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REVIEWS IN Aquaculture

REVIEW

Inorganic nanoparticles for use in aquaculture

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Abstract

Nanotechnology is a rising technology dealing with nanoparticle-based (1–100 nm) organic and inorganic materials. Such technology has a vital role in various industrial sectors, including pharmaceuticals, nuclear energy, fuel and energy, electronics, and bioengineering, while having potential applications to human, animal, plant, and environmental health. Even though nanomaterial applications can cover multi-areas of biological and natural fields, limited information are available in the aquaculture sector. Nowadays, the aquaculture sector is the most imperative field to meet animal protein requirements for human nutrition, and aquaculture disease outbreaks as well as the aquatic environment pollutants are significant hindrances in producing healthy aquatic products. The current review aims to enlighten the direction of nanotechnology in the aquaculture industry while providing more specific information about inorganic forms of nanoparticles used to develop several types of applications such as antimicrobial, antibiofilm and photocatalytic agents, as well as aquatic animal nutrition in the domain of aquaculture. A large number of inorganic nanoparticles and their use as animal feed and for water treatment are extensively described. Their potential risks in aquaculture are also presented and discussed. The aquaculture nanotechnology applications are expected to contribute to fish health improvement, harmful microbes control, and aquatic products nano-delivery in the forthcoming years.

KEYWORDS

antibiofilm, antimicrobial, aquatic animal nutrition, nanotechnology applications, photocatalytic

1 | INTRODUCTION

Nanotechnology has materialized as favourable key access to innovative prospects. It is the discipline of advancing and controlling elements at nanoscale dimensions (1–100 nm) through distinct resources surface.[1,2] Nowadays, nanotechnology helps to improve and develop several technologies and industry sectors such as information technology, energy, environmental science, medicine, homeland security, food safety and transportation.[3]

In aquaculture, nanotechnology progress has a major role in micronutrient delivery, feed production, and growth support of aquatic animals.[4] Recently, nanotechnology has received great awareness in agriculture-related fields, particularly in the discipline of aquaculture and fishery sector. According to the literature, nanotechnology has proven beneficial for the preparation of nutrient supplements, gene delivery, therapeutic factors, water treatment, and preservation among others.[5] The application of nanotechnology advances supports disease detection and prevention against pathogens, as well as improving the quality of aquaculture. Therefore, it is expected to enhance fish health, effectively control harmful microbes in water, and nano-deliver aquatic products.[6] Moreover, its development is useful for fish packaging techniques, while it is additionally applied to improve the flavour, odour, texture, and taste quality as well as to enhance the nutrients intake in fish.[7] The advances in nanotechnology are also advocated for improving bioavailability (functional factors), microencapsulating antimicrobials in packaging, reducing the decomposition process, and increasing the stability and shelf-life of fine ingredients. In addition, nanoparticles (NPs) are characterized by bacteriostatic properties, able to form microbial-resistant surfaces. For instance, silver (Ag) NPs have been utilized to suppress the growth of pathogens and increase the shelf life of meat products in various sectors of agri-food industries.[5,8] Furthermore, nanotechnology is one of the most effective and efficient tools to deal with water pollution in aquaculture, and such a technology is a less toxic, cost-effective, eco-friendly method for the water purification process. For example, the green synthesis method to develop magnetic konjac glucomannan aerogels is used to eliminate arsenic contamination from groundwater.[9] However, the most important function of NPs involved in drug delivery and feed additives is their ability as biological substances to pass through the cell membrane in the biological process.

NPs are primarily attached to target a specific antigen of pathogen and suppress the replication process at the cellular level. This function has led to different kinds of responses through the cell and reduced the mortality rate of fish. Also, several NPs types are capable of entering the antigen-presenting cell through different pathways and stimulating immune responses to the antigen,[10,11] while various types of nanomaterials are utilized for a fish vaccine, such as carbon nanotubes, biodegradable polymers, nanoliposomes and immune-stimulating complexes.[12]

Dietary administration is the most recognized method in fish farming techniques. In fact, various kinds of supplements have been demonstrated able to improve the fish immune system or control the severity of diseases.[13,14] All trace elements have a specific role in the immune system of culture animals. However, some essential minerals like zinc (Zn), manganese (Mn), copper (Cu) and selenium (Se) are associated with and improve or regulate the immune system, which helps to detoxify foreign factors.[15] Dietary supplements of different nanomaterials like Se, Zn and Mn are usually utilized for stress resistance improvement and bone mineralization of gilthead sea bream (*Sparus aurata*).[16]

However, the increasing applications of NPs in various sectors lead to new challenges concerning their fate in the environment and impact on living organisms.[17] Moreover, NPs caused more toxic effects on living microorganisms compared with their bulk forms.[18]

This review provides information on inorganic forms of different NPs used to develop different kinds of applications such as antimicrobial and photocatalytic activities, anti-biofouling, water treatment, and aquatic animal nutrition in the specialization of aquaculture while discussing the benefits and potential risks of their use.

2 | NANOPARTICLES AND THEIR FUNDAMENTAL ASPECTS

2.1 | Definitions and principles

Nanomaterials are defined based on their size characteristics, between 1 and 100 nm, and are composed of carbon, metal, metal oxides or organic matter.[19] The definition given by the European Commission states that '50% or more of the particles of a material in the number size distribution have one or more external dimensions in the size range between 1 and 100 nm'.[20] NPs have all three external dimensions in the nanoscale (between 1 and 100 nm) and possess unique physical, chemical, and biological properties that are not found in their bulk samples.[21] These particular properties are related to a high surface area to volume ratio and/or quantum effects.[22] Focusing on inorganic NPs, such nanomaterials have no carbon in their structure (metal and metal oxide NPs) and are highly stable compared with the organic ones. Metal-based NPs are synthesized from metals to nanometric sizes either by destructive or constructive methods. The commonly used metals are aluminium (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag) and zinc (Zn). The metal oxide-based NPs are produced by modifying the properties of their metal-based NPs in order to increase their reactivity. Aluminium oxide (Al_2O_3), Iron oxides (Fe_2O_3 & Fe_3O_4), Silicon dioxide (SiO_2), Titanium dioxide (TiO_2), Cerium dioxide (CeO_2) and Zinc oxide (ZnO) are common metal oxide NPs.[19,23]

2.2 | Synthesis and production

NPs are synthesized according to two strategies. The top-down methods produce NPs from bulk materials by using distribution techniques such as crushing, mechanical milling, chemical etching, e-beam evaporation, etc. The bottom-up approach requires molecular/ionic species as starting materials, which involve chemical reactions, nucleation, or biological synthesis via bacteria and fungi and the growth process to promote the formation of more complex clusters.[19,23] Sol–gel, spinning, chemical vapour deposition (CVD), pyrolysis and biosynthesis are the most commonly used bottom-up methods for NPs production.[19,24] Table 1 lists some inorganic NPs synthesis methods.

2.3 | Analyses and characterization

NPs possess unique physical and chemical properties explained by a relatively larger surface area in relation to the volume, increased reactivity or enhanced mechanical strength,[19] while they are generally characterized by their size, charges, and morphology. Several techniques such as electron and optical microscopy, light scattering, mass spectrometry, and bio-imaging have been used to characterize NPs.[26] In Table 2, the quantitative and qualitative parameters of NPs are summarized, accompanied by the respective analytical tools.

3 | APPLICATIONS OF INORGANIC NPS IN AQUACULTURE

Nanotechnology is a broad and multidisciplinary research sector that has been rising explosively over the globe in recent years. In the fisheries and aquaculture industry, these techniques promote the

TABLE 1 Methods of synthesis of inorganic nanoparticles

Approach	Classification	Synthesis method	References
Bottoms-up	Chemical	Chemical vapour deposition Sol–gel Hot solution decomposition Pyrolysis	[19,24,25]
	Physical	Spinning Physical vapour condensation	
	Biological	Biosynthesis (Bacteria/algae/fungi/plant extracts)	
Top-down	Physical	Mechanical milling Thermal decomposition Nanolithography Laser ablation	[19,23–25]

TABLE 2 Principal NPs properties and characterization methods

Characteristics	Methods	References
Size	Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM)	[25]
Shape	TEM, AFM, 3D-Electron Tomography, Field Emission Gun Transmission Electron Microscope (FEG-TEM), Field Emission Scanning Electron Microscopy (FE-SEM)	[25–29]
Surface area	Breuneur–Emmet–Teller surface analysis (BET), liquid Nuclear Magnetic Resonance (NMR), Differential Mobility Analyser (DMA), Scanning mobility particle sizer (SMPS)	[19,26]
Surface charge	Zeta potential measuring technique, DMA	[19]
Size distribution	Dynamic Light Scattering (DLS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	[26,28,29]
Concentration	Condensation Particle Counter (CPC)	[19]
Crystallography	X-Ray powder diffraction (XRD), Neutron diffraction, Selected area electron diffraction (SAED), Energy-dispersive detector (EDS)	[19,27]
Optical properties	Ultraviolet (UV–vis), Fourier transform infrared (FTIR), Infrared (IR) Spectroscopy, Scanning Transmission Electron Microscope-Electron Energy Loss Spectroscopy (STEM-EELS), Energy-dispersive X-ray spectroscopy (EDAX)	[26]
Structural defects	High-Resolution Transmission Electron Microscopy (HRTEM), Electron backscatter diffraction (EBSD)	[26]

enhancement of the cultivable species quality and the rapid confrontation of diseases, nutrients intake, drugs, hormones, and vaccines.[30] Inorganic NPs such as Ag-NPs, ZnO-NPs, Fe-NPs, FeO-NPs, Se-NPs and Al-NPs play the most important role in aquaculture and are involved in various direct and indirect applications, as summarized in Figure 1.

3.1 | Feed supplements and nutraceuticals

Among the direct applications, the dietary administration of NPs as feed supplements is helpful in terms of survival improvement, antioxidant status, growth performance, and immune response in aquatic organisms. However, the excess level of NPs diet supplements may also be toxic to aquatic species.[31,32] Controlling fish infection disease caused by microbial pathogens is another application of the NPs, which act as antibacterial, diagnosis tools, and vaccine delivery agents in aquaculture.[33] Figure 2 illustrates the main categories of inorganic NPs functionalities for improving nutritional and disease control aspects in aquaculture.

3.1.1 | Nutritional aspects

Inorganic NPs supplementation impacts nutritional values of aquatic feed that have been proved helpful in improving the growth performance, immunity, survival, and infection resistance in fish species like Red Sea bream (*Pagrus major*) and juvenile grass carp (*Ctenopharyngodon idella*).[34,35]

NPs processing is beneficial for solubilizing vitamins and carotenoids and enhancing the bioavailability of dietary supplements in aquaculture.[36,37] In fact, micronutrients incorporated in aquaculture feeds at a nanoscale size can penetrate cells more efficiently, and enhance consequently their assimilation process into the fish.[18] Some NPs with nutritional functions are consecutively presented in the following subsections.

Zn-NPs

Zn is an essential element implied in many metabolic pathways, protein synthesis, and energy consumption of fish.[18] Dietary supplementation of Zn is known to be helpful, regarding the increase of body weight, growth rate, antioxidant status, antibacterial activity, and immune system of different fish species such as coho salmon (*Oncorhynchus kisutch*), African catfish (*Clarias gariepinus*) and Mrigal (*Cirrhinus mrigala*).[38–40] However, the effect is dose-dependent so that high supplementation in Zn may be harmful in fish, requiring optimal dose determination.[41–44]

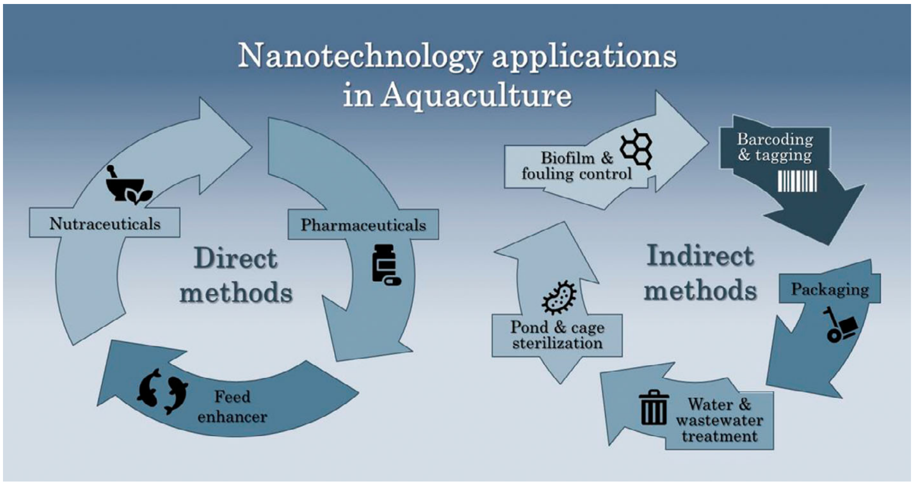

FIGURE 1 Direct and indirect applications of nanotechnology in aquaculture.

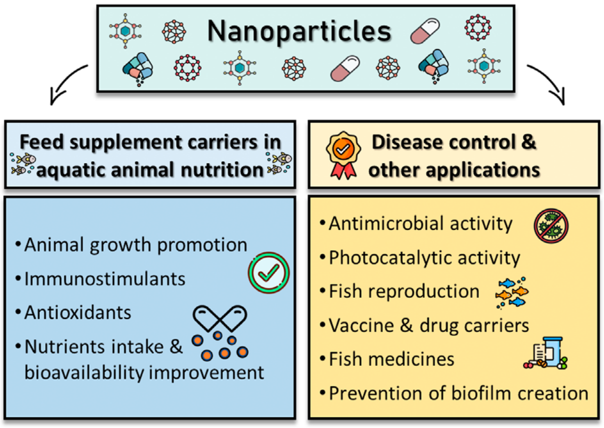

FIGURE 2 Direct applications of NPs in aquaculture.

The dietary administration of Zn in nanoform has been shown to induce positive effects on growth performance. For instance, ZnO-NPs feed supplementation was helpful for the improvement of growth, survival, and body composition of larval rainbow trout (*Oncorhynchus mykiss*) at 50 mg/kg for 70 days.[45] The same supplementation at a concentration of 20 mg/kg diet benefitted the growth, feeding efficiency, metabolic enzymes, serum profile and non-specific immune functions in rohu (*L. rohita*) fingerlings.[46] However, supplementing 10–15 mg/kg ZnO-NPs in common carp (*Cyprinus carpio*) feeding caused cytotoxicity and some alteration of oxidative biomarkers, whereas 5 mg/kg diet incorporation exhibited no negative response and was proved suitable for fish health improvement.[47] Using 30 mg/kg for a 90-day trial period, ZnO-NPs exhibited positive effects on growth performance, immune response, and haematological parameters of grass carp (*Ctepharyngodon idella*).[35] At the same concentration, ZnO-NPs enhanced the survival rate, total protein and antioxidant capacity, as well as the regulation in interleukins genes (IL 8, IL 1). By contrast, a higher dose of 60 mg/kg caused impairment in the immune and antioxidant systems and increased the inflammatory response.[48]

Fe-NPs

In aquatic animals, Fe plays an essential role in many physiological processes and takes part in redox reactions and electron transport associated with cellular respiration, growth rate, and fatty acid metabolism.[49] Fe deficiency was found to cause hypochromic microcytic anaemia in brook trout (*Salvelinus fontinalis*) and common carp (*Cyprinus carpio*).[50,51] It has been proved in aquatic feeding that dietary supplementations of Fe in nanoforms induced nutritional beneficial effects in aquatic species.[52–57] For example, enhanced growth performance and alkaline phosphatase activity were observed within goldfish (*C. auratus*), which received a Fe-NPs-containing diet (0.5 g/kg) for 60 days.[52] In addition, dietary Fe-NPs supplement (20 mg/kg) for a 90-day experimental trial showed an improvement in growth response, digestive enzyme function, food intake, better survival, and growth of *M. rosenbergii* post larvae. However, higher doses (30–50 mg/kg diet) provoked a negative response in freshwater prawns.[53] Another study revealed that a dose of 30 mg/100 g for 21 days was beneficial while a higher dose (50 mg/100 g) enhanced haematological and biochemical parameters for the Koi carp growth.[54] Moreover, *Anisomeles malabarica* leaf extracts Fe-NPs diet supplement proved beneficial, not only for the growth performance, but also for the enzymatic activity (protease, amylase and lipase) and the biochemical and haematological parameters of zebrafish, with the optimal dose being 40 mg/kg.[55] In Nile tilapia fish, the optimal dose was 63.75 mg/kg.[56] Similarly, dietary inclusion of Fe-NPs and ascorbic acid at 4 and 6 g/kg, respectively, in *C. gariepinus* improved its growth and survival and reduced mortality while contributing to the nutrients utilization, the biochemical parameters, the haematological profile, and the stress-reducing factor during hyperthermia stress.[57] Additionally, Fe-NPs feed supplementation at 40 mg/kg for a 60-day was helpful in order to achieve better growth and feed utilization in *Clarias batrachus*. Such a diet supplement is an inexpensive and environmentally friendly approach of high importance for catfish species.[58] The same amount of Fe-NPs (40 mg/kg) was also utilized in *Labeo rohita*, presenting enhanced growth, survival rate, immune system, bactericidal activity, and antioxidant activity, with no negative effects being observed for the 30-day experimental period.[59] Likewise, the dietary supplement of Fe-NPs (30 mg/kg) was used as the optimal nutritional level of juvenile channel catfish. However, even if Fe-NPs feed additives were essential for the physiological and haematological response of fish species, higher doses of Fe-NPs can affect negatively the growth and increase mortality and toxic phenomena like diarrhoea and histopathological damage to liver cells.[60–63]

Se-NPs

Se plays a vital role in the physiology of aquatic animals through protein biosynthesis, antioxidant activities, and immunity functions, enhancing growth, feed efficiency, fertility, and minimizing cell damage.[64]

Se-NPs have been proven as beneficial diet supplements for many fish species in enhancing the animal final weight and relative gain rate, antioxidant status as for glutathione peroxidase (GSH-Px) activities and muscle mass.[65] Se nanoforms are also suggested as an efficient source in aquafeed, due to their high bioavailability.[65] However, their effects are dose- and delivery form-dependent because excessive doses of Se-NPs may cause toxic effects on aquatic animals.[66]

Specifically, Se-NPs diet supplements had significant effects on the growth and biochemical parameters of yellow-tail seabream at 0.5 mg/kg for a duration of 8 weeks,[67] Nile tilapia at 0.7 mg/kg diet for a period of 10 weeks,[68] and African catfish (*Clarias gariepinus*) at the concentration 0.3 mg/kg diet for 12 weeks.[69] Further studies showed that Se-NPs supplementation (1–2 mg/kg diet) for 45 days improved the immune response, total protein content, and antioxidant activities in red sea bream (*Pagrus major*),[70] while the optimal dose applied in Nile tilapia fingerlings with beneficial effects on physiological parameters, immune response, and antioxidant activity was determined at 1 mg/kg diet for 90 days.[71] Similarly, Se-NPs dietary incorporation for 90 days in striped catfish improved growth behaviour, antioxidative capacity and liver wellbeing at 1.02–1.11 mg/kg diet without negative effects or accumulated Se levels within the liver, intestine, and gills.[72]

Furthermore, dietary supplementation of Se-NPs encapsulated form (diphenyl diselenide-loaded nanocapsules) improved the growth and antioxidant status of silver catfish (*Schilbe mystus*).[73] When combined with vitamin C (300 mg/kg), dietary Se-NPs supplementation (0.68 mg/kg) showed synergistic interactions that positively enhanced weight gain, specific growth rate and feed conversion efficiency in mahseer fish (*Tor putitora*).[74]

Mg-NPs

Magnesium (Mg) plays an important role in the activation of enzymes involved in the metabolism of lipids, proteins, and carbohydrates for the maintenance of intra- and extracellular homeostasis, transferring phosphate groups, and controlling ATP-dependent ion pumps. It has a key role in the immune mechanism while being a main component of bone in fish.[75] Beneficial effects of dietary MgO-NPs incorporation on growth performance, immunity, and general health were reported in *Macrobrachium rosenbergii* post larvae at the optimal concentration of 500 mg/kg during 90 days.[76] Furthermore, supplementing MgO-NPs at 0.02 mg/kg diet for 60 days in *Clarias gariepinus* showed improvement in fish blood lipid profile (triglycerides and cholesterol), kidney (Creatinine and Urea) and liver functions, antioxidant capacity, body weight, and body gain performance.[77]

Ag-NPs

Ag-NPs in adequate dose exerted beneficial effects on the immune system, growth performance and health status of aquatic animals.[78]

Ag-NPs supplementation in sodium caseinate encapsulated form for 30 days enhanced the growth, immune system, and disease resistance in *Macrobrachium rosenbergii*.[79] Administrating Ag-NPs at sub-lethal concentrations (13.6 and 21.6 μg/L) during a 6-day experimental period in zebrafish (*Danio rerio*) showed the increase of Oct4 antibody levels, while such antibody enlightened their key role in the growth stimulation of developing embryos. However, higher doses of Ag-NPs at 64 and 128 μg/L may be toxic to the fish metabolic system.[80]

Au-NPs

Au-NPs have been reported to improve the level of oxidative stress and hepatotoxic markers as well as to stimulate immune response in aquatic species. Oral administration of Au-NPs in shrimp (*Litopenaeus vannamei*) at an optimal concentration (2 μg/g) had beneficial effects on the immune system by up-regulating immune gene expression, while increasing survival rate and decreasing the resistance against *V. parahaemolyticus*.[81] Furthermore, Au-NPs coated with citrate or polyvinyl pyrrolidone exposed for 96 h at different concentrations of 4, 80 and 1600 μg/L induced different gene expressions like mRNA levels of antioxidant and inflammatory genes (*gst3*, *prdx6* and *il1β*), despite the repression of other antioxidant enzyme genes (*gr* and *cat*) in the gills of *Sparus aurata*.[82] Dietary additives of Au-NPs for 36 days showed up-regulation of *cox2* genes in the brain and skeletal muscles of zebrafish.[83] On the other hand, *Azolla microphylla* Au-NPs (2.5 mg/kg) showed protective effects on the liver against oxidative damage, tissue-damaging enzyme activities, and acetaminophen-induced hepatic damage in freshwater common carp fish.[84]

Cu-NPs

Cu microelement is involved in various biological, physiological, and metabolic functions of aquatic animals, and plays a vital role in growth performance. Cu is also a cofactor for several enzymes involved in the antioxidation capacity and metalloenzyme formation.[85] The dietary incorporation of Cu-NPs at different concentrations, with the basal diets at 20 mg/kg for 90 days in freshwater prawn *Macrobrachium rosenbergii* post larvae, enhanced the growth, survival and immune response, whereas higher doses of 40–80 mg/kg may lead to toxic effects.[86] Cu-NPs administrated at the optimal concentration of 8 mg/kg in a common carp diet for 8 weeks trial enhanced the growth, antioxidant activity, and immune response in Russian sturgeon *Acipenser gueldenstaedtii*.[87] Combined with vitamin C supplements (250–500 mg/kg diet), Cu-NPs (2 mg/kg diet) showed an enhancement of specific growth rate, weight gain, protein efficiency ratio, feed conversion ratio, lysozyme, alternative complement activity, catalase, glutathione peroxidase, haematocrit, and mean corpuscular within 15 days experimental trial.[88]

3.1.2 | Disease control aspects

Antimicrobial and antifungal activity

Inorganic NPs have exhibited antimicrobial activity against selective pathogenic bacteria (*E. coli*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Vibrio* spp.) and fungi (*Penicilium* and *Mucor* species).[36,37] Even though the NPs' advancement in aquaculture and farm animals is innovative, tests and experimental results are only available in laboratory-scale conditions.[89]

The possible action modes of metal-based NPs antimicrobial activities include alteration of membrane and cell structure by producing ROS and free radicals, which disrupt vital enzymes in the respiratory chain, inhibit microbial proteins/enzymes by increasing production of H_2O_2, and alter the metabolism process of microbes.[90]

Ag-NPs are among the most studied antimicrobial NPs in different aquatic species. Biogenic Ag-NPs appear as effective antibacterial agents against aquatic pathogens while being more stable, cost-effective, less toxic, and environmentally friendly compared with chemically synthetized NPs.[91–94] Among the panel of strains tested, Ag-NPs had bactericidal response against *Vibrio parahaemolyticus*, *V. harveyii*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*. Several green biogenic Ag-NPs have been reported to exhibit antimicrobial activity. As examples, red algae *Portieria hornemannii*-based synthetized Ag-NPs exhibited antibacterial activities against *Vibrio parahaemolyticus* and *Vibrio harveyii*, suggesting sufficient antibiotic properties against fish diseases.[95] *Azadirachta indica*-based synthesized NPs were used to enhance the immune system of mrigal (*Cirrhinus mrigala*) fingerlings and antibacterial challenges with *A. hydrophila* infections in aquatic animals.[96] The tea plants-based synthetized Ag-NPs (10 μg/ml) exhibited sufficient bactericidal activity against *Vibrio harveyi* infections in Indian white prawns (*Feneropenaeus indicus*) by in vitro methods.[97] *Litopenaeus vannamei* gut *Bacillus subtilis* Ag-NPs showed potential antibacterial activity against *Vibrio parahaemolyticus* and *Vibrio harveyi* on white-leg shrimp.[98] It was reported that Ag-NPs green synthesized by using plant extract of *Rumex hymenosepalus* had strong antibacterial activity against *V. parahaemolyticus*, increasing the survival rate of shrimp.[99] Additionally, Ag-NPs from Spirulina extract were efficient antibacterial agents against *V. parahemolyticus* at different concentrations, and also increased the survival rate of *Artemia nauplii*.[100]

Ag-NPs were used for their antifungal activity to treat white-spot disease *Ichthyophthirius multifiliis* and red-spot disease *Aphanomyces invadans* fungal infections in goldfish and other ornamental fish species.[101]

Similarly, ZnO-NPs exhibited potent antimicrobial effects against harmful bacteria (*Listeria monocytogenes*, *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Aeromonas hydrophila*) in water and fish tissues.[102] ZnO-NPs also inhibited the growth of *Aeromonas salmonicida*, *Yersinia ruckeri* and *Aphanomyces invadans* at concentrations of 15.75, 31.5 and 3.15 μg/ml, respectively. However, Ag-NPs were less cytotoxic compared with ZnO-NPs.[12]

Au-NPs were pointed out for their successful anti-parasite effects against *Heterosporis saurida* in lizard fish (*Saurida undosquamis*). Thus, they are considered as a new route to produce antimicrobial drugs in aquaculture.[103]

Nanodrug and vaccine delivery

Nanotechnology contributes significantly to pollutant-free cultured pond's prevalence, rapid identification of diseases, vaccines and delivery of drugs.[104] The use of NPs in drug-delivery is assigned to their particular properties such as controlled particle size, shape, surface charge, sustained release, regulation, target-specific, multi-route delivery pathways and degradation of nano-carriers.[105] Vaccination, a major concern in the last 20 years, plays an important role in aquaculture, since it is not only efficient but also cost-effective, while preventing only certain pathogenic diseases.[106,107] Nanovaccines are formulated with an antigen or a group of antigens containing appropriate NPs.[7] Most of the applied vaccines are kept and preserved in a liquid form at low temperatures. Regarding their applications, they are injected through blood networks due to their short life span, while especially the nano-vaccines exhibit the most imperative role in the aquaculture sector.[108] Organic NPs such as nano-chitosan and poly-(lactic-co-glycolic acid) (PLGA) are the most used NPs in fish vaccine delivery.[109] In literature, there is still a lack of studies reporting the use of inorganic metal-based NPs as vaccines.

Pathogen diagnosis

The diagnosis and treatment of bacterial diseases are crucial for the disease control of aquaculture species. Metal-based NPs have been used in pathogen detection, due to their unique optical and electrical properties, and can be detected by optic absorption fluorescence and electric conductivity.[110,111]

Au-NPs are important for the identification of fish pathogens in aquaculture.[112] For example, the polyclonal antibody-coated Au-NPs were effective in the recognition of *A. salmonicida* in fish tissues and were recognized as a promising approach regarding specific and rapid identification of *A. salmonicida* in fish tissues.[113]

3.2 | Remediation of contaminants

Biofouling and water pollution are among the main barriers regarding efficient production in aquaculture. Indirect applications of inorganic NPs in aquaculture concern the wastewater treatment, removal of chemical and biological contaminants, and control of biofouling. Metal-based NPs are able to deal with these problems, owing to their antibiofilm, antibacterial and photocatalytic activity.[114]

3.2.1 | Antibacterial and antibiofilm activity

NPs are successful antimicrobial agents from water sources, and have an imperative role in the water-treatment process.[115] Inorganic NPs were used to inhibit and eliminate water-borne pathogens.[116,117]

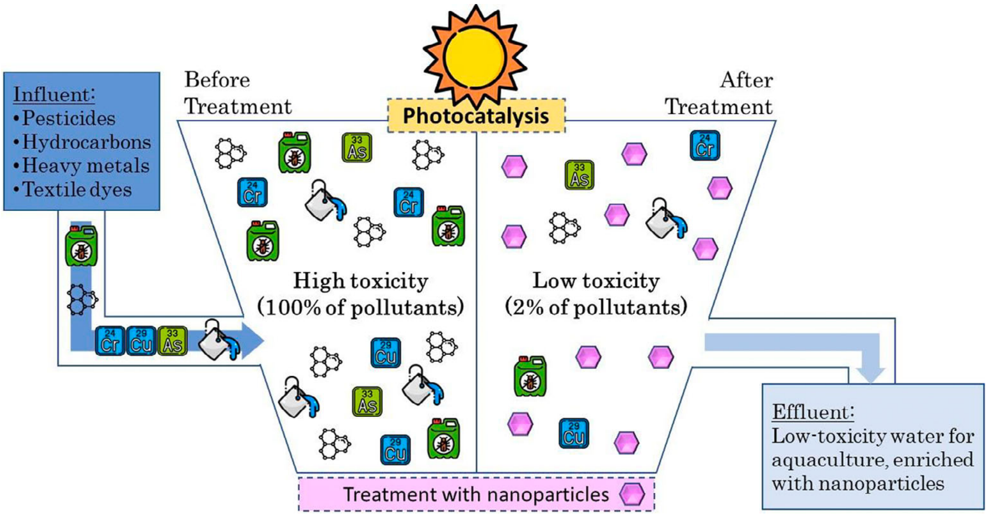

FIGURE 3 NPs as photocatalysers in the aquatic environment.

Ag-NPs

Ag-NPs (Nanocid) have been tested for inhibiting Gram-positive and Gram-negative fish pathogens like *Streptococcus iniae*, *Lactococcus garvieae*, *Yersinia ruckeri* and *Aeromonas hydrophila*, concluding that 90 min of exposure were enough for potent activity against *Yersinia ruckeri* and *Aeromonas hydrophila*.[116] Focusing specifically on aquaculture, Ag-NPs have shown an effective antimicrobial activity against aquatic pathogens without negative impact on aquatic animals.[117] Green synthetized Ag-NPs using *Moringa oleifera* extracts as reducing agents at the concentration of 0.8 mg/L were used to treat water pollutants, or to reduce bacterial diseases such as *Aeromonas hydrophila* that cause septicemia in Nile tilapia. The optimal level of green synthesized Ag-NPs had no negative response on fish health.[118] Moreover, *Emericella nidulans* synthetized Ag-NPs of 4 μg/ml strongly reduced the biofilm formation in *Pseudomonas aeruginosa* and *Staphylococcus aureus*.[119]

Au-NPs

Au-NPs were potent antibacterial agents against common waterborne pathogens like *Escherichia coli* and *Salmonella typhi*. The smallest form of Au-NPs (5 nm) dispersed on zeolites was efficient to eliminate 90%–95% of *Escherichia coli* and *Salmonella typhi* colony's pathogens in short time (90 min).[120]

Zn-NPs

ZnO nanorod coatings helped inhibit the growth of the marine bacteria *Acinetobacter* sp. AZ4C and algae *Tetraselmis* sp., as well as to prevent precursor of biofilm formation. This approach had also a significant effect on micro and macro fouling in the marine environment.[121] The same NPs type presented also bactericidal properties against common implant pathogens, namely *Pseudomonas aeruginosa*, *Staphylococcus epidermidis*, *Escherichia coli*, *Bacillus* spp., *Salmonella* spp., *Listeria monocytogenes* and *Staphylococcus aureus*.[122–124] Additionally, ZnO-NPs showed sufficient stabilizing effects, low toxicity, and reduced loss of NPs.[125,126] Such nanomaterials were also beneficial for the growth suppression of wastewater pathogens such as *Staphylococcus epidermidis*, *Proteus mirabilis*, *E. coli* and *K. pneumoniae* under UV irradiation, showing the highest activity on Gram-positive bacteria *Staphylococcus epidermidis*.[127]

Cu-NPs

The antibiofilm properties of Cu-NPs synthesized by one-pot methods against *Vibrio alginolyticus* (ATCC 17749), *Vibrio parahaemolyticus* (ATCC 17802), and *Aeromonas hydrophila* (ATCC 7966) were evaluated in *Artemia salina*. Cu-NPs at 100 ng/ml showed 60% inhibition of biofilm formation without toxic effect, and increased the survival rate of the species, indicating that such NPs can be used as a novel antibiofilm agent in aquaculture.[128] Likewise, green synthetized *Manilkara zapota* leaf extract Cu-NPs showed antimicrobial effects against *Sclerotium oryzae* (MTCC 12230), *Staphylococcus aureus* (ATCC 25923), *Rhizoctonia solani* (MTCC 12232), *Escherichia coli* (ATCC 25922), *Vibrio harveyi* (ATCC 35084), *Vibrio parahaemolyticus* (ATCC 33845), and *Bacillus subtilis* (ATCC 23857).[129]

Se-NPs

Se-NPs are known as antibiofilm and antimicrobial agents. For instance, biogenic *Bacillus licheniformis* cell-free extract Se-NPs were utilized as antimicrobial (25 mg/mL) and antibiofilm (20 mg/ml) agents against foodborne pathogens like *Bacillus cereus*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Escherichia coli* O157:H7, *Salmonella Typhimurium* and *Salmonella enteritidis*.[130] Another study reported that at 75 mg/ml, Se-NPs were able to partially remove biofilm formation while showing no toxic effects on *Artemia larvae*.[131] The same partial activities of Se-NPs were shown against clinical pathogens like *Staphylococcus aureus* (42%), *Pseudomonas aeruginosa* (34.3%), and *Proteus mirabilis* (53.4%).

Mg-NPs

MgO-NPs have been proven as effective antibacterial agents against gram-positive (*Staphylococcus aureus*) and gram-negative bacteria (*Escherichia coli*).[132] Biogenic *Aspergillus terreus* S1 MgO-NPs showed

TABLE 3 Some applications and data of inorganic NPs in aquaculture

NPs	Applications	Sources, size, shape and administration mode	Aquatic organisms	Recommended dose/results	References
Ag	Antibacterial	Ag-NPs coated with polyvinylpyrrolidone (PVP) 28.6 ± 3.1 nm 100–250–500–750 μg/L 10 days in *Aeromona veronii* infected fish	Nile tilapia (*Oreochromis niloticus*)	750 μg/L	157
		Biogenic Ag-Nps (*Persea americana*) 20–50 nm Feeding 10 days	Rohu (*Labeo rohita*)	5 μg/g encapsulated fish feed	158
		Aspergillus flavus Amylase-Ag-NPs 22.88–26.35 nm/spherical	Sea bass (*Dicentrarchuslabrax*) larvae	1.6 μg/ml against *A. hydrophila* 2.5 μg/ml against *St. agalactiae* 3.2 μg/ml against *Listeria* sp 3.6 μg/ml against *St. faecium*	159
	Growth promotion	*Aspergillus flavus* Amylase-Ag-NPs 22.88–26.35 nm/spherical 1.5, 10, 20%—8 weeks	Sea bass (*Dicentrarchuslabrax*) larvae	5% (0.2 mg/ml) of encapsulated Amy-AgNPs	159
	Antioxidant and immunostimulant	Ag-NPs coated with PVP	Rohu (*Labeo rohita*)	10–15 μg/kg	78
	Antibiofilm	*Spirulina platensis*—Ag-NPs 29 nm/spherical	–	100 μg/ml 85.63% inhibition against *Pseudomonas aeruginosa* PA14	160
	Photocatalytic degradation	*Chloroxylon swietenia*-Ag-NPs 6.9 nm/spherical and rod-shaped	–	>90% degradation Coomassie blue and crystal violet >95% degradation congo red	161
	Antioxidant and catalytic activity	*Acmella oleracea* Ag-NPs 45–60 nm	–	IC_{50}: 298.69 μg/ml Reduction of 4-nitrophenol	162
Au	Antibacterial	Marine polysaccharide laminarin-Au-NPs 10–80 nm/spherical	Crustaceans (*Daphnia similis* and *shrimp* (*Artemia salina*)	up to 400 μg/ml against *A. hydrophila*	163
	Antibacterial, antioxidant, and immune response	*Turnera diffusa*-Au-NPs 24 nm/spherical	Longfin yellowtail (*Seriola rivoliana*)	800 μg/ml against *A. hydrophila*	164
	Antibacterial activity	*Pyrenacantha grandiflora*-Au-NPs 11 nm/star-shaped Well diffusion assay	–	MIC: 0.063 mg/ml against beta-lactamase producing *K. pneumonia*	165
	Antimicrobial and antioxidant activity	*Thraustochytrium kinnei*-Au-NPs 10–85 nm/cubical in nature	–	Maximum inhibition against *Klebsiella pneumonia*	166
	Antibiofilm	Marine polysaccharide laminarin-Au-NPs 10–80 nm/spherical		100 μg/ml	163
	Photocatalytic degradation	Marine polysaccharide laminarin-Au-NPs 10–80 nm/spherical	–	Decoloration of Methylene blue in the presence of Au-NPs 50 mg/50 ml	163
Cu	Antibacterial activity	Fenugreek-Cu-NPs 15 nm/spherical shape	–	0.5, 1 1.5, 2, and 2.5 mM	167
	Antibacterial and Photocatalytic activity	*Cardiospermum halicacabum*-Cu-NPs 10 ± 2 nm/spherical	–	1 mg/ml >90% killing Gram+ bacteria such as *Bacillus subtilis* 93% degradation Methylene blue dye	168

TABLE 3 (Continued)

NPs	Applications	Sources, size, shape and administration mode	Aquatic organisms	Recommended dose/results	References
	Antifungal activity	Chemical reduction process-Cu-NPs 11–34 nm/spherical 10, 20 mg/L—14 days	Common carp (*Cyprinus carpio*)	20 mg/L against *Saprolegnia* spp.	169
	Wastewater treatment	*Chlamydomonas reinhardtii*-Cu-NPs 10 nm/spherical	–	10 mg/L	170
Fe	Antibacterial activity	Fe-NPs (Super paramagnetic iron oxide NPs) 8–12 nm	–	3.21 to 6.42 μM (low bacterial load −15–60 min) 267.81 μM (high load—15 min) 104.09 μM (high load—60 min)	28
		Co-precipitation Fe-NPs 16 ± 3 nm/Spherical	–	6–48 mg/L and 1.5–6 mg/L	29
	Growth performance, biochemical constituents, haematological parameters, and antioxidant activity	*Camellia sinensis* Fe-NPs 114 nm/hexagonal and spherical	Blue Gourami (*Trichogaster trichopterus*) Fingerlings	40 mg/kg	171
	Growth performance, biochemical constituents, haematological parameters	Co-precipitation-Fe-NPs 50–90 nm/irregular cluster appearance	Koi carp (*Cyprinus carpio var. koi*)	30 mg/kg	54
	Antioxidant and immune response	Commercial-Fe-NPs 20–40 nm/spherical	Common carp (*Cyprinus carpio*)	25%, 50%, and 75% of IFe-NPs LC_{50} 96 h	172
	Photocatalytic activity	Sodium borohydride-Fe-NPs 12.5 nm/spherical bead-like structures	–	1.0 g of Fe-NPs	173
Mg	Antibacterial activity	Pomegranate peels & cauliflower-Mg-NPs 11 nm/spherical Well diffusion method	–	100 μl loaded against *Bacillus cereus* (MTCC 430), *Staphylococcus aureus* (MTCC 3160), *E.coli* (MTCC 1698) and *Klebsiella pneumoniae* (MTCC10309)	174
	Antifungal and antibiofilm activity	*Burkholde riarinojensis*-Mg-NPs 26.70 nm/spherical granular structures	–	15.36 μg/ml	175
	Growth, immune response, and disease resistance in fish	Commercial-Mg-NPs 20 nm/spherical	Asian sea bass (*Lates calcarifer*)	500 mg 42 days	176
	Photocatalytic activity	Commercial-Mg-NPs 30–90 nm/spherical Ultrasonic radiation	–	Adsorption capacity of 487.60 mg/g 90% removal of Malachite green—15 min	177
Se	Antibacterial activity	*Blumea axillaris*-Se-NPs 40 nm/spherical Disc diffusion technique	–	40 μg/20 μl against *Aeromonas* species	178
	Antibacterial and antioxidant activity	*Kappaphycus alvareerzii* and *Halimeda opuntia*-Se-NPs 30–80 nm/spherical	–	100 μl IC_{50}: 19.4 μg/ml and 18.7 μg/ml	179

(Continues)

TABLE 3 (Continued)

NPs	Applications	Sources, size, shape and administration mode	Aquatic organisms	Recommended dose/results	References
	Antibacterial activity	Se- NPs coated with extract *Sargassum angustifolium* 40 nm/spherical	White leg shrimp (*Litopenaeus vannamei*, synonym *Penaeus vannamei*)	MIC: 200 μg/ml against *Vibrio harveyi* MIC: 400 μg/ml	180
	Growth performance in fish	Commercial-Se-NPs 30–50 nm/spherical	Nile Tilapia (*Oreochromis niloticus*)	1 mg/kg 30 days	181
Zn	Antibacterial activity	Chemical precipitation-Zn-NPs 50 nm/hexagonal	–	30 μg/ml and 40 μg/ml	182
		Aloe vera gel-Zn-NPs 37.5–63.75 nm/spherical	–	50, 100, 200, 300, 400, and 500 μg/disc	183
		Halimeda opuntia-Zn-NPs 33 nm/hexagonal	–	1, 2.5, 5, 7.5, and 10 μg/ml	184
	Antifungal activity	*Ulva fasciata*-Zn-NPs 50 nm/spherical Feeding 40 or 60 mg/kg—8 weeks	Nile tilapia (*Oreochromis niloticus*)	40 mg/kg	185
	Antibiofilm activity	*Emblica officinalis*-Zn-NPs 3–11 nm/quasi spherical	–	Antibiofilm against *Streptococcus pyogenes* MTCC 442, *Bacillus cereus* MTCC 1272, *Escherichia coli* MTCC 1687, and *Pseudomonas aeruginosa* MTCC	186
	Photocatalytic activity	ZnO-NPs Quince seed mucilage 25 nm	–	80% degradation of methylene blue—2 h	187

not only antibacterial activity against *Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Escherichia coli* and *Candida albicans*, but also the capacity to remove 97.5% of chromium ions from tanning effluent.[133] Likewise, MgO-NPs with 20 nm average size exhibited strong antibacterial effects against pathogens like *Campylobacter jejuni* (2 mg/ml), *Escherichia coli* O157:H7, and *Salmonella Enteritidis* (8 mg/ml).[134] MgO-NPs produced from co-precipitation synthesis were also able to inhibit *Escherichia coli* and *Staphylococcus aureus*.[135] Another remediation example MgO-NPs synthesized from *Dalbergia sissoo* leaf extract presented efficiency, not only in the photocatalytic degradation of methylene blue dye (81%), but also against *Escherichia coli* and *Ralstonia solanacearum*.[136]

3.2.2 | Photocatalytic degradation activity

Photocatalytic degradation is a light-induced catalytic reaction that reduces or oxidizes organic molecules like dyes through redox reactions. The reactions take place on a semiconductor surface such as metal oxide, which is able to form charge carriers when exposed to light and activated by the generated electron–hole pairs.[137]

Metal nanocomposites are helpful regarding the degradation of different kinds of pollutants, including alcohols, aldehydes, acids, phenolic compounds, and dyes under UV irradiation, while novel metal composites combined with the ultrasonic method are able to completely degrade pollutant molecules.[138,139] Figure 3 illustrates the application of inorganic NPs in photocatalysis for pollutant's treatment.

Metal-based NPs (Ag-NPs, Au-NPs, Fe-NPs and Cu-NPs) have been tested for their photocatalytic degradation activity of organic dyes in wastewater treatment.[140–143]

For example, various green synthetized Ag-NPs using *Konjac glucomannan* extract, *Coscinium fenestratum* stem extract, and Ulva *Lactuca* as reducing agents, have been proved to degrade under visible light conditions mono- and di-azo dyes contaminants like methylene blue, methyl orange, acid orange 74, naphtol blue-black and naphtol green B acidic in wastewater.[140,144,145] Moreover, green synthetized *Saccharomyces cerevisiae* yeast extract Ag-NPs and *Parkia speciosa* leaf extract Ag-NPs presented efficient photocatalytic activity, regarding the degradation of methylene blue under solar irradiation conditions.[146,147]

Biogenic and green synthetized Cu-NPs have shown excellent photocatalytic degradation of dyes under sunlight irradiation. The degradation efficiency using biogenic *Escherichia* sp. SINT7 Cu-NPs reached, for example, 97.1% for congo-red, 90.6% for Malachite green, 88.4% for direct blue 1, and 83.6% for reactive black-5 within 5 h.[148] Whereas green synthesized Cu-NPs using *Manilkara zapota* leaf extract exhibited photocatalytic degradation activity of methyl violet, malachite green, and coomassie brilliant blue by 92.2%, 94.9%

TABLE 4 Some negative effects of NPs in aquaculture fishes

NPs	Fish species	Concentration, size, contact time and route(s) of administration	Observation	Recommended doses	References
Ag	Atlantic salmon (*Salmo salar*)	Commercial Ag-NPs (3–220 nm) 1, 20, and 100 μg/L (48 h, static renewal)	Bioaccumulation of Ag in gills Inhibition of Na+/K+ ATPase	<1 μg/L <20 μg/L	192
	African catfish (*Clarias gariepinus*)	Ag-NPs (<100 nm) 0, 25, 50, and 75 mg/L (2 weeks)	DNA damage with all concentrations in gill, kidney, liver and muscle Dose dependent	Negative effects in all concentrations	193
	African catfish (*Clarias gariepinus*)	Co-precipitation Ag-NPs (13 nm) 0, 6.25, 12.5, 25, 50 and 100 mg/L (96 h)	Alterations in behaviour, blood profile, neurological, and branchial antioxidant parameters	Dose dependent-negative effects LC_{50} 21.38 mg/L	194
	Rohu (*Labeo rohita*)	Ag-NPs (50–100 nm) 5, 10, 25, 50 and 100 mg/kg (7 days)	Reduction in haematology parameters Increase in antioxidant enzymes Histological changes in muscle, gill and liver	Negative effects in all concentrations	195
Cu	Nile tilapia (*Oreochromis niloticus*)	Commercial-CuO-NPs (55 nm spherical and oval shapes) 0.05 mL/L (4 and 21 days)	Haematological changes and oxidative stress	<0.05 mL/L	196
	Common carp (*Cyprinus carpio*)	CuO-NPs (20–40 nm) 10, 50, 100, 200, 300, 500 and 1000 mg/L (4 days-30 days)	Inhibition of growth after 30 days exposition at 100 mg/L	<100 mg/L	197
	Zebra fish (*Danio rerio*) embryos	Cu-NPs (69 ± 18 nm) 0.01, 0.05, 0.1, 0.5, and 1 mg/L (96 h)	Retarded hatching embryos Morphological malformation, mortality in gastrula stage	<0.1 mg/L	198
Fe	*L. rohita*	Fe_2O_3-NPs (100 nm) 500 mg/L (25 days)	Alteration in haematological, ionoregulatory and enzymological parameters	<500 mg/L	199
	Mozambique tilapia (*Oreochromis mossambicus*)	Fe_2O_3-NPs (29–40 nm) 0.5, 5, and 50 μg/L (96 h)	Change in haematological and biochemical parameters Hepatic tissue damage	Less toxic up 50 μg/ml but cause hepatic tissue damage with an acute period exposure (48 h)	200
TiO_2	Common carp (*Cyprinus carpio*)	TiO_2-NPs (21 nm) 10 mg/L (25 days)	Bioaccumulation of Cd in presence of TiO_2; Cd concentration increased by 146%		201
	Nile Tilapia (*Oreochromis niloticus*)	Commercial-TiO_2-NPs (13-31 nm/spherical) 1 mg/ml (4 weeks)	Alteration of intestinal microbiota Strong inflammatory response	<1 mg/ml	202
	Oreochromis niloticus	TiO2-NPs (21 nm) 1–5-25 mg/L (14 days)	Decrease of ATPase activity in kidney	All concentrations decrease ATPase activity	203
ZnO	Common carp (*Cyprinus carpio*)	ZnO-NPs (30 nm) 50 mg/L (30 days)	Severe histopathological alteration, Zn bioaccumulation in liver > gill > intestine > brain and muscle, decrease of SOD activity		204

and 78.8% within 50, 40 and 60 min under solar light irradiation, respectively.[129] Moreover, Au-NPs degraded efficiently methylene blue at a yield of 75% while Fe-NPs at 92%.[149,150]

Regarding semiconductor metal oxide NPs, ZnO-NPs, TiO-NPs and MgO-NPs were proven to have photocatalytic degradation ability.[151–153] Green synthetized *Kalopanax septemlobus* ZnO-NPs and

Amomum longiligulare ZnO-NPs were indicated as suitable photocatalysts for the degradation of methylene blue dye under UV light irradiation.[154,155] Additionally, magnesium aluminate ($MgAl_2O_4$) NPs synthesized by the sol–gel method showed successful photocatalytic degradation of 50% for methyl orange within 80 min under UV light irradiation.[156]

Other applications of inorganic NPs in aquaculture can be found in the literature. Table 3 lists recent and relevant potential applications of inorganic NPs, as well as related data, including sources, characteristics, administration mode, targeted aquatic organisms, as well as recommended doses as a function of the chemical nature of the NP metal element.

4 | POTENTIAL RISKS OF INORGANIC NANOPARTICLES IN AQUACULTURE

The use of inorganic NPs in aquaculture presents evident benefits, either directly in animal diet or as supplements, or indirectly as degrading agents of pollutants in water and wastewater. Such functions provide aquatic health protection through disease control, anti-biofouling, water treatment and aquatic nutrition due to the inorganic NPs unique properties, efficacy related to the higher surface area, higher solubility, induction of systemic activity, higher mobility and high bioavailability among others.[21,188] Nevertheless, their applications present potential risks associated with dose-dependent toxicity and low biodegradability.[189] Inorganic NPs may generate adverse biological concerns, cytotoxicity and genotoxicity by potential translocation to various aquatic animals tissues and organs, releasing toxic ions, causing oxidative stress, inflammation, lysosomal impairment and subsequent damage to proteins and enzymes, cell membranes and DNA.[190] Green NPs appear as convenient route to the production of eco-friendly and cost effective NPs. However, their toxicity toward aquatic biota has to be evaluated.[191] Moreover, metal-based NPs have been reported to cause more toxic effects on living organisms compared with their bulk forms.[4,18] Table 4 summarizes some in vivo and in vitro toxicity evaluations of NPs in different fish species.

5 | CONCLUSION

Nanotechnology appears to be a modern tool for the progress of aquaculture and seafood industries by controlling various types of bacterial and viral diseases in aquatic animals. In the aquaculture sector, NPs are used for different application areas such as wastewater treatment, biofouling control, fishpond sterilization, harvest packaging, animal feeding, and animal health care. This review provides information about a variety of inorganic NPs, including their techniques of synthesis and characterization, as well as the doses used to develop optimal aquaculture applications. NPs are efficient in the photocatalytic degradation of pollutants in water and wastewater, such as metals and antibiotics, while their antimicrobial properties were also beneficial regarding disease control in aquaculture. Supplementation of inorganic NPs in animal diets at low levels enhanced growth, disease control, enzymatic reaction, and immune system response of aquatic animals without negative responses. Further studies may be focused in the future on the development of different kinds (nanosensors, nanomembranes, nanorods, bimetallic, colloidal, polymers) of nanoparticles using cost-effective green synthesis methods for reducing toxicity.

AUTHOR CONTRIBUTIONS

Seerengaraj Vijayaram: Conceptualization; writing–original draft; literature search; table preparation; validation. **Konstantina Tsigkou:** Writing–review and editing; figure editing & creation; literature search & check; validation. **Antonio Zuorro:** Writing–review and editing; validation. **Yun-Zhang Sun:** Writing–review and editing; validation. **Holy Rabetafika:** Writing–review and editing; table preparation; literature search; validation. **Hary Razafindralambo:** Writing–review and editing; manuscript outline; supervision; validation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ORBI at https://orbi.uliege.be/myorbi. Existing literature was used, as well as open and restricted access papers, peer review journals, relevant reports that are available in literature databases such as ORBI, Google scholar, and Pubmed.

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REFERENCES

1. Matteucci F, Giannantonio R, Calabi F, Agostiano A, Gigli G, Rossi M. Deployment and exploitation of nanotechnology nanomaterials and nanomedicine. *AIP Conference Proceedings*. Vol 1990. AIP Publishing LLC; 2018:20001.
2. Shaalan M, Saleh M, El-Mahdy M, El-Matbouli M. Recent progress in applications of nanoparticles in fish medicine: a review. *Nanomed Nanotechnol Biol Med*. 2016;12(3):701-710.
3. Mobasser S, Firoozi AA. Review of nanotechnology applications in science and engineering. *J Civ Eng Urban*. 2016;6(4):84-93.
4. Khosravi-Katuli K, Prato E, Lofrano G, Guida M, Vale G, Libralato G. Effects of nanoparticles in species of aquaculture interest. *Environ Sci Pollut Res*. 2017;24(21):17326-17346.
5. Dar AH, Rashid N, Majid I, Hussain S, Dar MA. Nanotechnology interventions in aquaculture and seafood preservation. *Crit Rev Food Sci Nutr*. 2020;60(11):1912-1921.
6. Muruganandam M, Chipps SR, Ojasvi PR. On the advanced technologies to enhance fisheries production and management. *Acta Sci Agric*. 2019;3(8):216-222.

7. Nasr-Eldahan S, Nabil-Adam A, Shreadah MA, Maher AM, El-Sayed AT. A review article on nanotechnology in aquaculture sustainability as a novel tool in fish disease control. *Aquac Int*. 2021;29:1459-1480.
8. Ogunkalu OA. Utilization of nanotechnology in aquaculture and seafood sectors. *Eurasian J Food Sci Technol*. 2019;3(1):26-33.
9. Ye S, Jin W, Huang Q, et al. Development of Mag-FMBO in clay-reinforced KGM aerogels for arsenite removal. *Int J Biol Macromol*. 2016;87:77-84.
10. Delgado CL. *Fish to 2020: Supply and Demand in Changing Global Markets*. Vol 62. WorldFish; 2003.
11. Kwasek K, Thorne-Lyman AL, Phillips M. Can human nutrition be improved through better fish feeding practices? A review paper. *Crit Rev Food Sci Nutr*. 2020;60(22):3822-3835.
12. Shaalan MI, El-Mahdy MM, Theiner S, El-Matbouli M, Saleh M. In vitro assessment of the antimicrobial activity of silver and zinc oxide nanoparticles against fish pathogens. *Acta Vet Scand*. 2017;59(1):1-11.
13. Menanteau-Ledouble S, Krauss I, Santos G, Fibi S, Weber B, El-Matbouli M. Effect of a phytogenic feed additive on the susceptibility of Onchorhynchus mykiss to Aeromonas salmonicida. *Dis Aquat Organ*. 2015;115(1):57-66.
14. Menanteau-Ledouble S, Krauss I, Goncalves RA, Weber B, Santos GA, El-Matbouli M. Antimicrobial effect of the Biotronic Top3 supplement and efficacy in protecting rainbow trout (*Oncorhynchus mykiss*) from infection by *Aeromonas salmonicida* subsp. salmonicida. *Res Vet Sci*. 2017;114:95-100.
15. El Basuini MF, El-Hais AM, Dawood MAO, et al. Effects of dietary copper nanoparticles and vitamin C supplementations on growth performance, immune response and stress resistance of red sea bream, Pagrus major. *Aquac Nutr*. 2017;23(6):1329-1340.
16. Izquierdo MS, Ghrab W, Roo J, et al. Organic, inorganic and nanoparticles of Se, Zn and Mn in early weaning diets for gilthead seabream (*Sparus aurata*; Linnaeus, 1758). *Aquacult Res*. 2017;48(6):2852-2867.
17. Bundschuh M, Filser J, Lüderwald S, et al. Nanoparticles in the environment: where do we come from, where do we go to? *Environ Sci Eur*. 2018;30(1):1-17.
18. Abbas WT. Advantages and prospective challenges of nanotechnology applications in fish cultures: a comparative review. *Environ Sci Pollut Res*. 2021;28(7):7669-7690.
19. Ealia SAM, Saravanakumar MP. A review on the classification, characterisation, synthesis of nanoparticles and their application. *IOP Conference Series: Materials Science and Engineering*. Vol 263. IOP Publishing; 2017:32019.
20. Rauscher H, Roebben G, Mech A, et al. *An Overview of Concepts and Terms Used in the European Commission's Definition of Nanomaterial*. Publ Off Eur Union; 2019.
21. Auffan M, Rose J, Bottero JY, Lowry GV, Jolivet JP, Wiesner MR. Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. *Nat Nanotechnol*. 2009;4(10):634-641.
22. Sharma VK, Filip J, Zboril R, Varma RS. Natural inorganic nanoparticles: formation, fate, and toxicity in the environment. *Chem Soc Rev*. 2015;44(23):8410-8423.
23. Ju-Nam Y, Lead J. Manufactured nanoparticles and natural aquatic colloids: an overview of their chemical aspects, interactions and potential environmental implications. *Sci Total Environ*. 2008;400:396-414.
24. Sánchez-López E, Gomes D, Esteruelas G, et al. Metal-based nanoparticles as antimicrobial agents: an overview. *Nanomaterials*. 2020;10(2):292.
25. Ijaz I, Gilani E, Nazir A, Bukhari A. Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. *Green Chem Lett Rev*. 2020;13(3):223-245.
26. Mourdikoudis S, Pallares RM, Thanh NTK. Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. *Nanoscale*. 2018;10(27):12871-12934.
27. Elayaraja S, Liu G, Zagorsek K, et al. TEMPO-oxidized biodegradable bacterial cellulose (BBC) membrane coated with biologically-synthesized silver nanoparticles (AgNPs) as a potential antimicrobial agent in aquaculture (In vitro). *Aquaculture*. 2021;530:735746.
28. Kumar M, Gupta G, Varghese T, et al. Synthesis and characterisation of super-paramagnetic iron oxide nanoparticles (SPIONs) for minimising Aeromonas hydrophila load from freshwater. *Curr Nanosci*. 2022;18(2):224-236.
29. Kumar M, Gupta G, Varghese T, Srivastava PP, Gupta S. Preparation and characterization of glucose-conjugated super-paramagnetic iron oxide nanoparticles (G-SPIONs) for removal of Edwardsiella tarda and Aeromonas hydrophila from water. *Microsc Res Tech*. 2022;85(5):1768-1783.
30. Rather MA, Sharma R, Aklakur M, et al. Nanotechnology: a novel tool for aquaculture and fisheries development. A prospective mini-review. *Fish Aquac J*. 2011;16(1–5):3.
31. Muralisankar T, Bhavan PS, Radhakrishnan S, Seenivasan C, Manickam N, Srinivasan V. Dietary supplementation of zinc nanoparticles and its influence on biology, physiology and immune responses of the freshwater prawn, *Macrobrachium rosenbergii*. *Biol Trace Elem Res*. 2014;160(1):56-66.
32. Ashouri S, Keyvanshokooh S, Salati AP, Johari SA, Pasha-Zanoosi H. Effects of different levels of dietary selenium nanoparticles on growth performance, muscle composition, blood biochemical profiles and antioxidant status of common carp (*Cyprinus carpio*). *Aquaculture*. 2015;446:25-29.
33. Okeke ES, Chukwudozie KI, Nyaruaba R, et al. Antibiotic resistance in aquaculture and aquatic organisms: a review of current nanotechnology applications for sustainable management. *Environ Sci Pollut Res*. 2022;29(46):69241-69274.
34. El Basuini MF, El-Hais AM, Dawood MAO, et al. Effect of different levels of dietary copper nanoparticles and copper sulfate on growth performance, blood biochemical profiles, antioxidant status and immune response of red sea bream (*Pagrus major*). *Aquaculture*. 2016;455:32-40.
35. Faiz H, Zuberi A, Nazir S, Rauf M, Younus N. 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 Agric Biol*. 2015;17(3):568-574.
36. Singha S, Das K, Jha N. Nano-systems for micronutrient delivery in aquaculture: a critical analysis. *Ann Aquac Res*. 2017;4:1046.
37. Jampilek J, Kos J, Kralova K. Potential of nanomaterial applications in dietary supplements and foods for special medical purposes. *Nanomaterials*. 2019;9(2):296.
38. Yu HR, Li LY, Shan LL, Gao J, Ma CY, Li X. Effect of supplemental dietary zinc on the growth, body composition and anti-oxidant enzymes of coho salmon (*Oncorhynchus kisutch*) alevins. *Aquac Rep*. 2021;20:100744.
39. Mahboub HH, Shahin K, Zaglool AW, Roushdy EM, Ahmed SAA. Efficacy of nano zinc oxide dietary supplements on growth performance, immunomodulation and disease resistance of African catfish *Clarias gariepinus*. *Dis Aquat Organ*. 2020;142:147-160.
40. Rajan MR, Rohini R. Impact of different quantity of zinc oxide nanoparticles on growth and hematology of Mrigal *Cirrhinus mrigala*. *J Water Environ Nanotechnol*. 2021;6(1):62-71.
41. Swain PS, Rao SBN, Rajendran D, Dominic G, Selvaraju S. Nano zinc, an alternative to conventional zinc as animal feed supplement: a review. *Anim Nutr*. 2016;2(3):134-141.
42. Du Z, Luo W, Liu Y, et al. The dietary zinc requirement of a benthic fish *Paramisgurnus dabryanus*. *Aquacult Res*. 2020;51(4):1346-1352.

43. Meiler KA, Cleveland B, Radler L, Kumar V. Oxidative stress-related gene expression in diploid and triploid rainbow trout (*Oncorhynchus mykiss*) fed diets with organic and inorganic zinc. *Aquaculture*. 2021;533:736149.
44. Mohseni M, Hamidoghli A, Bai SC. Organic and inorganic dietary zinc in beluga sturgeon (*Huso huso*): effects on growth, hematology, tissue concertation and oxidative capacity. *Aquaculture*. 2021;539:736672.
45. Shahpar Z, Johari SA. Effects of dietary organic, inorganic, and nanoparticulate zinc on rainbow trout, Oncorhynchus mykiss larvae. *Biol Trace Elem Res*. 2019;190(2):535-540.
46. Mondal AH, Behera T, Swain P, et al. Nano zinc vis-à-vis inorganic zinc as feed additives: effects on growth, activity of hepatic enzymes and non-specific immunity in rohu, *Labeo rohita* (Hamilton) fingerlings. *Aquacult Nutr*. 2020;26(4):1211-1222.
47. Taheri S, Banaee M, Nematdoost Haghi B, Mohiseni M. Evaluation of nephrotoxic effects of aflatoxins on common carp (*Cyprinus carpio*). *Iran J Toxicol*. 2017;11(2):51-58.
48. Awad A, Zaglool AW, Ahmed SAA, Khalil SR. Transcriptomic profile change, immunological response and disease resistance of *Oreochromis niloticus* fed with conventional and nano-zinc oxide dietary supplements. *Fish Shellfish Immunol*. 2019;93:336-343.
49. Farooq A, Verma AK, Hittinahalli CM, Harika N, Pai M. Iron supplementation in aquaculture wastewater and its effect on the growth of spinach and pangasius in nutrient film technique based aquaponics. *Agric Water Manag*. 2023;277:108126.
50. Kawatsu H. Studies on the anemia of fish-V. Dietary iron deficient anemia in brook trout, *Salvelinus fontinalis*. *Bull Freshw Fish Res Lab*. 1972;22:59-67.
51. Sakamoto S. Iron deficiency symptoms of carp. 1978.
52. Akbary P, Jahanbakhshi A. Nano and macro iron oxide (Fe_2O_3) as feed additives: effects on growth, biochemical, activity of hepatic enzymes, liver histopathology and appetite-related gene transcript in goldfish (*Carassius auratus*). *Aquaculture*. 2019;510:191-197.
53. Srinivasan V, Bhavan PS, Rajkumar G, Satgurunathan T, Muralisankar T. Effects of dietary iron oxide nanoparticles on the growth performance, biochemical constituents and physiological stress responses of the giant freshwater prawn *Macrobrachium rosenbergii* post-larvae. *Int J Fish Aquat Stud*. 2016;4(2):170-182.
54. Sangeetha K, Rajan MR. Evaluation of different quantity of iron oxide nanoparticles on growth, haematological and biochemical characteristics of koi carp. *Agric Sci Dig Res J*. 2021;41(2):338-344.
55. Rajan MR, Mangalaraj MD, Dhandapani S. Impact of different quantity of green synthesized iron oxide nanoparticles on growth, enzymatic, biochemical changes and hematology of zebrafish *Danio rerio*. *Int J Pharm Sci Nanotechnol*. 2021;14(5):5603-5611.
56. El-Shenawy AM, Gad DM, Yassin SA. Effect of iron nanoparticles on the development of fish farm feeds. *Alex J Vet Sci*. 2019;60(1):102-115.
57. Oluyemi GK. Effects of ascorbic acid and iron nanoparticles supplements on hyperthermia-induced stress in African catfish, *Clarias gariepinus* (Burchell, 1822). *J Basic Appl Zool*. 2021;82(1):1-9.
58. Akter N, Alam MJ, Jewel MAS, Ayenuddin M, Haque SK, Akter S. Evaluation of dietary metallic iron nanoparticles as feed additive for growth and physiology of Bagridae catfish *Clarias batrachus* (Linnaeus, 1758). *Int J Fish Aquat Stud*. 2018;6(3):371-377.
59. Behera T, Swain P, Rangacharulu PV, Samanta M. Nano-Fe as feed additive improves the hematological and immunological parameters of fish, *Labeo rohita* H. *Appl Nanosci*. 2014;4(6):687-694.
60. Council NR. *Nutrient Requirements of Fish*. National Academies Press; 1993.
61. Gatlin DM III, Wilson RP. Dietary copper requirement of fingerling channel catfish. *Aquaculture*. 1986;54(4):277-285.
62. Lim C, Klesius PH, Duncan PL. Immune response and resistance of channel catfish to *Edwardsiella ictaluri* challenge when fed various dietary levels of zinc methionine and zinc sulfate. *J Aquat Anim Health*. 1996;8(4):302-307.
63. Sealey WM, Lim C, Klesius PH. Influence of the dietary level of iron from iron methionine and iron sulfate on immune response and resistance of channel catfish to *Edwardsiella ictaluri*. *J World Aquac Soc*. 1997;28(2):142-149.
64. Khalil HS, Maulu S, Verdegem M, Abdel-Tawwab M. Embracing nanotechnology for selenium application in aquafeeds. *Rev Aquac*. 2023;15(1):112-129.
65. Dawood MAO, El BMF, Yilmaz S, et al. Selenium nanoparticles as a natural antioxidant and metabolic regulator in aquaculture: a review. *Antioxidants*. 2021;10(9):1364.
66. Susitharan V, Sindhu C. Nanotechnological approaches in aquaculture. *Vigyan Varta*. 2021;2(9):31-36.
67. Ziaei-nejad S, Hosseini SM, Seyed Mortezaei SR. Effects of selenium nanoparticles supplemented feed on biochemical indices, growth and survival of yellow-tail seabream (*Acanthopagrus latus*). *J Agric Sci Technol*. 2021;23(5):1001-1011.
68. Neamat-Allah ANF, Mahmoud EA, Abd El Hakim Y. Efficacy of dietary Nano-selenium on growth, immune response, antioxidant, transcriptomic profile and resistance of *Nile tilapia*, *Oreochromis niloticus* against *Streptococcus iniae* infection. *Fish Shellfish Immunol*. 2019;94:280-287.
69. Abdel-Tawwab M, Mousa MAA, Abbass FE. Growth performance and physiological response of African catfish, *Clarias gariepinus* (B.) fed organic selenium prior to the exposure to environmental copper toxicity. *Aquaculture*. 2007;272(1–4):335-345.
70. Dawood MAO, Koshio S, Zaineldin AI, et al. Dietary supplementation of selenium nanoparticles modulated systemic and mucosal immune status and stress resistance of red sea bream (Pagrus major). *Fish Physiol Biochem*. 2019;45(1):219-230.
71. Rathore SS, Murthy HS, Mamun MAA, et al. 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*. 2021;199(8):3073-3088.
72. El-Sharawy ME, Hamouda M, Soliman AA, et al. Selenium nanoparticles are required for the optimum growth behavior, antioxidative capacity, and liver wellbeing of striped catfish (*Pangasianodon hypophthalmus*). *Saudi J Biol Sci*. 2021;28(12):7241-7247.
73. Baldissera M D, Souza CF, Alessio KO, et al. Diphenyl diselenide-loaded nanocapsules in silver catfish feed enhance growth, improve muscle antioxidant/oxidant status and increase selenium deposition: advantages of nanotechnology for fish health. *Aquacult Res*. 2020;51(10):4196-4205.
74. Khan KU, Zuberi A, Nazir S, Ullah I, Jamil Z, Sarwar H. Synergistic effects of dietary nano selenium and vitamin C on growth, feeding, and physiological parameters of mahseer fish (*Tor putitora*). *Aquac Rep*. 2017;5:70-75.
75. Mir Rasekhian ME, Khara H, Pourali HR. Effects of dietary magnesium supplementation on the growth performance, body composition, and immune indices of juvenile Persian sturgeon, Acipnser Persicus. *Casp J Environ Sci*. 2022;20(3):557-564.
76. Srinivasan V, Bhavan PS, Rajkumar G, Satgurunathan T, Muralisankar T. Dietary supplementation of magnesium oxide (MgO) nanoparticles for better survival and growth of the freshwater prawn Macrobrachium rosenbergii post-larvae. *Biol Trace Elem Res*. 2017;177(1):196-208.
77. Thabet SR, Abdel-Galil MAA, Osman AS, Ahmed NS, Mousa MA. Biochemical effects of magnesium oxide nanoparticles in clarias gariepinus.
78. Popoola OM, Behera BK, Kumar V. Dietary silver nanoparticles as immunostimulant on rohu (*Labeo rohita*): effects on the growth, cellular ultrastructure, immune-gene expression, and survival against *Aeromonas hydrophila*. *Fish Shellfish Immunol Rep*. 2023;4:100080.

79. Thanigaivel S, Thomas J, Vickram AS, et al. Efficacy of encapsulated biogenic silver nanoparticles and its disease resistance against *Vibrio harveyi* through oral administration in *Macrobrachium rosenbergii*. *Saudi J Biol Sci.* 2021;28(12):7281-7289.
80. Sarkar B, Verma SK, Akhtar J, et al. Molecular aspect of silver nanoparticles regulated embryonic development in zebrafish (*Danio rerio*) by Oct-4 expression. *Chemosphere*. 2018;206:560-567.
81. Tello-Olea M, Rosales-Mendoza S, Campa-Córdova AI, et al. Gold nanoparticles (AuNP) exert immunostimulatory and protective effects in shrimp (*Litopenaeus vannamei*) against *Vibrio parahaemolyticus*. *Fish Shellfish Immunol*. 2019;84:756-767.
82. Na-Phatthalung P, Teles M, Tort L, Oliveira M. Gold nanoparticles exposure modulates antioxidant and innate immune gene expression in the gills of *Sparus aurata*. *Genomics*. 2018;110(6):430-434.
83. Geffroy B, Ladhar C, Cambier S, Treguer-Delapierre M, Brèthes D, Bourdineaud JP. Impact of dietary gold nanoparticles in zebrafish at very low contamination pressure: the role of size, concentration and exposure time. *Nanotoxicology*. 2012;6(2):144-160.
84. Kunjiappan S, Bhattacharjee C, Chowdhury R. Hepatoprotective and antioxidant effects of *Azolla microphylla* based gold nanoparticles against acetaminophen induced toxicity in a fresh water common carp fish (*Cyprinus carpio* L.). 2015.
85. Dawood MAO. Dietary copper requirements for aquatic animals: a review. *Biol Trace Elem Res*. 2022;200(12):5273-5282.
86. Muralisankar T, Bhavan PS, Radhakrishnan S, Seenivasan C, Srinivasan V. The effect of copper nanoparticles supplementation on freshwater prawn *Macrobrachium rosenbergii* post larvae. *J Trace Elem Med Biol*. 2016;34:39-49.
87. Wang H, Zhu H, Wang X, et al. Comparison of copper bioavailability in copper-methionine, nano-copper oxide and copper sulfate additives in the diet of Russian sturgeon *Acipenser gueldenstaedtii*. *Aquaculture*. 2018;482:146-154.
88. Delavari NM, Gharaei A, Mirdar HJ, Davari A, Rastiannasab A. Modulatory effect of dietary copper nanoparticles and vitamin C supplementations on growth performance, hematological and immune parameters, oxidative status, histology, and disease resistance against *Yersinia ruckeri* in rainbow trout (*Oncorhynchus mykiss*). *Fish Physiol Biochem*. 2022;48(1):33-51.
89. Shiwen H, Ling W, Lianmeng L, Yuxuan H, Lu L. Nanotechnology in agriculture, livestock, and aquaculture in China. *A Rev Agron Sustain Dev*. 2015;35:369-400.
90. Nisar P, Ali N, Rahman L, Ali M, Shinwari ZK. Antimicrobial activities of biologically synthesized metal nanoparticles: an insight into the mechanism of action. *J Biol Inorg Chem*. 2019;24:929-941.
91. Arasu MV, Arokiyaraj S, Viayaraghavan P, et al. One step green synthesis of larvicidal, and azo dye degrading antibacterial nanoparticles by response surface methodology. *J Photochem Photobiol B Biol*. 2019;190:154-162.
92. Li S, Shen Y, Xie A, et al. Green synthesis of silver nanoparticles using *Capsicum annuum* L. extract. *Green Chem*. 2007;9(8):852-858.
93. Song JY, Kim BS. Rapid biological synthesis of silver nanoparticles using plant leaf extracts. *Bioprocess Biosyst Eng*. 2009;32(1):79-84.
94. Valsalam S, Agastian P, Esmail GA, Ghilan AKM, Al-Dhabi NA, Arasu MV. Biosynthesis of silver and gold nanoparticles using *Musa acuminata* colla flower and its pharmaceutical activity against bacteria and anticancer efficacy. *J Photochem Photobiol B Biol.* 2019;201:111670.
95. Fatima R, Priya M, Indurthi L, Radhakrishnan V, Sudhakaran R. Biosynthesis of silver nanoparticles using red algae *Portieria hornemannii* and its antibacterial activity against fish pathogens. *Microb Pathog*. 2020;138:103780.
96. Rather MA, Bhat IA, Sharma N, Gora A, Ganie PA, Sharma R. Synthesis and characterization of *Azadirachta indica* constructed silver nanoparticles and their immunomodulatory activity in fish. *Aquacult Res*. 2017;48(7):3742-3754.
97. Vaseeharan B, Ramasamy P, Chen JC. Antibacterial activity of silver nanoparticles (AgNps) synthesized by tea leaf extracts against pathogenic *Vibrio harveyi* and its protective efficacy on juvenile *Feneropenaeus indicus*. *Lett Appl Microbiol*. 2010;50(4):352-356.
98. Sivaramasamy E, Zhiwei W, Li F, Xiang J. Enhancement of vibriosis resistance in *Litopenaeus vannamei* by supplementation of biomastered silver nanoparticles by *Bacillus subtilis*. *J Nanomed Nanotechnol*. 2016;7(352):2.
99. Alvarez-Cirerol FJ, López-Torres MA, Rodríguez-León E, et al. Silver nanoparticles synthesized with Rumex hymenosepalus: a strategy to combat early mortality syndrome (EMS) in a cultivated white shrimp. *J Nanomater*. 2019;2019:1-15.
100. Palanisamy S, Anjali R, Rajasekar P, Kannapiran E, Vaseeharan B, Prabhu NM. Synthesis and distribution of bioinspired silver nanoparticles using spirulina extract for control of *Vibrio parahaemolyticus* infection in aquaculture. *Asian J Chem*. 2017;29(4):857-863.
101. Daniel S, Sironmani TA, Dinakaran S. Nano formulations as curative and protective agent for fish diseases: studies on red spot and white spot diseases of ornamental gold fish *Carassius auratus*. *Int J Fish Aquat Stud.* 2016;4:255-261.
102. El-Saadony MT, Alkhatib FM, Alzahrani SO, et al. Impact of mycogenic zinc nanoparticles on performance, behavior, immune response, and microbial load in *Oreochromis niloticus*. *Saudi J Biol Sci*. 2021;28(8):4592-4604.
103. Saleh M, Kumar G, Abdel-Baki AA, Al-Quraishy S, El-Matbouli M. In vitro antimicrosporidial activity of gold nanoparticles against *Heterosporis saurida*. *BMC Vet Res*. 2016;12(1):1-6.
104. Lal J, Tameshwar S, Kashyap N. Nanotechnology: an innovative approach for sustainable fisheries and aquaculture.
105. Latif F, Aziz S, Kousar S, Iqbal R, Shahzad MM. Volume 2: Animal Health Perspectives.
106. Vinitnantharat S, Gravningen K, Greger E. Fish vaccines. *Adv Vet Med*. 1999;41:539-550.
107. FAO F. Agriculture Organization of the United Nations. The State of World Fisheries and Aquaculture. Rome, Italy. pp. 190. 2016.
108. Assefa A, Abunna F. Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. *Vet Med Int*. 2018;2018:1-10.
109. Rajeshkumar S, Venkatesan C, Sarathi M, et al. Oral delivery of DNA construct using chitosan nanoparticles to protect the shrimp from white spot syndrome virus (WSSV). *Fish Shellfish Immunol*. 2009;26(3):429-437.
110. Hegde M, Pai P, Shetty MG, Babitha KS. Gold nanoparticle based biosensors for rapid pathogen detection: a review. *Environ Nanotechnol, Monit Manag*. 2022;18:100756.
111. Mokhtarzadeh A, Eivazzadeh-Keihan R, Pashazadeh P, et al. Nanomaterial-based biosensors for detection of pathogenic virus. *TrAC Trends Anal Chem*. 2017;97:445-457.
112. Saleh M, Soliman H, Schachner O, El-Matbouli M. Direct detection of unamplified spring viraemia of carp virus RNA using unmodified gold nanoparticles. *Dis Aquat Organ*. 2012;100(1):3-10.
113. Saleh M, Soliman H, Haenen O, El-Matbouli M. Antibody-coated gold nanoparticles immunoassay for direct detection of *Aeromonas salmonicida* in fish tissues. *J Fish Dis*. 2011;34(11):845-852.
114. Maksoud MIAA, El-Sayyad GS, Ashour AH, et al. Antibacterial, antibiofilm, and photocatalytic activities of metals-substituted spinel cobalt ferrite nanoparticles. *Microb Pathog*. 2019;127:144-158.
115. Pradeep T. Noble metal nanoparticles for water purification: a critical review. *Thin Solid Films*. 2009;517(24):6441-6478.
116. Soltani M, Ghodratnema M, Ahari H, Ebrahimzadeh MHA, Atei M, Dastmalchi F, et al. The inhibitory effect of silver nanoparticles on the bacterial fish pathogens, *Streptococcus iniae*, *Lactococcus garvieae*, *Yersinia ruckeri*, *Aeromonas hydrophila*. 2009.

117. Johari SA, Kalbassi MR, Soltani M, Yu IJ. Toxicity comparison of colloidal silver nanoparticles in various life stages of rainbow trout (*Oncorhynchus mykiss*). 2013.
118. El-Houseiny W, Mansour MF, Mohamed WAM, et al. Silver nanoparticles mitigate *Aeromonas hydrophila*-induced immune suppression, oxidative stress, and apoptotic and genotoxic effects in *Oreochromis niloticus*. *Aquaculture*. 2021;535:736430.
119. Kirtane AR, Kalscheuer SM, Panyam J. Exploiting nanotechnology to overcome tumor drug resistance: challenges and opportunities. *Adv Drug Deliv Rev*. 2013;65(13–14):1731-1747.
120. Lima E, Guerra R, Lara V, Guzmán A. Gold nanoparticles as efficient antimicrobial agents for *Escherichia coli* and *Salmonella typhi*. *Chem Cent J*. 2013;7(1):1-7.
121. Al-Fori M, Dobretsov S, Myint MTZ, Dutta J. Antifouling properties of zinc oxide nanorod coatings. *Biofouling*. 2014;30(7):871-882.
122. Jones N, Ray B, Ranjit KT, Manna AC. Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms. *FEMS Microbiol Lett*. 2008;279(1):71-76.
123. Liu Y j, He L l, Mustapha A, Li H, Hu ZQ, Lin M s. Antibacterial activities of zinc oxide nanoparticles against *Escherichia coli* O157: H7. *J Appl Microbiol*. 2009;107(4):1193-1201.
124. Jaisai M, Baruah S, Dutta J. Paper modified with ZnO nanorods: antimicrobial studies. *Beilstein J Nanotechnol*. 2012;3(1):684-691.
125. Jansson T, Clare-Salzler ZJ, Zaveri TD, et al. Antibacterial effects of zinc oxide nanorod surfaces. *J Nanosci Nanotechnol*. 2012;12(9): 7132-7138.
126. Li M, Zhu L, Lin D. Toxicity of ZnO nanoparticles to *Escherichia coli*: mechanism and the influence of medium components. *Environ Sci Technol*. 2011;45(5):1977-1983.
127. Elmi F, Alinezhad H, Moulana Z, et al. The use of antibacterial activity of ZnO nanoparticles in the treatment of municipal wastewater. *Water Sci Technol*. 2014;70(5):763-770.
128. Chari N, Felix L, Davoodbasha M, Ali AS, Nooruddin T. In vitro and in vivo antibiofilm effect of copper nanoparticles against aquaculture pathogens. *Biocatal Agric Biotechnol*. 2017;10:336-341.
129. Kiriyanthan RM, Sharmili SA, Balaji R, et al. Photocatalytic, antiproliferative and antimicrobial properties of copper nanoparticles synthesized using *Manilkara zapota* leaf extract: a photodynamic approach. *Photodiagnosis Photodyn Ther*. 2020;32:102058.
130. Shakibaie M, Forootanfar H, Golkari Y, Mohammadi-Khorsand T, Shakibaie MR. Anti-biofilm activity of biogenic selenium nanoparticles and selenium dioxide against clinical isolates of *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Proteus mirabilis*. *J Trace Elem Med Biol*. 2015;29:235-241.
131. Khiralla A. Antibiofilm effects of selenium nanoparticles on some foodborne pathogens. *LWT Food Sci*. 2015;63:1001-1007.
132. Umaralikhan L, Mohamed Jaffar MJ. Green synthesis of MgO nanoparticles and it antibacterial activity. *Iran J Sci Technol Trans A Sci*. 2018;42(2):477-485.
133. Saied E, Eid AM, Hassan SED, et al. The catalytic activity of biosynthesized magnesium oxide nanoparticles (Mgo-nps) for inhibiting the growth of pathogenic microbes, tanning effluent treatment, and chromium ion removal. *Catalysts*. 2021;11(7):821.
134. He Y, Ingudam S, Reed S, Gehring A, Strobaugh TP, Irwin P. Study on the mechanism of antibacterial action of magnesium oxide nanoparticles against foodborne pathogens. *J Nanobiotechnol*. 2016; 14(1):1-9.
135. Imani MM, Safaei M. Optimized synthesis of magnesium oxide nanoparticles as bactericidal agents. *J Nanotechnol.* 2019;2019:1-6.
136. Khan MI, Akhtar MN, Ashraf N, et al. Green synthesis of magnesium oxide nanoparticles using *Dalbergia sissoo* extract for photocatalytic activity and antibacterial efficacy. *Appl Nanosci.* 2020;10(7):2351-2364.
137. Nagajyothi PC, Prabhakar Vattikuti SV, Devarayapalli KC, Yoo K, Shim J, Sreekanth TVM. Green synthesis: photocatalytic degradation of textile dyes using metal and metal oxide nanoparticles-latest trends and advancements. *Crit Rev Environ Sci Technol*. 2020;50(24): 2617-2723.
138. Wen B, Ma J, Chen C, Ma W, Zhu H, Zhao J. Supported noble metal nanoparticles as photo/sono-catalysts for synthesis of chemicals and degradation of pollutants. *Sci China Chem*. 2011;54(6):887-897.
139. Niu Y, Huang P, Li F, et al. Noble metal decoration and presulfation on TiO_2: increased photocatalytic activity and efficient esterification of n-butanol with citric acid. *Int J Photoenergy*. 2016;2016:1-12.
140. Chen J, Liu Y, Xiong Y, et al. Konjac glucomannan reduced-stabilized silver nanoparticles for mono-azo and di-azo contained wastewater treatment. *Inorgan Chim Acta*. 2021;515:120058.
141. Paul B, Bhuyan B, Purkayastha DD, Dey M, Dhar SS. Green synthesis of gold nanoparticles using *Pogestemon benghalensis* (B) O. Ktz. leaf extract and studies of their photocatalytic activity in degradation of methylene blue. *Mater Lett*. 2015;148:37-40.
142. Bibi I, Nazar N, Ata S, et al. Green synthesis of iron oxide nanoparticles using pomegranate seeds extract and photocatalytic activity evaluation for the degradation of textile dye. *J Mater Res Technol*. 2019;8(6):6115-6124.
143. Fathima JB, Pugazhendhi A, Oves M, Venis R. Synthesis of eco-friendly copper nanoparticles for augmentation of catalytic degradation of organic dyes. *J Mol Liq*. 2018;260:1-8.
144. Ragam PN, Mathew B. Unmodified silver nanoparticles for dual detection of dithiocarbamate fungicide and rapid degradation of water pollutants. *Int J Environ Sci Technol*. 2020;17(3):1739-1752.
145. Kumar P, Govindaraju M, Senthamilselvi S, Premkumar K. Photocatalytic degradation of methyl orange dye using silver (Ag) nanoparticles synthesized from *Ulva lactuca*. *Colloids Surfaces B Biointerfaces*. 2013; 103:658-661.
146. Roy K, Sarkar CK, Ghosh CK. Photocatalytic activity of biogenic silver nanoparticles synthesized using yeast (*Saccharomyces cerevisiae*) extract. *Appl Nanosci.* 2015;5(8):953-959.
147. Ravichandran V, Vasanthi S, Shalini S, Shah SAA, Tripathy M, Paliwal N. Green synthesis, characterization, antibacterial, antioxidant and photocatalytic activity of *Parkia speciosa* leaves extract mediated silver nanoparticles. *Results Phys*. 2019;15:102565.
148. Noman M, Shahid M, Ahmed T, et al. Use of biogenic copper nanoparticles synthesized from a native *Escherichia* sp. as photocatalysts for azo dye degradation and treatment of textile effluents. *Environ Pollut*. 2020;257:113514.
149. Rabeea MA, Owaid MN, Aziz AA, Jameel MS, Dheyab MA. Mycosynthesis of gold nanoparticles using the extract of *Flammulina velutipes*, Physalacriaceae, and their efficacy for decolorization of methylene blue. *J Environ Chem Eng*. 2020;8(3):103841.
150. Madivoli ES, Kareru PG, Maina EG, Nyabola AO, Wanakai SI, Nyang'au JO. Biosynthesis of iron nanoparticles using *Ageratum conyzoides* extracts, their antimicrobial and photocatalytic activity. *SN Appl Sci*. 2019;1(5):1-11.
151. Zheng Y, Fu L, Han F, et al. Green biosynthesis and characterization of zinc oxide nanoparticles using *Corymbia citriodora* leaf extract and their photocatalytic activity. *Green Chem Lett Rev*. 2015;8(2):59-63.
152. Mohammadi L, Bazrafshan E, Noroozifar M, Ansari-Moghaddam A, Barahuie F, Balarak D. Removing 2,4-dichlorophenol from aqueous environments by heterogeneous catalytic ozonation using synthesized MgO nanoparticles. *Water Sci Technol*. 2017;76(11):3054-3068.
153. Nigro M, Bernardeschi M, Costagliola D, et al. n-TiO_2 and $CdCl_2$ co-exposure to titanium dioxide nanoparticles and cadmium: genomic, DNA and chromosomal damage evaluation in the marine fish European sea bass (*Dicentrarchus labrax*). *Aquat Toxicol*. 2015;168: 72-77.
154. Lu J, Batjikh I, Hurh J, et al. Photocatalytic degradation of methylene blue using biosynthesized zinc oxide nanoparticles from bark extract of Kalopanax septemlobus. *Optik (Stuttg)*. 2019;182:980-985.

155. Liu YC, Li J, Ahn J, et al. Biosynthesis of zinc oxide nanoparticles by one-pot green synthesis using fruit extract of *Amomum longiligulare* and its activity as a photocatalyst. *Optik (Stuttg)*. 2020;218:165245.
156. Talebi R, Khademolhoseini S, Rahnamaeiyan S. Preparation and characterization of the magnesium aluminate nanoparticles via a green approach and its photocatalyst application. *J Mater Sci Mater Electron*. 2016;27(2):1427-1432.
157. Elgendy MY, Shaalan M, Abdelsalam M, Eissa AE, El-Adawy MM, Seida AA. Antibacterial activity of silver nanoparticles against antibiotic-resistant *Aeromonas veronii* infections in *Nile tilapia*, *Oreochromis niloticus* (L.), in vitro and in vivo assay. *Aquacult Res*. 2022; 53(3):901-920.
158. Mani R, Vijayakumar P, Dhas TS, et al. Synthesis of biogenic silver nanoparticles using butter fruit pulp extract and evaluation of their antibacterial activity against *Providencia vermicola* in Rohu. *J King Saud Univ*. 2022;34(3):101814.
159. Barakat KM, Abouelwafa A, El-Sayed HS, Beltagy EA. Silver nanoparticles mediated-marine fungal amylase improving *Dicentrarchus labrax* larvae growth performance. 2022.
160. LewisOscar F, Nithya C, Vismaya S, et al. In vitro analysis of green fabricated silver nanoparticles (AgNPs) against *Pseudomonas aeruginosa* PA14 biofilm formation, their application on urinary catheter. *Prog Org Coatings*. 2021;151:106058.
161. Nga NTA, Raghavendra VB, Sindhu R, et al. Green fabrication of silver nanoparticles using Chloroxylon swietenia leaves and their application towards dye degradation and food borne pathogens. *Food Chem Toxicol*. 2022;165:113192.
162. Bhardwaj S, Lata S, Garg R. Phyto-mediated green synthesis of silver nanoparticles using Acmella oleracea leaf extract: antioxidant and catalytic activity. *Pharmacogn Mag*. 2022;18(77):22.
163. Vijayakumar S, Chen J, Kalaiselvi V, et al. Antibacterial and antibiofilm activities of marine polysaccharide laminarin formulated gold nanoparticles: an ecotoxicity and cytotoxicity assessment. *J Environ Chem Eng*. 2021;9(4):105514.
164. Reyes-Becerril M, Ruvalcaba F, Sanchez V, et al. Green synthesis of gold nanoparticles using *Turnera diffusa* Willd enhanced antimicrobial properties and immune response in Longfin yellowtail leukocytes. *Aquacult Res*. 2021;52(7):3391-3402.
165. Murei A, Pillay K, Samie A. Syntheses, characterization, and antibacterial evaluation of *P. grandiflora* extracts conjugated with gold nanoparticles. *J Nanotechnol*. 2021;2021:1-10.
166. Kalidasan K, Asmathunisha N, Gomathi V, Dufossé L, Kathiresan K. Isolation and optimization of culture conditions of *Thraustochytrium kinnei* for biomass production, nanoparticle synthesis, antioxidant and antimicrobial activities. *J Mar Sci Eng*. 2021;9(6):678.
167. Ghuglot R, Titus W, Agnihotri AS, Krishnakumar V, Krishnamoorthy G, Marimuthu N. Stable copper nanoparticles as potential antibacterial agent against aquaculture pathogens and human fibroblast cell viability. *Biocatal Agric Biotechnol*. 2021;32:101932.
168. Karuppannan SK, Ramalingam R, Khalith SBM, Dowlath MJH, Raiyaan GID, Arunachalam KD. Characterization, antibacterial and photocatalytic evaluation of green synthesized copper oxide nanoparticles. *Biocatal Agric Biotechnol*. 2021;31:101904.
169. Alwash SW, Alfaragi JK, AlSaadi TM. Assessment of the mint-copper nanoparticles treatment to control the infection of Saprolegniasis in *Cyprinus carpio* L. *Ann Rom Soc Cell Biol*. 2021;25:16010-16019.
170. Žvab U, Kukulin DS, Fanetti M, Valant M. Bioremediation of copper polluted wastewater-like nutrient media and simultaneous synthesis of stable copper nanoparticles by a viable green alga. *J Water Process Eng*. 2021;42:102123.
171. Paulpandian P, Beevi IS, Somanath B, Kamatchi RK, Paulraj B, Faggio C. Impact of *Camellia sinensis* iron oxide nanoparticle on growth, hemato-biochemical and antioxidant capacity of blue gourami (*Trichogaster trichopterus*) fingerlings. *Biol Trace Elem Res Published Online*. 2022;201:1-13.
172. Khoei AJ. Evaluation of potential immunotoxic effects of iron oxide nanoparticles (IONPs) on antioxidant capacity, immune responses and tissue bioaccumulation in common carp (*Cyprinus carpio*). *Comp Biochem Physiol Part C Toxicol Pharmacol*. 2021;244:109005.
173. Akintayo CO, Aremu OH, Igboama WN, Nelana SM, Ayanda OS. Performance evaluation of ultra-violet light and iron oxide nanoparticles for the treatment of synthetic petroleum wastewater: kinetics of COD removal. *Materials (Basel)*. 2021;14(17):5012.
174. Muthulakshmi M, Naganandhini B. Biosynthesis of magnesium oxide nanoparticles using the extracts of *Puniga granatum* peels and *Brassica oleracea*. *Nanoscale Rep*. 2020;3(1):10-14.
175. Abdel-Aziz MM, Emam TM, Elsherbiny EA. Bioactivity of magnesium oxide nanoparticles synthesized from cell filtrate of endobacterium *Burkholderia rinojensis* against *Fusarium oxysporum*. *Mater Sci Eng C*. 2020;109:110617.
176. Deilamy Pour H, Mousavi SM, Zakeri M, Keyvanshokooh S, Kochanian P. Synergistic effects of selenium and magnesium nanoparticles on growth, digestive enzymes, some serum biochemical parameters and immunity of Asian sea bass (*Lates calcarifer*). *Biol Trace Elem Res*. 2021;199(8):3102-3111.
177. Das P, Debnath P, Debnath A. Enhanced sono-assisted adsorptive uptake of malachite green dye onto magnesium ferrite nanoparticles: kinetic, isotherm and cost analysis. *Environ Nanotechnol Monit Manag*. 2021;16:100506.
178. Dash JP, Mani L, Nayak SK. Antibacterial activity of Blumea axillaris synthesized selenium nanoparticles against multidrug resistant pathogens of aquatic origin. *Egypt J Basic Appl Sci*. 2022;9(1):65-76.
179. Rajashree R. Marine biomolecule mediated synthesis of selenium nanoparticles and their antimicrobial efficiency against fish and crustacean pathogens. 2022.
180. Mansouri-Tehrani HA, Keyhanfar M, Behbahani M, Dini G. Synthesis and characterization of algae-coated selenium nanoparticles as a novel antibacterial agent against *Vibrio harveyi*, a *Penaeus vannamei* pathogen. *Aquaculture*. 2021;534:736260.
181. Dawit Moges F, Hamdi H, Al-Barty A, et al. Effects of selenium nanoparticle on the growth performance and nutritional quality in Nile tilapia, *Oreochromis niloticus*. *PLoS One*. 2022;17(6): e0268348.
182. Krithika G, Saraswathy R, Muralidhar M, et al. Zinc oxide nanoparticles: synthesis, characterization and antibacterial activity. *J Nanosci Nanotechnol*. 2017;17(8):5209-5216.
183. Puja P, Mondal K, Mandal M. The use of aloe vera gel functionalized biogenic zinc-oxide nanoparticles against fish putative pathogens. *Aquat Sci Eng*. 2021;36(3):101-108.
184. Anand KV, Mahalakshmi D, Selvan SM, et al. Biomass extract of green macroalga *Halimeda opuntia* assisted ZnO nanoparticles: preparation, physico-chemical characterization, and antibacterial activity against *Vibrio harveyi*. *Biomass Convers Biorefinery*. 2022; 1-9.
185. Diab AM, Shokr BT, Shukry M, Farrag FA, Mohamed RA. Effects of dietary supplementation with green-synthesized zinc oxide nanoparticles for candidiasis control in *Oreochromis niloticus*. *Biol Trace Elem Res*. 2022;200:1-16.
186. Kaur T, Putatunda C, Vyas A, Kumar G. Zinc oxide nanoparticles inhibit bacterial biofilm formation via altering cell membrane permeability. *Prep Biochem Biotechnol*. 2021;51(4):309-319.
187. Moghaddas SMTH, Elahi B, Javanbakht V. Biosynthesis of pure zinc oxide nanoparticles using Quince seed mucilage for photocatalytic dye degradation. *J Alloys Compd*. 2020;821:153519.
188. Manjunatha SB, Biradar DP, Aladakatti YR. Nanotechnology and its applications in agriculture: a review. *J Farm Sci*. 2016;29(1):1-13.
189. Sengul AB, Asmatulu E. Toxicity of metal and metal oxide nanoparticles: a review. *Environ Chem Lett*. 2020;18(5):1659-1683.
190. Khan I, Saeed K, Khan I. Nanoparticles: properties, applications and toxicities. *Arab J Chem*. 2019;12(7):908-931.

191. Kamaraj C, Karthi S, Reegan AD, et al. Green synthesis of gold nanoparticles using *Gracilaria crassa* leaf extract and their ecotoxicological potential: issues to be considered. *Environ Res*. 2022;213:113711.
192. Farmen E, Mikkelsen HN, Evensen Ø, et al. Acute and sub-lethal effects in juvenile Atlantic salmon exposed to low μg/L concentrations of Ag nanoparticles. *Aquat Toxicol*. 2012;108:78-84.
193. Sayed AEDH. Genotoxicity detection following exposure to silver nanoparticles in African catfish (*Clarias gariepinus*). *Int J Nanopart*. 2016;9(1):41-53.
194. Mahboub HH, Khedr MHE, Elshopakey GE, et al. Impact of silver nanoparticles exposure on neuro-behavior, hematology, and oxidative stress biomarkers of African catfish (*Clarias gariepinus*). *Aquaculture*. 2021;544:737082.
195. Rajkumar KS, Kanipandian N, Thirumurugan R. Toxicity assessment on haemotology, biochemical and histopathological alterations of silver nanoparticles-exposed freshwater fish *Labeo rohita*. *Appl Nanosci*. 2016;6:19-29.
196. Fırat Ö, Erol R, Fırat Ö. An investigation on freshwater fish *Oreochromis niloticus* (Linnaeus, 1758): assessing hemotoxic effects of different copper compounds used as nanomaterial or pesticide. *Bull Environ Contam Toxicol*. 2022;108(3):549-554.
197. Zhao J, Wang Z, Liu X, Xie X, Zhang K, Xing B. Distribution of CuO nanoparticles in juvenile carp (*Cyprinus carpio*) and their potential toxicity. *J Hazard Mater*. 2011;197:304-310.
198. Bai W, Tian W, Zhang Z, et al. Effects of copper nanoparticles on the development of zebrafish embryos. *J Nanosci Nanotechnol*. 2010;10(12):8670-8676.
199. Remya AS, Ramesh M, Saravanan M, Poopal RK, Bharathi S, Nataraj D. 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*. 2015;27(2):151-160.
200. Karthikeyeni S, Siva Vijayakumar T, Vasanth S, Arul Ganesh MM, Subramanian P. Biosynthesis of iron oxide nanoparticles and its haematological effects on fresh water fish *Oreochromis mossambicus*. *J Acad Indus Res*. 2013;10:645-649.
201. Zhang X, Sun H, Zhang Z, Niu Q, Chen Y, Crittenden JC. Enhanced bioaccumulation of cadmium in carp in the presence of titanium dioxide nanoparticles. *Chemosphere*. 2007;67(1):160-166.
202. Sherif AH, El-Sharawy ME, El-Samannoudy SI, et al. The deleterious impacts of dietary titanium dioxide nanoparticles on the intestinal microbiota, antioxidant enzymes, diseases resistances and immune response of *Nile tilapia*. *Aquacult Res*. 2021;52(12):6699-6707.
203. Canli EG, Canli M. Nanoparticles (Al_2O_3, CuO, TiO_2) decrease ATPase activity in the osmoregulatory organs of freshwater fish (*Oreochromis niloticus*); histopathological investigations of tissues by transmission electron microscope. *Histopathol Investig Tissues Transm Electron Microsc*. 2019;7:2019.
204. Hao L, Chen L, Hao J, Zhong N. Bioaccumulation and sub-acute toxicity of zinc oxide nanoparticles in juvenile carp (*Cyprinus carpio*): a comparative study with its bulk counterparts. *Ecotoxicol Environ Saf*. 2013;91:52-60.

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