singapore, Singapore, pp 497–519.

Lee SY, Kim HJ, Patel R, Im SJ, Kim JH, Min BR (2007) Silver nanoparticles immobilized on thin film composite polyamide membrane: characterization, nanofiltration, antifouling properties. Polym Adv Technol 18:562–568. https://doi.org/10.1002/pat.918

Leela A, Vivekanandan M (2008) Tapping the unexploited plant resources for the synthesis of silver nanoparticles. Afr J Biotech 7:3162

Lemire JA, Harrison JJ, Turner RJ (2013) Antimicrobial activity of metals: mechanisms, molecular targets and applications. Nat Rev Microbiol 11(6):371–384

Leung TLF, Bates AE (2013) More rapid and severe disease outbreaks for aquaculture at the tropics: implications for food security". J Appl Ecol 50(1):215–222. https://doi.org/10.1111/1365-2644.12017

Levchenko V, Reisfeld R (2017) Enhancement of fluorescence of EuEDTA chelate complex in sol-gel glasses by surface plasmons of copper nanoparticles. Opt Mater 74:187–190. https://doi.org/10.1016/j.optmat.2017.04.040

Li L, Lin SL, Deng L, Liu ZG (2013) Potential use of chitosan nanoparticles for oral delivery of DNA vaccine in black seabream Acanthopagrus schlegelii Bleeker to protect from Vibrio parahaemolyticus. J Fish Dis 36:987–995

Li F, Huang J, Wang M, Chen L, Xiao Y (2021) Sources, distribution and dynamics of antibiotics in *Litopenaeus vannamei* farming environment. Aquaculture 545:737200. https://doi.org/10.1016/j.aquaculture.2021.737200

Limbu SM, Chen LQ, Zhang ML, Du ZY (2021) A global analysis on the systemic effects of antibiotics in cultured fish and their potential human health risk: a review. Rev Aquac 13:1015–1059

Liu Y, Wang FQ, Shah Z, Cheng XJ, Kong M, Feng C et al (2016) Nano-polyplex based on oleoyl-carboxymethy-chitosan (OCMCS) and hyaluronic acid for oral gene vaccine delivery. Colloids Surf B: Biointerfaces 145:492–501. https://doi.org/10.1016/j.colsurfb.2016.05.035

Liu X, Steele JC, Meng XZ (2017) Usage, residue, and human health risk of antibiotics in Chinese aquaculture: a review. Environ Pollut 223:161–169. https://doi.org/10.1016/j.envpol.2017.01.003

Liu C, Tan L, Zhang L et al (2021) A review of the distribution of antibiotics in water in different regions of China and current antibiotic degradation pathways. Front Environ Sci 9:1–24. https://doi.org/10.3389/fenvs.2021.692298

Longbaf Dezfouli M, Ghaedtaheri A, Keyvanshokooh S, Salati AP, Mousavi SM, Pasha-Zanoosi H (2019) Combined or individual effects of dietary magnesium and selenium nanoparticles on growth performance, immunity, blood biochemistry and antioxidant status of Asian seabass (Lates calcarifer) reared in freshwater. Aquac Nutr 25(6):1422–1430

Lozano I, Díaz NF, Muñoz S, Riquelme C (2017) Antibiotics in Chilean aquaculture: a review. Antibiot Use Anim 3:25–44. https://doi.org/10.5772/intechopen.71780

Lulijwa R, Kajobe R (2018) Aquaculture production and its contribution to development in the Rwenzori region Uganda use of abattoir wastes for livestock feeding View project Artemia Study View project. Afr J Trop Hydrobiol Fish 16:56–62

Lulijwa R, Rupia EJ, Alfaro AC (2020) Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers. Rev Aquac 12:640–663. https://doi.org/10.1111/raq.12344

Mahboub HH, Shahin K, Zaglool AW, Roushdy EM, Ahmed SA (2020) Efficacy of nano zinc oxide dietary supplements on growth performance, immuno-modulation and disease resistance of African catfish Clarias gariepinus. Dis Aquat Org 142:147–160. https://doi.org/10.3354/dao03531

Mal J, Veneman WJ, Nancharaiah YV, van Hullebusch ED, Peijnenburg WJ, Vijver MG, Lens PN (2017) A comparison of fate and toxicity of selenite, biogenically, and chemically synthesized selenium nanoparticles to zebrafish (Danio rerio) embryogenesis. Nanotoxicology 11(1):87–97. https://doi.org/10.1080/17435390.2016.1275866

Malhotra N, Lee JS, Liman RAD, Ruallo JMS, Villaflores OB, Ger TR, Hsiao CD (2020) Potential toxicity of iron oxide magnetic nanoparticles: a review. Molecules 25(14):3159. https://doi.org/10.3390/molecules25143159

Matatkova O, Michailidu J, Miškovská A, Kolouchová I, Masák J, Čejková A (2022) Antimicrobial properties and applications of metal nanoparticles biosynthesized by green methods. Biotechnol Adv 58:107905. https://doi.org/10.1016/j.biotechadv.2022.107905

Mathur P, Jha S, Ramteke S, Jain NK (2018) Pharmaceutical aspects of silver nanoparticles. Artif Cells Nanomed Biotechnol 46:115–126. https://doi.org/10.1080/21691401.2017.1414825

Matteucci F, Giannantonio R, Calabi F, Agostiano A, Gigli G, Rossi M (2018) Deployment and exploitation of nanotechnology nanomaterials and nanomedicine. In: AIP conference proceedings (vol 1990, No. 1). https://doi.org/10.1063/1.5047755

Maulu S, Hasimuna OJ, Haambiya LH, Monde C, Musuka CG, Makorwa TH et al (2021) Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations. Front Sustain Food Syst 5:609097. https://doi.org/10.3389/fsufs.2021.609097

Meiler KA, Kumar V (2021) Organic and inorganic zinc in the diet of a commercial strain of diploid and triploid rainbow trout (Oncorhynchus mykiss): effects on performance and mineral retention. Aquaculture 545:737126. https://doi.org/10.1016/j.aquaculture.2021.737126

Michalk DL, Kemp DR, Badgery WB, Wu J, Zhang Y, Thomassin PJ (2019) Sustainability and future food security—a global perspective for livestock production. Land Degrad Dev 30:561–573

Mohd-Aris A, Muhamad-Sofie MHN, Zamri-Saad M, Daud HM, Ina-Salwany MY (2019) Live vaccines against bacterial fish diseases: a review. Vet World 12(11):1806–1815. https://doi.org/10.14202/vetworld.2019.1806-1815

Mohd Yusof H, Abdul Rahman NA, Mohamad R, Zaidan UH, Samsudin AA (2020) Biosynthesis of zinc oxide nanoparticles by cell-biomass and supernatant of Lactobacillus plantarum TA4 and its antibacterial and biocompatibility properties. Sci Rep 10(1):19996. https://doi.org/10.1038/s41598-020-76402-w

Mongillo JF (2007) Nanotechnology 101. Greenwood Press, Westport, CT, pp 4–13

Mondal H, Thomas J (2022) A review on the recent advances and application of vaccines against fish pathogens in aquaculture. Aquacult Int 30(4):1971–2000. https://doi.org/10.1007/s10499-022-00884-w

Monteiro SH, Andrade GM, Garcia F, Pilarski F (2018) Antibiotic residues and resistant bacteria in aquaculture. Pharmaceut Chem J 5:127–147

Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramirez JT, Yacaman MJ (2005) The bactericidal effect of silver nanoparticles. Nanotechnology 16:2346–2353. https://doi.org/10.1088/0957-4484/16/10/059

Musharraf M, Khan MA (2019) Requirement of fngerling Indian major carp, Labeo rohita (Hamilton) for dietary iron based on growth, whole body composition, haematological parameters, tissue iron concentration and serum antioxidant status. Aquaculture 504:148–157

Nagelkerken I, Connell SD (2015) Global alteration of ocean ecosystem functioning due to increasing human CO2 emissions. Proc Natl Acad Sci USA 112(43):13272–13277. https://doi.org/10.1073/pnas.151085611

Nasr-Eldahan S, Nabil-Adam A, Shreadah MA et al (2021) A review article on nanotechnology in aquaculture sustainability as a novel 69270. Environ Sci Pollut Res (2022) 29:69241–69274. https://doi.org/10.1007/s10499-021-00677-7

Ninawe AS, Hameed ASS, Selvin J (2016) Advancements in diagnosis and control measures of viral pathogens in aquaculture: an Indian perspective. Aquacult Int 25:251–264. https://doi.org/10.1007/s10499-016-0026-9

Noriega-Treviño ME, Quintero GC, Guajardo PJM, Morales SJE (2012) Desinfección y purificación de agua mediante nanopartículas metálicas y membranas compósitas. Tecnol CiencAgua III:87–100

Nriagu JO (1996) A history of global metal pollution. Science 272(5259):223–223. https://doi.org/10.1126/science.272.5259.223

Okoye CO, Okeke ES, Okoye KC, Echude D, Andong FA, Chukwudozie KI, Okoye HU, Ezeonyejiaku CD (2022) Occurrence and fate of pharmaceuticals, personal care products (PPCPs) and pesticides

in African water systems: a need for timely intervention. Heliyon 8(3):e09143. https://doi.org/10.1016/j.heliyon.2022.e09143
Ostaszewska T, Chojnacki M, Kamaszewski M, Sawosz-Chwalibóg E (2016) Histopathological effects of silver and copper nanoparticles on the epidermis, gills, and liver of Siberian sturgeon. Environ Sci Pollut Res 23:1621–1633. https://doi.org/10.1007/s11356-015-5391-9
Özgür ME, Ulu A, Balcıoğlu S, Özcan I, Köytepe S, Ateş B (2018) The toxicity assessment of iron oxide (Fe3O4) nanoparticles on physical and biochemical quality of rainbow trout spermatozoon. Toxics 6(4):62. https://doi.org/10.3390/toxics6040062
Parlapani FF, Boziaris IS, DeWitt CAM (2023) Pathogens and their sources in freshwater fish, sea finfish, shellfish, and algae. In: Present knowledge in food safety. Academic Press, pp 471–492. https://doi.org/10.1016/B978-0-12-819470-6.00056-1
Patel M, Kumar R, Kishor K et al (2019) Pharmaceuticals of emerging concern in aquatic systems: chemistry, occurrence, effects, and removal methods. Chem Rev 119:3510–3673. https://doi.org/10.1021/acs.chemrev.8b00299
Pelgrift RY, Friedman AJ (2013) Nanotechnology as a therapeutic tool to combat microbial resistance. Adv Drug Deliv Rev 65(13):1803–1815. https://doi.org/10.1016/j.addr.2013.07.011
Phillips MJ, Allison EH (2016) Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61:126–131. https://doi.org/10.1016/j.foodpol.2016.02.005
Plant KP, LaPatra SE (2011) Advances in fish vaccine delivery. Dev Comp Immunol 35(12):1256–1262
Plaza-Diaz J, Ruiz-Ojeda FJ, Gil-Campos M, Gil A (2019a) Mechanisms of action of probiotics. Adv Nutition 10(suppl_1):S49–S66. https://doi.org/10.1016/j.dci.2011.03.007
Plaza-Diaz J, Ruiz-Ojeda FJ, Gil-Campos M, Gil A (2019b) Mechanisms of action of probiotics. Adv Nutition 10(suppl_1):S49–S66. https://doi.org/10.1093/advances/nmy063
Pradeep T (2009) Noble metal nanoparticles for water purification: a critical review. Thin Solid Films 517(24):6441–6478. https://doi.org/10.1016/j.tsf.2009.03.195
Rahman MT, Nielsen R, Khan MA (2021) Pond aquaculture performance over time: a perspective of small-scale extensive pond farming in Bangladesh. Aquac Econ Manag 48:47–52. https://doi.org/10.1080/13657305.2021.1979122
Rahman MT, Sobur MA, Islam MS, Ievy S, Hossain MJ, El Zowalaty ME, ..., Ashour HM (2020) Zoonotic diseases: etiology, impact, and control. Microorganisms 8(9):1405. https://doi.org/10.3390/microorganisms8091405
Rajesh Kumar S, Ishaq Ahmed VP, Parameswaran V, Sudhakaran R, Sarath Babu V, Sahul Hameed AS (2008) Potential use of chitosan nanoparticles for oral delivery of DNA vaccine in Asian sea bass (Lates calcarifer) to protect from Vibrio (Listonella) anguillarum. Fish Shellfish Immunol 25:47–56. https://doi.org/10.1016/j.fsi.2007.12.004
Rajkumar KS, Kanipandian N, Thirumurugan R (2016) Toxicity assessment onhaemotology, biochemical and histopathological alterations of silver nanoparticles-exposed freshwater fish Labeo rohita. Appl Nanosci 6:19–29. https://doi.org/10.1007/s13204-015-0417-7
Ramani BM (2023) The problem of malnutrition and hunger in India. Vidhyayana-An Int Multidiscip Peer-Reviewed E-J-ISSN 2454-8596 8(si6):652–660
Rathi Sre PR, Reka M, Poovazhagi R, Arul Kumar M, Murugesan K (2015) Antibacterial and cytotoxic effect of biologically synthesized silver nanoparticles using aqueous root extract of Erythrina indica lam. Spectrochim Acta Mol Biomol Spectrosc 135:1137–1144. https://doi.org/10.1016/j.saa.2014.08.019
Rathore SS, Murthy HS, Mamun MAA, Nasren S, Rakesh K, Kumar BTN, ..., Khandagale AS (2021) Nano-selenium supplementation to ameliorate nutrition physiology, immune response, antioxidant system and disease resistance against Aeromonas hydrophila in monosex Nile tilapia (Oreochromis niloticus). Biol Trace Elem Res 199:3073–3088. https://doi.org/10.1007/s12011-020-02416-0
Remya AS, Ramesh M, Saravanan M, Poopal RK, Bharathi S, Nataraj D (2015) Iron oxide nanoparticles to an Indian major carp, Labeo rohita: impacts on hematology, iono regulation and gill Na+/K+ ATPase activity. J King Saud Univ-Sci 27(2):151–160. https://doi.org/10.1016/j.jksus.2014.11.002
Richardson SD, Kimura SY (2019) Water analysis: emerging contaminants and current issues. Anal Chem 92:473–505
Rico A, Van den Brink PJ (2014) Probabilistic risk assessment of veterinary medicines applied to four major aquaculture species produced in Asia. Sci Total Environ 468:630–641. https://doi.org/10.1016/j.scitotenv.2013.08.063
Ritchie H, Roser M (2017) Meat and seafood production & consumption. Our World in Data

Rivas-Aravena A, Fuentes Y, Cartagena J, Brito T, Poggio V, La Torre J et al (2015) Development of a nanoparticle-based oral vaccine for Atlantic salmon against ISAV using an alphavirus replicon as adjuvant. Fish Shellfish Immunol 45:157–166. https://doi.org/10.1016/j.fsi.2015.03.033

Rivera-Ferre MG, L opez-i-Gelats F, Howden M, Smith P, Morton JF, Herrero M (2016) Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. Wiley Interdiscip Rev Clim Change 7:869–892

Romero J, Feijoó CG, Navarrete P (2012) Antibiotics in aquaculture–use, abuse and alternatives. Health Environ Aquac 159(1):159–198

Rymuszka A, Siwicki AK (2004) Impact of selected groups of pesticides as stressors of fish immune systems – current challenges in fish disease prevention and treatment(Eds) A.K. Siwicki, J. Antychowicz, W. Szweda,Wyd. IRS, Olsztyn: 237–245

Saffari S, Keyvanshokooh S, Zakeri M, Johari SA, Pasha-Zanoosi H (2017) Effects of different dietary selenium sources (sodium selenite, selenomethionine and nano selenium) on growth performance, muscle composition, blood enzymes and antioxidant status of common carp (*Cyprinus carpio*). Aquac Nutr 23:611–617. https://doi.org/10.1111/anu.12428

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

Saima S, Fiaz M, Zafar R, Ahmed I, Arshad M (2020) Dissemination of antibiotic resistance in the environment. In: Antibiotics and antimicrobial resistance genes in the environment. Elsevier, pp 99–116.https://doi.org/10.1016/B978-0-12-818882-8.00006-1

Salah I, Parkin IP, Allan E (2021) Copper as an antimicrobial agent: recent advances. RSC Adv 11(30):18179–18186. https://doi.org/10.1039/d1ra02149d

Saleh M, Kumar G, Abdel-Baki AA, Al-Quraishy S, El-Matbouli M (2016) In vitro antimicrosporidial activity of gold nanoparticles against *Heterosporis saurida*. BMC Vet Res 12:1–6. https://doi.org/10.1186/s12917-016-0668-x

Salma U, Shafiujjaman M, Al Zahid M, Faruque MH, Habibullah-Al-Mamun M, Hossain A (2022) Widespread use of antibiotics, pesticides, and other aqua-chemicals in finfish aquaculture in Rajshahi District of Bangladesh. Sustainability 14(24):17038. https://doi.org/10.3390/su142417038

Salze GP, Davis DA (2015) Taurine: a critical nutrient for future fish feeds. Aquaculture 370(437):215–229. https://doi.org/10.1016/j.aquaculture.2014.12.006

Sankar R, Maheswari R, Karthik S, Shivashangari KS, Ravikumar V (2014) Anticancer activity of Ficus religiosa engineered copper oxide nanoparticles. Mater Sci Eng: C 44:234–239. https://doi.org/10.1016/j.msec.2014.08.030

Santos L, Ramos F (2018) Antimicrobial resistance in aquaculture: current knowledge and alternatives to tackle the problem. Int J Antimicrob Agents 52:135–143. https://doi.org/10.1016/j.msec.2014.08.030

Sarkar B, Bhattacharjee S, Daware A, Tribedi P, Krishnani KK, Minhas PS (2015a) Selenium nanoparticles for stress-resilient fish and livestock. Nanoscale Res Lett 10:1–14. https://doi.org/10.1186/s11671-015-1073-2

Sarkar B, Kumar M, Verma S, Rathore RM (2015b) Effect of dietary nanosilver on gut proteases and general performance in zebrafish (Danio rerio). Int J Aquat Biol 3:60–67

Schar D, Klein EY, Laxminarayan R et al (2020) Global trends in antimicrobial use in aquaculture. Sci Rep 10:1–9. https://doi.org/10.1038/s41598-020-78849-3

Sellegounder D, Kannan M, Deepa S, Senthilkumaran B, Basavaraju Y (2016) Effect of copper nanoparticles exposure in the physiology of the common carp (Cyprinus carpio): biochemical, histological and proteomic approaches. Aquac Fish 1:15–23. https://doi.org/10.1016/j.aaf.2016.09.003

Seyedi J, Kalbassi MR, Esmaeilbeigi M, Tayemeh MB, Moghadam JA (2021) Toxicity and deleterious impacts of selenium nanoparticles at supranutritional and imbalance levels on male goldfish (Carassius auratus) sperm. J Trace Elem Med Biol 66:126758. https://doi.org/10.1016/j.jtemb.2021.126758

Shah BR, Mraz J (2020a) Advances in nanotechnology for sustainable aquaculture and fisheries. Rev Aquacult 12:925–942. https://doi.org/10.1111/raq.12356

Shah BR, Mraz J (2020b) Advances in nanotechnology for sustainable aquaculture and fisheries. Rev Aquac 12(2):925–942

Shukry M, Albogami S, Gewaily M, Amer AA, Soliman AA, Alsaiad SM, El-Shehawi AM, Dawood MA (2022) Growth performance, antioxidative capacity, and intestinal histomorphology of grey mullet (Liza ramada)–fed dietary zinc nanoparticles. Biol Trace Elem Res 5:2406–2415. https://doi.org/10.1007/s12011-021-02844-6

Siddiqi KS, Husen A, Rao RA (2018) A review on biosynthesis of silver nanoparticles and their biocidal properties. J Nanobiotechnology 16:1–28. https://doi.org/10.1186/s12951-018-0334-5

Silva LP, Silveira AP, Bonatto CC, Reis IG, Milreu PV (2017) Silver nanoparticles as antimicrobial agents: Past, present, and future. In: Nanostructures for antimicrobial therapy. Elsevier, pp 577–596.https://doi.org/10.1016/B978-0-323-46152-8.00026-3

Sim W, Barnard RT, Blaskovich MAT, Ziora ZM (2018) Antimicrobial silver in medicinal and consumer applications: a patent review of the past decade (2007–2017). Antibiotics 7:93. https://doi.org/10.3390/antibiotics7040093

Singh A, Gautam PK, Verma A, Singh V, Shivapriya PM, Shivalkar S, Sahoo AK, Samanta SK (2020) Green synthesis of metallic nanoparticles as effective alternatives to treat antibiotics resistant bacterial infections: a review. Biotechnol Rep 25:e00427. https://doi.org/10.1016/j.btre.2020.e00427

Skalny AV, Aschner M, Jiang Y, Gluhcheva YG, Tizabi Y, Lobinski R, Tinkov AA (2021) Molecular mechanisms of aluminum neurotoxicity: update on adverse effects and therapeutic strategies. In Adv Neurotoxicol 5:1–34. https://doi.org/10.1016/bs.ant.2020.12.001. (Academic Press)

Sodhi KK, Kumar M, Balan B et al (2021) Perspectives on the antibiotic contamination, resistance, metabolomics, and systemic remediation. SN Appl Sci 3:1–13. https://doi.org/10.1007/s42452-020-04003-3

Son R, Rusul G, Sahilah AM, Zainuri A, Raha AR, Salmah I (1997) Antibiotic resistance and plasmid profile of Aeromonas hydrophila isolates from cultured fish, Telapia (Telapia mossambica). Lett Appl Microbiol 24(6):479–482. https://doi.org/10.1046/j.1472-765X.1997.00156.x

Sørum H (2008) Antibiotic resistance associated with veterinary drug use in fish farms. In: Improving farmed fish quality and safety. Woodhead Publishing, pp 157–182. https://doi.org/10.1533/9781845694920.1.157

Srikanth K, Pereira E, Duarte AC, Rao JV (2016) Evaluation of cytotoxicity, morphological alterations and oxidative stress in Chinook salmon cells exposed to copper oxide nanoparticles. Protoplasma 253:873–884. https://doi.org/10.1007/s00709-015-0849-7

Summer M, Ali S, Tahir HM, Abaidullah R, Fiaz U, Mumtaz S et al (2024) Mode of action of biogenic silver, zinc, copper, titanium and cobalt nanoparticles against antibiotics resistant pathogens. J Inorg Organomet Polym Mater:1–35.https://doi.org/10.1007/s10904-023-02935-y

Sun R, Chen J, Pan C et al (2020) Antibiotics and food safety in aquaculture. J Agric Food Chem 68:11908–11919. https://doi.org/10.1021/acs.jafc.0c03996

Swain P, Nayak SK, Sasmal A, Behera T, Barik SK, Swain SK et al (2014) Antimicrobial activity of metal based nanoparticles against microbes associated with diseases in aquaculture. World J Microbiol Biotechnol 30(9):2491–2502. https://doi.org/10.1007/s11274-014-1674-4

Swain P, Das R, Das A, Padhi SK, Das KC, Mishra SS (2019) 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. https://doi.org/10.1111/anu.12874

Sysoenko MV, Kerimova EE (2019) Aquaculture in Russia: state and problems of development. Eur Scien Assoc 5–3(51):155–157. https://doi.org/10.1088/1755-1315/548/7/072003

Tallis H, Lubchenco J (2014) Working together: a call for inclusive conservation. Nature 515(7525):27–28

Tang S, Zheng J (2018) Antibacterial activity of silver nanoparticles: structural effects. Adv Healthc Mater 7:e1701503

Thangapandiyan S, Monika S (2020) Green synthesized zinc oxide nanoparticles as feed additives to improve growth, biochemical, and hematological parameters in freshwater fish Labeo rohita. Biol Trace Elem Res 195:636–647. https://doi.org/10.1007/s12011-019-01873-6

Thilsted SH, Thorne-Lyman A, Webb P, Bogard JR, Subasinghe R, Phillips MJ, Allison EH (2016) Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61:126–131

Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515(7528):518–522. https://doi.org/10.1038/nature13959

Tusevljak N, Dutil L, Rajić A, Uhland FC, McClure C, St-Hilaire S et al (2013) Antimicrobial use and resistance in aquaculture: findings of a globally administered survey of aquaculture-allied professionals. Zoonoses Public Health 60(6):426–436. https://doi.org/10.1111/zph.12017

United Nations (2022) World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. Available online: https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100 (accessed on 1 September 2022)

United Nations Food and Agriculture Organization (FAO) (2013) The state of food insecurity in the world 2013.http://www.fao.org/publications/2013/sofi/en. Accessed onNovember 30, 2013

Vadlapudi V, Amanchy R (2017) Phytofabrication of silver nanoparticles using myriostachya wightiana as a novel bioresource, and evaluation of their biological activities. Braz Arch Biol Technol 60:113. https://doi.org/10.1590/1678-4324-2017160329

Valenti WC, Kimpara JM, Preto BL, Moraes-Valenti P (2018) Indicators of sustainability to assess aquaculture systems. EcologicalIndicators 88:402–413. https://doi.org/10.1016/j.ecolind.2017.12.068

Vali S, Majidiyan N, Yalsuyi AM, Vajargah MF, Prokić MD, Faggio C (2022) Ecotoxicological effects of silver nanoparticles (Ag-NPs) on parturition time, survival rate, reproductive success and blood parameters of adult common molly (Poecilia sphenops) and their larvae. Water 14(2):144. https://doi.org/10.3390/w14020144

Vanni MJ, Craig DL (1997) Nutrient recycling and herbivory as mechanisms in the -top–down|| effect of fish on algae in lakes. Ecology 78(1):21–40. https://doi.org/10.1890/0012-9658(1997)078[0021:NRAHAM]2.0.CO;2

Venkatesan J, Kim SK, Shim MS (2016) Antimicrobial, antioxidant, and anticancer activities of biosynthesized silver nanoparticles using marine algae Ecklonia cava. Nanomaterials 6(12):235. https://doi.org/10.3390/nano6120235

Vidya PV, Chitra KC (2019) Irreversible histopathological modifications induced by iron oxide nanoparticles in the fish, Oreochromis mossambicus (Peters, 1852). In Biol Forum–An Int J 11(1):01–06

Vimal S, Taju G, Nambi KSN, Abdul Majeed S, Sarath Babu V, Ravi M et al (2012) Synthesis and characterization of CS/TPP nanoparticles for oral delivery of gene in fish. Aquaculture 358–359:14–22. https://doi.org/10.1016/j.aquaculture.2012.06.012

Vincent M, Hartemann P, Engels-Deutsch M (2016) Antimicrobial applications of copper. Int J Hyg Environ Health 219(7):585–591. https://doi.org/10.1016/j.ijheh.2016.06.003

Waite R, Beveridge M, Brummett R, Castine S, Chaiyawannakarn N, Kaushik S et al (2014) Improving productivity and environmental performance of aquaculture. WorldFish. http://www.worldresourcesreport.org. Accessed 12-05-2023

Wang T, Long X, Liu Z, Cheng Y, Yan S (2015) Effect of copper nanoparticles and copper sulphate on oxidation stress, cell apoptosis and immune responses in the intestines of juvenile Epinephelus coioides. Fish Shellfish Immunol 44(2):674–682. https://doi.org/10.1016/j.fsi.2015.03.030

Wang T, Wen X, Hu Y, Zhang X, Wang D, Yin S (2019) Copper nanoparticles induced oxidation stress, cell apoptosis and immune response in the liver of juvenile Takifugu fasciatus. Fish Shellfish Immunol 84:648–655. https://doi.org/10.1016/j.fsi.2018.10.053

Wang Y, Han J, Li W, Xu Z (2007) Effect of different selenium source on growth performances, glutathione peroxidase activities, muscle composition and selenium concentration of allogynogenetic crucian carp (Carassius auratus gibelio). Anim Feed Sci Tech 134:243–251. https://doi.org/10.1016/j.anifeedsci.2006.12.007

Willson MF, Halupka KC (1995) Anadromous fish as keystone species in vertebrate communities. Conserv Biol 9:489–497

Woody CA, O'Neal S (2012) Effects of copper on fish and aquatic resources. http://www.asgdc.state.ak.us/

Wu Y, Zhou Q, Li H, Liu W, Wang T, Jiang G (2010) Effects of silver nanoparticles on the development and histopathology biomarkers of Japanese medaka (Oryzias latipes) using the partial-life test. Aquat Toxicol 100(2):160–167. https://doi.org/10.1016/j.aquatox.2009.11.014

Yaqoob AA, Umar K, Ibrahim MNM (2020) Silver nanoparticles: various methods of synthesis, size affecting factors and their potential applications—a review. Appl Nanosci 10:1369–1378. https://doi.org/10.1007/s13204-020-01318-w

Yin IX, Zhang J, Zhao IS, Mei ML, Li Q, Chu CH (2020) The antibacterial mechanism of silver nanoparticles and its application in dentistry. Int J Nanomed 15:2555–2562

Youn S-J, Taylor WW, Lynch AJ, Cowx IG, Beard TD Jr, Bartley D et al (2014) Inland capture fishery contributions to global food security and threats to their future. Glob Food Sec 3(3–4):142–148. https://doi.org/10.1016/j.gfs.2014.09.005

Yu HR, Li LY, Shan LL, Gao J, Ma CY, Li X (2021) Effect of supplemental dietary zinc on the growth, body composition and anti-oxidant enzymes of coho salmon (Oncorhynchus kisutch) alevins. Aquac Rep 20:100744. https://doi.org/10.1016/j.aqrep.2021.100744

Zahid M, Rashid A, Akram S, Rehan ZA, Razzaq W (2018) A comprehensive review on polymeric nano-composite membranes for water treatment. J Membr Sci Technol 8:1–20. https://doi.org/10.4172/2155-9589.1000179

Zaman SB, Hussain MA, Nye R et al (2017) A review on antibiotic resistance: alarm bells are ringing. Cureus. https://doi.org/10.7759/cureus.1403

Zhang XF, Liu ZG, Shen W, Gurunathan S (2016) Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches. Int J Mol Sci 17:1534. https://doi.org/10.3390/ijms17091534

Zhao L, Sun J, Yang Y, Ma X, Wang Y, Xiang Y (2016) Fish consumption and all-cause mortality: a meta-analysis of cohort studies. Eur JClin Nutr 70(2):155–161. https://doi.org/10.1038/ejcn.2015.72

Zhou X, Wang Y, Gu Q, Li W (2009) Effects of different dietary selenium sources (selenium nanoparticle and selenomethionine) on growth performance, muscle composition and glutathione peroxidase enzyme activity of crucian carp (*Carassius auratus gibelio*). Aquac 291:78–88. https://doi.org/10.1016/j.aquaculture.2009.03.007

Zhu P, Burney J, Chang J, Jin Z, Mueller ND, Xin Q, Ciais P (2022) Warming reduces global agricultural production by decreasing cropping frequency and yields. Nat Clim Chang 12(11):1016–1023. https://doi.org/10.1038/s41558-022-01492-5

Zitoun R (2019) Copper speciation in different marine ecosystems around New Zealand (Doctoral dissertation, University of Otago). http://hdl.handle.net/10523/9214. Accessed 18 Sept 2023

Zodrow K, Brunet L, Mahendra S, Li D, Zhang A, Li Q, Alvarez PJ (2009) Polysulfone ultrafiltration membranes impregnated with silver nanoparticles show improved biofouling resistance and virus removal. Water Res 43(3):715–723. https://doi.org/10.1016/j.watres.2008.11.014