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Enhancing Aquaculture using Nanotechnology: A Review

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Abstract

The advent of nanotechnology is a laudable discovery, and to a large extent, it has the potential to solve many nagging problems in the aquaculture industry. For instance, the challenge of recurring resistance of bacteria to antibiotics, and the myriad of different antibiotics in the market coupled with their toxic effect on fish and water is a serious concern. Nanotechnology provides new tools (Nanomaterials) that can find applications in various aspects of aquaculture with little or no risk of toxicity. These include Nanosensors, DNA nano-vaccines, nano-gene delivery, smart drug delivery, nanobarcoding, fish growth enhancement using nano-selenite, nano delivery of nutraceuticals, nanofilteration, nano-polymers, nano-coating, nano-feed to improve buoyancy and availability of feed during feeding, and nano-net treatment and so on. These products are readily available in the market. They can also be synthesized for application in the areas highlighted above. This paper presents a review of nanotechnology and its application to enhance various aspects of aquaculture to find effective management strategies to solve hydra-headed challenges bedevilling the aquaculture industry by maximizing the full potential of nanomaterials.

1. Introduction

Aquaculture can be defined as the farming of aquatic organisms including fish, crustaceans, molluscs, and aquatic plants in different types of aquatic environments such as oceans, lakes, ponds, streams and rivers [1]. Although aquacultural practice has existed for over 4000 years, it became exploited on a wider scale in the mid-twentieth century [2]. In view of this, aquaculture as an emerging industry requires more research and innovation, especially with the demand for increased food production, and food security by the teaming population.

Although various technologies have been employed to solve several challenges in aquaculture, among all these technologies, nanotechnology has promising potential to deal with these challenges. It helps to improve on some of the existing viable technologies thereby increasing production, reducing environmental degradation, enhancing the ability of fish to absorb drugs, rapid disease detection and control, and consequently, ensuring food safety [3]

Nanotechnology involves the application of materials at the nanoscale with a primary size in the 1–100 nanometer range. [4]. Nanotechnology has a wide spectrum of uses which makes it possible to contribute immensely, and significantly as an evolving technology in aquaculture. Its application includes sterilization of ponds, water treatment, nano feed, detection and control of

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fish diseases, efficient delivery of nutrients and drugs etc [5]. Synthesized nanomaterials are also referred to as engineered nanomaterials. These materials are produced in different physical forms such as nanoparticles (NPs), nanorods, nanotubes, nanospheres, and nanowires etc. The main classes involving chemicals are metallic NPs or NMs e.g Silver nanoparticles (AgNPs), metal oxide (TiO_2) NP, carbon-based nanomaterials (Carbon nanotubes – CNTs), carbon fullerene spheres and quite a several composite (nanocomposites) produced from more than a single chemical substance; for instance, Chitosan-silver nanocomposite, nanoceramic, quantum dots and so on [4].

This review provides a general study on the beneficial application of nanomaterials to provide an effective management strategy to solve several problems facing the fisheries and the aquaculture industry.

2. Methodology

This review paper was carried out using different journals with high-impact factors, some of which are indexed in Scopus, Schimago, Google Scholar, Web of Science etc. Keywords or phrases used during online search include: DNA Nano Vaccine, Fish nanosensor, Nano drug delivery, Nano tagging and nano-coating of fisheries resources, Nano preservation of fish, Fishing gear and craft construction using nanomaterials, fish growth enhancement using nanoparticles, nanomaterials in wastewater treatment etc. articles were collated from full-length research articles, review paper, book chapters, yearbooks and handbooks etc. of all the materials used, only 3% of the publications are between 1990-1999; 25% were between 2000-2009, 66% are between 2011 and 2020 while only 3% are between 2021-2024. This shows that the majority of the journals used are between 2011-2020. It also revealed that more work was done within this period on nanotechnology in aquaculture than in the previous years and even in the past 3 years. The search and the review show that much more work has already been done on fish feed improvement, fish growth enhancement and nutrition than every other aspect of aquaculture using nanomaterials. This is followed by fish health management, disease diagnosis, prevention and control, and pond water treatment using nanomaterials. However, much work is still required in the following areas: nanotoxicity, post-harvest management, fishing gear and craft design using nanomaterials. In addition, mariculture (although not discussed in this review) which is another aspect of aquaculture requires an innovative approach so that several sea fish species which could not be reared in a freshwater environment can be easily domesticated, and thus make more animal protein available to the teaming population. Amid the search for new technology in solving global fisheries and aquaculture problems. The research in fisheries is still at the fundamental level and hence offers many new research opportunities.

3. Nanotechnology tools and their application in different fields of aquaculture

3.1 Enhancement of fish growth and survival rate

Research has revealed that different selenium sources (NanoSe and selenomethionine) supplements in basal diet could improve the final weight, relative gain rate, antioxidant status and glutathione peroxidase (GSH-PX) activities and muscles Se concentration on crucian carp (*Carassius auratus gibelio*). It was then discovered that NanoSe appeared to be more effective than organic selenomethionine in increasing muscle selenium content [6]. At the nano level delivery of these nutraceuticals, the growth and performance of the experimental fishes were assessed to be higher [7] [8] [9] [10].

Nanoparticles can also be used to deliver nutraceuticals in fish feed as well as in neutragenomes studies. Moreover, various nano-formulations of feed help to maintain better consistency and taste of feed. It can also be used to enhance the stability and availability of fish feed during feeding, thus preventing unnecessary wastage and pollution in aquaculture due to inappropriate texture, poor stability, and lack of buoyancy of the fish pellet [11]. In this regard, a little addition of nanomaterials will be required. For instance, the addition of single-walled carbon nanotubes to rainbow trout feed can produce a hard pellet that does not fragment easily in water. According to Ramsden *et al* [12], rainbow trout readily eat food containing up to 100 mg/kg of 1M TiO_2 NP without loss of appetite or growth rate, so the inclusion of a small quantity of Nm to fish feed to modify the physical properties of the fish pellet can be considered a practicable suggestion for the aqua-feed industry.

3.2 Nano net/ cage treatment

Treatment of fishing nets or cages using nanomaterial gives the best increase in the survival rate of fish. It increases the pH, and the water quality improves significantly. This also shows a broad and impressive prospect in aquaculture [13].

3.3 Tagging and Nanobarcoding

Nanobarcoding is a monitoring device, which consists of metallic strips containing nanoparticles where variations in the strips provide the method of encoding information. This tag has the ability to hold more information, be scanned from a distance and be used as a tracking device to monitor the metabolism, swimming pattern, and feeding behaviour of fish.

Fish nano-barcoding involves the use of DNA barcodes, a standardized DNA sequence to identify and study fish species based on their genetic profiles. It is more accurate than the conventional morphological method. Nano-barcoding helps in monitoring aquatic biodiversity and supports conservation. It helps the processing industry and exporters monitor the fish source or track the delivery status of their aqua product until it reaches the market, which makes it complies with standards and regulations. It also helps to monitor and ensure the genetic integrity of farmed fish and identify unintended hybridization. With Fish barcoding, evolutionary relationship and population genetics studies of fish species become easier, thus helping to understand their genetic diversity. Through fish barcoding, endangered species could be easily identified and protected from extinction, thus aiding conservation and effective management. Furthermore, with nanosensors and synthetic DNA tagged with colour-coded probes, nano barcode devices could detect pathogens and monitor temperature change, leakage etc, thus improving the product quality [14] [15].

3.4 Water filtration and remediation

Nano-enabled technologies are available today for the removal of contaminants from water. Nano-materials in the form of activated materials like carbon or alumina, with the additions of Zeolite and iron-containing compounds, can be used for the removal of aerobic and anaerobic biofilms, ammonia, nitrite, and nitrates contaminants. Likewise, the ultrafine nanoscale powder made from iron serves as an effective tool to reduce contaminants such as trichloroethane, carbon tetrachloride, dioxins and polychlorinated biphenyls to simpler carbon compounds which are less toxic, thus paving the way to nano aquaculture [16].

Ultra-thin membrane filters with a uniformly arrayed nanopore or nanoporous structure for nanoscale separation have been developed and can be used to separate foreign materials at nanoscale size (for enhanced filtration) including isolation or separation of nanoscale materials that require a high degree of purity and high yield of recovery with intrinsic functional and morphological characteristics remaining intact during diagnostic studies [17] [18].

Nanofiltration helps to remove a great number of foreign minute substances from water. They can also help to remove low concentrations of halogenated compounds such as pesticides, and heavy metals. Nanotech products such as iron and selenium have been successfully used in the highly integrated aquaculture industry for water remediation and better production [19].

3.5 Nanotechnology in water quality monitoring, treatment and management.

3.5.1 Water treatment using nanomaterial (Nano-863).

According to Wen *et al* [20], an experiment was performed using Nano-863 (nanometer 863) to treat water being used for growing fish, without changing the water for six months. The effect on water quality when investigated shows that NH_3-N, NO_2-N, NO_3-N, and CD were lower (0.58, 0.13, 0.89, and 8.95 respectively) when compared with that of conventional water changing (1.58, 0.28, 2.33, and 19.22). Economically, it saves the cost involved in changing water. The pH value is also higher and more tolerable (7.20) than the control group (5.60). Therefore, nano -863 can improve water quality and is more conducive to the growth of fish.

Nano-863 was also used in shrimp farming and there was a tremendous enhancement in their survival rate [15]. One million tailed shrimps were used in each of the experimental and control groups. At the end of the research, seven hundred and thirty thousand (730,000) tailed shrimps survived in the test group, while only three hundred and sixty (360,000) thousand survived in the control group; hence, the survival rate of the test group doubled that of the control group. Nano -863 can also enhance the activity and energy of water, and shrimp appetite, and promote growth and development. It also has a very strong antibacterial, and algae disease protection efficacy [21].

3.5.2 Nanocheck

Nanocheck is a water-cleaning product for swimming pools and fishponds. It has been used in cleaning fish ponds and swimming pools. It uses 40nm particles of a lanthanum-based compound which absorbs phosphate from the water and prevents the growth of algae. It is also used to remove heavy metals in water thus reducing the high cost spent in removing heavy metals. Besides, nanoscale delivery of weedicides and soil-wetting agents will be very useful for aquatic weed control in large water bodies, and mitigation of stress due to climate change and aquatic pollution [22].

3.5.3 Nanostructures and nanosensors

The development of nano biosensors allows the detection of very low concentrations of parasites, bacteria, viruses and pollutants in the water [22]. This helps to easily track the disease agent and provide an immediate solution before it gets out of control, instead of long-time conventional methods of isolation and biochemical characterization, which could lead to a serious economic impact. Therefore nanotechnology, through nanosensors and nanostructures assists in early detection and eradication of pathogens. A wide range of pathogens can be easily detected using electrical nanosensors, such as single virus particles most of which are larger than the nano-scale size (>100 nm) [20]. It was reported that immuno-target gold nanoparticles can be influenced, using a specific antibody towards biomolecules of interest. For instance, immunoglobulin G-capped gold nanoparticles, can be functionalized to bind particularly to antibodies generated against bacteria such as *Staphylococcus aureus*, and *S. pyrogenes* etc.

The use of porous nanostructures, and nanosensors such as AgNP, Titanium oxide NP, nanocomposites, and nanotubes (Carbon nanotubes) can be used to trace viruses, bacteria, other parasites and heavy metals in the fish body or pond water [20]. It is also applicable in removing chemicals, and metals in water. More so, a U.S. patent has already been filed for a “smart membrane” to remove nitrogenous wastes from water (patent number: 7632406, issue 15, Dec.2009) [4].

3.6 Harvest and Post-harvest technology

To catch fish, fishing lures are planted to reflect light to attract the attention of fish. However, these conventional lures reflect light only in one direction. To overcome this challenge, the surface of the lures is coloured and then nano-coated with a polyamide film which enhances the chance of catching fish two or three times compared to when a lure without a polyimide coating is used [14].

Efforts have been made in the food packaging industry to use nanomaterials to improve keeping quality of fishery products. Nanomaterials have properties such as antibacterial, antifungal, pathogen/toxins detection, product improvement etc. All these help to improve shelf life, freshness and product stability [23, 24, 25, 26, 27].

Quality decay such as the colour and flavour of food products can be kept or slowed down using nanostructures such as nanoemulsion, nanofibers, and nanoparticles [28, 29]. Also, there are many reports about the use of essential oils encapsulated in diverse nanostructures, including cyclic oligosaccharides [30, 31, 32] nanotubes [33, 34], polymeric nanoparticles [35, 36, 37], solid-state lipid nanoparticles [38, 39] and so on. Furthermore, nanoparticles-impregnated ice can be used for diverse food packaging applications. For example, silver nanoparticles, extracted from banana midrib and integrated into nano-ice, have been reported to reduce the microbial load on the flathead grey mullet (*Mugil cephalus*) surface and inhibit the growth of *Acinetobacter* [40]. In seafood preservation, biosynthesized silver nanoparticles are preferred to chemical synthesis [41]. In addition, some animals, such as oysters, prawns, and fish, have been used for nanoparticle synthesis. These organisms possess abundant bioactive compounds, such as minerals, oils, proteins, lipids, flavonoids, vitamins, polyphenols, fibres, polysaccharides (fucoidan, laminarin and alginate), terpenoids, and carotenoids; with many possible ethnobotanical functions [42, 43].

Different forms of chitosan nanoparticles possessing antimicrobial properties have been investigated [44]. For example, nanocomposite films produced with chitosan nanoparticles and gelatin, with the addition of certain essential oil, show high antimicrobial activity against the four common food pathogens (E. coli, *Salmonella enteritidis*, *S. aureus*, and *Listeria monocytogenes*) [43, 45]. Findings from several types of research on chitosan point out the fact that chitosan is a promising edible coating material for seafood. Seafood coated with chitosan or chitosan nanoparticles can extend their shelf life and improve their microbiological quality [46]. Chitosan is considered an efficient antimicrobial agent because of its polycationic nature [47]. Chitosan nanoparticles are highly bioactive present [48]. Many reports show that bio-nanocomposite films, made with chitosan nanoparticles and gelatin gives an improved barrier property [43]. It has also been reported that nano-chitosan is a more effective antibacterial agent, compared to coating silver carp fillets with chitosan alone (*Hypophthalmichthys molitrix*).

3.7 Nanotechnology in fish health management: Disease diagnosis, treatment and control.

The aquaculture industry has suffered serious losses due to diseases caused by pathogens [3]. At present, traditional disinfection and sterilization methods are often used to control aquatic diseases, and various chemical disinfectants, antibiotics (which often result in resistant strains or species), and other drugs are frequently used in large quantities. The cost of these chemical drugs is very high, stimulation is strong, efficiency is low, and there are numerous side effects, thus, various related problems cannot be fundamentally solved, which in turn leads to many adverse effects [21] [22] [3] [49]. However, the emergence of nanotechnology in fish disease diagnosis, treatment and control has brought great relief the to aquaculture industry. These include:

3.7.1 Use of Nano Titanium oxide

Apart from the fact that nano TiO_2 can degrade the organic pollutants in water, it also has the sterilization and disinfection ability. Under ultraviolet irradiation conditions, nano TiO_2 can produce highly active hydroxyl -OH, superoxide ion -O, peroxyl radical -OOH, and other free radicals with high oxidation capacity. These free radicals can interact with biomacromolecules, such as lipids, proteins, enzymes, and nucleic acid molecules in bacteria, viruses, and other microorganisms, which can destroy cell structures through a series of chain reactions to achieve the sterilization and disinfection effect through protein denaturation and lipolysis of bacteria, and their sterilization efficiency is much higher than that of traditional bactericide [50] [51] [52]. In natural environments, nano TiO_2 shows strong sterilization effects only in the presence of sunlight. The catalytic effect of sunlight is similar to ultraviolet without the need for additional use of artificial light, which is conducive to the promotion and application of the technology in the aquaculture industry. Nano titania and nano silver also help to reduce the build-up of bacteria in aquaculture systems [53]. Also, antibacterial coating on the fish tank wall and pipework help to prevent biofouling which is similar to polymers and films used for food packaging. This nanocoating can also be used on recirculating aquacultural systems, thus preventing biofouling or biofilm.

Nano Ti O_2 provides a desirable sterilization efficiency on certain bacteria such as *E. coli*, *Aeromonas hydrophila*, and *Vibrio angularum*. In UV light, 0.1g/L of nano Ti O_2 could reach a sterilization rate above 96% after 2 hours and it could still keep a sterilization rate above 96% after 2h in the sun. The photocatalytic sterilization efficiency of Nano Titanium oxide is a function of its concentration or reaction time. Without adequate concentration or reaction time, the sterilization will not be effective [3].

Nanotechnology has also been used to treat water pollution, which is one of the main problems in aquaculture. Water treatment, related to the photo-catalysis and adsorption efficiencies of nanomaterials, produces effective and inexpensive approaches to water purification. For example, to eliminate arsenite contamination from groundwater, magnetic konjac-glucomannan aerogels (MKGA) have been developed with green step features [54]. Nevertheless, graphene nano-sheets and graphene oxide, linked to the removal of several types of pollutants from water, have attracted tremendous attention in the last few years [55. 56]. Graphene oxide-titanium oxide nanocomposites have been used for adsorption, and removal of heavy metal and organic compounds from residual water [57, 58]. Features such as low cost, non-toxicity, efficient photo-catalysis, and biological/chemical stability point out the fact that titanium oxide is a promising candidate for wastewater treatment. Moreover, several studies have been carried out to study the photocatalytic activity of titanium dioxide, and what is responsible for its ability to destroy a wide range of Gram -negative and Gram-positive bacteria, filamentous and unicellular fungi, algae, protozoa, mammalian viruses and bacteriophages [59. It was discovered that the actual action resides in the production of reactive oxygen radicals (ROR) and peroxides that can destroy cell walls and membranes. Therefore, Nanoparticles can degrade microbes and toxins by the production of reactive oxygen species or radicals. Through the application of similar techniques, it was possible to use iron nanoparticles to break down polychlorinated biphenyls and dioxins into less toxic carbon compounds from groundwater [60].

3.7.2 DNA Nano Vaccine

The use of Chitosan and polylactide - coglycoside- acid (PLGA) of vaccine antigen together with mild inflammatory inducers will give a high level of protection to fishes and shellfish instead of oil emulsion as adjuvant which could cause major draw-back due to unacceptable level of side effect on the fishes. The protective effect of PLGA on fish is not only against bacterial disease but also on certain viral diseases. It can be applied to water-containing fish as capsules (containing nanoparticles). They contain short strands of DNA which aids its absorption into the fish cells. The capsule breaks by ultrasound mechanism which in turn releases DNA, thereby eliciting an immune response to fish due to vaccination. Oral administration of this vaccine with the release of the active agent for vaccination will reduce the cost and stress of disease management, drug administration, and vaccine delivery. This could be carried out through feeding by making the vaccine as part of the fish feed ingredients in the fish pellet, thus leading to sustainable aquaculture [61]. Mesoporous silica nanoparticles can also be used for the controlled release of vaccines or as a drug delivery matrix [62].

In a study conducted by Liu *et al*. [63], grass carp treated with an OMP-loaded PLGA nano vaccine (poly lactic-co-glycolic acid) showed a higher immune response against *A. hydrophila* infection compared to carp treated with a DNA vaccine encapsulated with single-walled carbon nanotubes. This nano vaccine induced the expression of various immune-related genes, such as interferon I (IFN-I), tumour necrosis factor (TNFα), C-reactive protein (CRP), interleukin (IL-8), IgM, MHC I, and CD8 in the kidney of grass carp. Another study by Dash *et al*. [64] demonstrated the effectiveness of OMP conjugated with PLGA and PLA nanoparticles as vaccines in *L. rohita*, providing enhanced protection against *A. hydrophila* infection. Both PLGA/PLA OMP nanoparticles exhibited promising results by activating the innate immune response in fish without any adverse effects. They also showed increased agglutinating titre, hemolytic activity, specific antibody titre, and RPS upon challenge with *A. hydrophila*. Guo et al. [65] tested specific protein-encapsulated SW-CNTs (Single wall carbon nanotubes) in zebrafish and found improved antigen delivery and prolonged immune response. Nanoparticle-encapsulated aerA vaccines demonstrated enhanced antibody production and an increased survival rate compared to the free-aerA-injected group against *A. hydrophila* infection. Vijayakumar *et al*. [66] explored the use of fucoidan-coated gold nanoparticles (FU-Au) for antimicrobial therapy in controlling *A. hydrophila* infection in *Oreochromis mossambicus*. Administration of FU-Au nanoparticles resulted in an increased survival rate and improved recovery from bacterial infection. Likewise, Dubey *et al*. [67] demonstrated the protective immunity conferred by oral administration of OmpW using PLGA nanoparticles in *Labeo rohita* against *Aeromonas* infection, suggesting its potential for prophylactic application in aquaculture farms.

3.7.3 Gene delivery

The emergence of new carrier systems for gene delivery represents an enabling technology for treating many genetic disorders. Nevertheless, a critical barrier to successful gene therapy is how to produce an efficient and safe delivery vehicle. Non-viral delivery systems have always been proposed as alternatives to viral vectors because of their safety, stability and possibility for large-scale production [68]. Some approaches employ DNA complexes which contain lipid, protein, peptide or polymeric carriers, and ligands capable of targeting DNA complexes to cell-surface receptors on the target cells, and ligands for directing the intracellular traffic of DNA to the nucleus. Highly reliable results were reported in the formation of complexes between Chitosan and DNA [69]. Although Chitosan increases transformation efficiency, the addition of appropriate ligands to the DNA chitosan complex seems to achieve a more efficient gene delivery through receptor -mediated endocytosis [70]. These results suggest that chitosan has comparable efficacy without the associated toxicity of their synthetic vectors and therefore, can be an effective gene delivery vehicle *in vivo*.

3.7.4 Smart drug delivery

Nano-scale device helps to detect and

treat infection, and health problems. With the aid of a smart delivery system that poses multifunctional characteristics such as pre-programmed, and time-controlled; monitoring the effect of the delivery of probiotics, hormones, chemicals, and vaccines can be made possible. It also helps in monitoring and improving fish health. Due to the poor stability of pharmaceuticals in water, several fish medicines are being delivered through food, hence Nm has given a better hope, being used to make new drug delivery systems for humans, which could also be used for veterinary medicine, including those for fishes. This includes a solid core drug delivery system (SCDDS). This is done by coating a solid NP with the fatty acid shell to contain the drug of interest. This approach is carried out at relatively low temperatures and pressure, making it useful for sensitive pharmaceuticals [71].

3.7.5 Nanodelivery of nutraceuticals

Most nano-encapsulated health supplements and Nutraceuticals containing nano additives such as vitamins, antimicrobials, antioxidants, flavourings, colourants, and preservatives which are used for health management, value addition, and stress mitigation in fish and shellfish is an evolving area of aquaculture research. They also help to enhance absorption and bioavailability in the body, e.g. nano calcium and nano magnesium [72].

3.8 Applications in Aquaculture systems, boats and fishing gear.

Nanotechnology offers a high abundance opportunity of new building materials, textiles, fabrics and electronic devices [73]. For engineering in aquaculture, any material that can add to the strength for fish cage construction without adding extra weight would be of great advantage. Here, Carbon nanotubes (CNT) are particularly noteworthy. CNT fibres are lightweight and very strong. New generation CNT fibres have a strength-to-weight ratio that is thirty [74] times higher than Kevlar and one hundred and seventeen [10] times than that of steel [75]. This makes CNT fibres the strongest material known to mankind.

Traditional mooring lines can be strengthened by weaving CNT fibres into the strands of the rope to increase its tensile strength beyond 10–20 GPa which is more than several of the current rope technologies [76].

4. Toxicological effects of Nanotechnology.

Currently, the potential toxicity of nanoparticles in biological systems is becoming a public concern. Nanomaterials may constitute a new source of pollutants to the environment, and research is being focused on the potential negative impact they could produce [77, 78]. Due to its extremely small size, nanoparticles can penetrate through the cell membranes and cause genotoxicity. The intrinsic chemical reactivity of nanomaterials results in higher production of reactive oxygen species and free radicals, and its production is one of the main toxicity mechanisms of nanoparticles. This may produce not only inflammation and oxidative stress but also damage to proteins and DNA. It has been demonstrated that the nanomaterial's potential to produce DNA mutation and major structural damage to mitochondria could even result in cell death [79, 80, 81]. Many studies have reported the toxic effects of nanomaterials on aquatic organisms. For instance, Omosanya, *et al* [82] reported an increased liver accumulation of six-fold with stronger toxicity of about five-fold at LC_{50} in Medeka fish-fed Selenium nanoparticles-based diet compared to the control [83]. Due to the hyperaccumulation of these nanoparticles, there was an increased oxidative stress response [84]. Likewise, oxidative stress and acute toxicity were observed in common carp (*Cyprino carpio*) when a higher dose of citrate-capped silver nanoparticles was administered [85]. Another report shows that when fed rainbow trout (*Oncorhynchus mykiss*) with feed supplemented with ZnO NPs, Zn was observed scattered all through its liver, altering metabolic processes and resulting in oxidative stress [86]. Another report on ZnONP toxicity was found in common carp juveniles, showing disruption in the effective performance of the liver and kidney when fed with 50-500mg/kg feed for 42 days. Also, Afifi *et al* [87] reported acute and sub-acute toxicity of AgNPs (Silver nanoparticles) in Tilapia tissues and brain *(O. niloticus* and *Tilapia zilli)* at 4 mg/L and 2 mg/L respectively. The result of biochemical and molecular assay shows that at 4mg/g of AgNPs, there was a total breakdown in the antioxidant system of the brain and tissues of *O. niloticus* and *Tilapia zilli* . High mortality was also recorded due to acute toxicity when silver nanoparticles were administered to Roach (Rutilus rutilus) and Goldfish (*Carassius auratus*) at 6.0 mg/L, 10.0 mg/L and 15.0 mg/L,. The incident occurred after 12 hours of AgNPs administration [88].

Finally, Several Nanotoxicology studies have been conducted to evaluate, at molecular levels, their potential risks to the environment [89] which also determines the necessary regulation to be put in place. However, a sustainable approach to the application of nanotechnology in the fisheries and aquaculture industries will require more studies. Till now, data have shown that due to the small size of the nanomaterials in food compared to the non-nanomaterials, especially when green chemistry approach is involved, there is a very low possibility of nanotoxicity if handled within the permissible limit. However uncontrolled use of nanomaterials in fisheries and aquaculture practices could impair fish health, resulting in aquatic pollution with a grave impact on the aquatic ecosystem [90, 91, 92, 93].

5. Conclusion

Nanotechnology, although still evolving, is a promising technology that is capable of taking the aquaculture industry to the next level. It will increase the standard of living since fisheries and aquaculture play a major role in food availability, economic growth and poverty alleviation. Although not yet in the mainstream, and most scientific communities are unaware of its significant potential, if effectively and efficiently deployed, it can bring economic revolutions thus fulfilling sustainable development goals 1 and 2 (SGD 1 and 2) of the World Health Organization, not only in aquaculture and fisheries industry but also in other sectors or fields of human endeavour.

Conflict of Interest

The authors declare that there is no conflict of interest in this review article

References

[1] FAO (2016). State of World Fisheries and Aquaculture 2016 (Spanish). Food and Agriculture Org., S. l., Rome.

[2] Dias J.D, Simões N.R, and Bonecker C.C (2012). Net cages in fish farming: a scientometric analysis. *Acta Limnologica Brasiliensia* 24: 12– 17.

[3] Huang S, Wang L, Liu L, Hou Y. and Li L. (2015) Nanotechnology in agriculture, livestock and aquaculture in China. A review. *Agronomy for Sustainable Development* 35: 369– 400.

[4] Handy, R.D (2012). Fish Briefing Paper: Nanotechnology in Fisheries and Aquaculture. Fisheries Society of the British isle

[5] Bhattacharyya A, Reddy S.J, Hasan M.M, Adeyemi M.M, Marye R.R (2015). Nanotechnology-a unique future technology in aquaculture for the food security. *International Journal of Bioassays* 4: 4115–4126.

[6] Zhao D, Wang J, Sun B.H, Sun B.H, Gao J.Q, and Xu R (2000). Development and application of TiO_2 photocatalysis as an antimicrobial agent. *J Liaoning Univ. (Nat. Sci. Ed.)* 2:173–174 (in Chinese with English abstract)

[7] Deng Y.S. and Chen Q. J (2003). Effects of Nano-selenium on the growth of Nile tilapia (*Oreochromis niloticus). Inland Aquat. Prod* 6:28–30 (In Chinese).

[8] Wang, Y. and Li, J. 2011. Effects of chitosan nanoparticles on survival, growth and meat quality of tilapia, *Oreochromis nilotica. Nanotoxicol*., 5(3): 425-431.

[9] Chen, Y.; Zhu, X.; Yang, Y.; Han, D.; Jin, J. and Xie, S. 2014. Effect of dietary chitosan on growth performance, haematology, immune response, intestine morphology, intestine microbiota and disease resistance in gibel carp *(Carassius auratus gibelio). Aquacult. Nutr*. 20(5): 532- 546.

[10] Abdel-Ghany, H.M. and Salem, M.E.S. 2020. Effects of dietary chitosan supplementation of farmed fish; a review. *Rev. Aquacult*., 12(1): 438-452.

[11] Handy, R. D. and Poxton, M. G. (1993). Nitrogen pollution in mariculture – toxicity and excretion of nitrogenous compounds by marine fish. *Rev Fish Biol* Fish, 3, 205–241.

[12] Ramsden, C. S., Smith, T. J., Shaw, B. S. and

Handy, R. D. (2009). Dietary exposure to titanium dioxide nanoparticles in rainbow trout, (*Oncorhynchus mykiss*): no effect on growth, but subtle biochemical disturbances in the brain. *Ecotoxicology,* 18, 939–951.

[13] Liu A.X, Cao Y.J, Dai M, and Liao Z.W (2008). Nanomaterial application in carp aquaculture experiment. Fish Modernization 2:24–27. doi: 10.3969/j.issn.1007-9580.2008.02.006, In Chinese with English abstract.

[14] Rather M.A, Sharma R, Aklakur M, Ahmad S, Kumar N, and Khan M. (2011) Nanotechnology: A novel tool for aquaculture and fisheries development. A prospective mini-review. *Fisheries and Aquaculture Journal* 16: 1– 5.

[15] Isibor, P.O; Adeogun, A.O; and Enuneku, A.A (2024): Nanocitosan-Based Enhancement of Fisheries and Aquaculture. Fish nanotagging and Barcoding. *Springer nature*. Pp 219-237.

[16] Kim, D; Lee J; Kim, B; Shin Y; Park J; Kim U; Lee, M; Kim, S.B; and Kim, S (2023): Ultral thin membrane filter with a uniformly arrayed nanopore structure for nanoscale separation of extracellular vesicles without cake formation. *Nanoscale Advances*. Royal Society of Chemistry, Vol. 5 Issue 3, 640-549. https://doi.org/10.1039/D2NA00227B

[17] Li, Q. L., Mahendra, S., Lyon, D. Y., Brunet, L., Liga, M. V., Li, D. and Alvarez, P. J. J. (2008). Antimicrobial nanomaterials for water disinfection and microbial control: Potential applications and implications. *Water Res*, 42, 4591–4602.

[18] Pradeep, T. and Anshup (2009). Noble metal nanoparticles for water purification: a critical review. *Thin Solid Films*, 517, 6441–6478.

[19] Wen J.Q, Cai D.W, Ding Y.L, Yu L.S, and Huang J.W (2003): Summary report on experiment of Qiangdi nanometer 863 biological assistant growth unit in sea shrimp farming. *J Mod Fish Inf* 10:12–15 (in Chinses with English abstract).

[20] Patolsky, F., Zheng, G. F., Hayden, O., Lakadamyali, M., Zhuang, X. W. and Lieber, C. M. (2004). Electrical detection of single viruses. *Proc. Nat Acad. Sci*. U S A, 101, 14017–14022.

[21] Yang X.L (2003). Drug residue status in our country's aquatic products and control countermeasures. *Aquat Prod Sci Technol Inf* 2:68–71 (in Chinese

[22] Gjedrem, T (2015): Disease resistant fish and shellfish are within reach: a review. *Journal of Marine Science and Engineering* 3: 146– 153.

[23] Jiang, X., Valdeperez, D., Nazarenus, M., Wang, Z., Stellacci, F., Parak, W. J., & del Pino, P. (2015). Future perspectives towards the use of nanomaterials for smart food packaging and quality control. Particle & Particle Systems Characterization, 32(4), 408–416. https://doi.org/10.1002/ppsc.201400192

[24] Kumar, H., Kuˇ ca, K., Bhatia, S. K., Saini, K., Kaushal, A., Verma, R., Bhalla, T. C., & Kumar, D. (2020). Applications of nanotechnology in sensor-based detection of foodborne pathogens. *Sensors*, 20(7), 1966. https://doi.org/10.3390/s20071966

[25] Kuswandi, B. (2016). Nanotechnology in food packaging. In S. Ranjan, N. Dasgupta, & E. Lichtfouse (Eds.), Nanoscience in food and agriculture 1. Sustainable agriculture reviews (Vol. 20). *Cham: Springer*. https://doi.org/10.1007/978-3-319-39303-2_6.

[26] Mihindukulasuriya, S. D. F., & Lim, L. T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology*, 40 (2), 149–167. https://doi.org/10.1016/j.tifs.2014.09.009

[27] Sibaja-Luis, A. I., Ramos-Campos, E. V., de Oliveira, J. L., & Fernandes, L. (2019). Trends in aquaculture sciences: From now to use of nanotechnology for disease control. *Reviews in Aquaculture*, 11(1), 119–132. https://doi.org/10.1111/raq.12229

[28] Chellaram, C., Murugaboopathi, G., John, A. A., Sivakumar, R., Ganesan, S., Krithika, S., Krithika, S., & Priya, G. (2014). Significance of nanotechnology in food industry. *APCBEE Procedia*, 8, 109 –113. https://doi.org/10.1016/j.apcbee.2014.03.010

[29] Ozogul, Y., Yuvka, I., Ucar, Y., Durmus, M., Kosker, A. R., Oz, M., & Ozogul, F. (2017). Evaluation of effects of nanoemulsion based on herb essential oils (rosemary, laurel, thyme and sage) on sensory, chemical and microbiological quality of rainbow trout *(Oncorhynchus mykiss*) fillets during ice storage. LWT-*Food Sci.Tech.,* 75, 677–684. https://doi.org/10.1016/j.lwt.2016.10.009

[30] Abarca, R. L., Rodrıguez, F. J., Guarda, A., Galotto, M. J., & Bruna, J. E. (2016). Characterization of beta-cyclodextrin inclusion complexes containing an essential oil component. *Food Chemistry*, 196, 968–975. https://doi.org/10.1016/j. foodchem.2015.10.023

[30] Abarca, R. L., Rodrıguez, F. J., Guarda, A., Galotto, M. J., & Bruna, J. E. (2016). Characterization of beta cyclodextrin inclusion complexes containing an essential oil component. *Food Chemistry*, 196, 968–975. https://doi.org/10.1016/j.foodchem.2015.10.023

[31] Hill, L. E., Gomes, C., & Taylor, T. M. (2013). Characterization of beta-cyclodextrin inclusion complexes containing essential oils (trans-cinnamaldehyde, eugenol, cinnamon bark, and clove bud extracts) for antimicrobial delivery applications. LWT -*Food Sci.Tech.,* 51(1), 86–93. https://doi.org/10.1016/j.lwt.2012.11.011

[32] Siqueira-Lima, P. S., Araujo, A. A. S., Lucchese, A. M., Quintans, J. S., Menezes, P. P., Alves, P. B., de Lucca, W., Santos, M. R. V., Bonjardim, L. R., & Quintans-Junior, L. J. (2014). b-cyclodextrin complex containing Lippia grata leaf essential oil reduces orofacial nociception in mice – evidence of possible involvement of descending inhibitory pain modulation pathway. *Basic and Clinical Pharmacology and Toxicology*, 114, 188–196. https://doi.org/10.1111/bcpt.12145

[33] Kim, J., Park, N., Na, J. H., & Han, J. (2016). Development of natural insect-repellent loaded halloysite nanotubes and their application to food packaging to prevent Plodia interpunctella infestation. *Journal of Food Science*, 81(8), E1956–E1965. https://doi.org/10.1111/1750-3841.13373

[34] Lee, S. B., Kim, J. Y., Kim, K., Ahn, K. J., Kim,

T., & Oh, J. M. (2020). Encapsulation and release control of fish pathogen utilizing cross-linked alginate networks and clay nanoparticles for use with a potential oral vaccination. *Applied Sciences*, 10(8), 2679. https://doi.org/10.3390/app10082679

[35] Christofoli, M., Costa, E. C. C., Bicalho, K. U., de Cassia-Domingues, V., Peixoto, M. F., Fernandes-Alves, C. C., Araujo, W. L., & de Melo-Cazal, C. (2015). Insecticidal effect of nanoencapsulated essential oils from *Zanthoxylum rhoifolium* (Rutaceae) in Bemisia tabaci populations. *Industrial Crops and Products*, 70, 301–308. https://doi.org/10.1016/j.indcrop.2015.03.025

[36] De Oliveira, E. F., Paula, H. C. B., & de Paula, R. C. M. (2014). Alginate/cashew gum nanoparticles for essential oil encapsulation. *Colloids and Surfaces* B, 113, 146–151. https://doi.org/10.1016/j.colsurfb.2013.08.038

[37] Liakos, I. L., Grumezescu, A. M., Holban, A. M., Florin, I., D'Autilia, F., Carzino, R., Bianchini, P., & Athanassiou, A. (2016). Polylactic acid—lemon grass essential oil nanocapsules with antimicrobial properties. *Pharmaceuticals*, 9(3), 42. https://doi.org/10.3390/ph9030042

[38] Cortes-Rojas, D. F., Souza, C. R. F., & Oliveira, W. P. (2014). Encapsulation of eugenol rich clove extract in solid lipid carriers. *Journal of Food Engineering*, 127, 34–42 https://doi.org/10.1016/j.jfoodeng.2013.11.027

[39] Moghimipour, E., Ramezani, Z., & Handali, S. (2013). Solid lipid nanoparticles as a delivery system for Zataria multiflora essential oil: Formulation and characterization. *Current Drug Delivery*, 10, 151–157. https://doi.org/10.2174/1567201811310020001

[40] Daniel, S. K., Sureshkumar, V., & Sivakumar, M. (2016). Nano ice based on silver nanoparticles for fish preservation. *International Journal of Fisheries and Aquaculture Studies*, 4(5), 162–167

[41] Huang, Y., Mei, L., Chen, X., & Wang, Q. (2018). Recent developments in food packaging based on nanomaterials. *Nanomaterials*, 8(10), 830. https://doi.org/10.3390/ nano8100830

[42] Kushnerova, N. F., Fomenko, S. E., Sprygin, V. J., Kushnerova, T. V., Khotimchenko, Y. S., Kondrateva, E. V., and Drugova, L. A. (2010). An extract from the brown alga Laminaria japonica: A promising stress-protective preparation. *Russian Journal of Marine Biology*, 36(3), 209–214. https://doi.org/10.1134/S1063074010030077

[43] Hosseini, S. F., Rezaei, M., Zandi, M., & Farahmandghavi, F. (2016). Development of bioactive fish gelatin/chitosan nanoparticles composite films with antimicrobial properties. *Food Chemistry*, 194, 1266–1274. https://doi.org/10.1016/j.foodchem.2015.09.004

[44] O'Callaghan, K. A., & Kerry, J. P. (2016). Preparation of low-and medium-molecular weight chitosan nanoparticles and their anti-microbial evaluation against a panel of microorganisms, including cheese-derived cultures. *Food Control*, 69, 256–261. https://doi.org/10.1016/j.foodcont.2016.05.005

[45] Hosseini, S. F., Rezaei, M., Zandi, M., & Farahmandghavi, F. (2015). Fabrication of bio- nanocomposite films based on fish gelatin reinforced with chitosan nanoparticles. *Food Hydrocolloids*, 44, 172–182. https://doi.org/10.1016/j.foodhyd.2014.09.004

[46] Mohan, C. O., Ravishankar, C. N., Lalitha, K. V., & Gopal, T. S. (2012). Effect of chitosan edible coating on the quality of double filleted Indian oil sardine (*Sardinella longiceps*) during chilled storage. *Food Hydrocolloids*, 26(1), 167–174. https://doi.org/10.1016/j.foodhyd.2011.05.005

[47] Suptijah, P. Y., Gushagia, D., & Sukarsa, D. R. (2008). Study of inhibitory effects of chitosan on quality deterioration of catfish (*Pangasius hypopthalmus*) fillet at room temperature storage. *JPHP*I, 11(2), 89101

[48] Yang, Z., Yue, G. H., & Wong, S. M. (2021). VNN disease and status of breeding for resistance to NNV in aquaculture. *Aquac. Fish*.. https://doi.org/10.1016/j. aaf.2021.04.001

[49] Lafferty K.D, Harvell C.D, Conrad J.M, Friedman C.S, Kent M.L, and Kuris A.M. (2015) Infectious diseases affect marine fisheries and aquaculture economics. *Annual Review of Marine Science* 7: 471– 496.

[50] Yu J.C, Tang H.Y, and Yu J.G (2002). Bacterieadal and photocatalytic activities of TiO_2 thin films prepared by sol–gel and reverse micelle methods. *J Photochem Photobiol A Chem* 3:211–219. https://doi.org/10.1016/S1010- 6030(02)00275-7.

[51] Sonawane R.S, Hegde S.G, and Dongare M.K (2003): Preparation of titanium (VI) oxide thin film photocatalyst by sol–gel dip coating. *Material Chemistry and Physic* 3:744–746. https://doi.org/10.1016/S0254-0584(02)00138-4

[52] Zhou X, Wang Y, Gu Q, and Li W, (2009). Effects of different dietary selenium sources (selenium nanoparticle and selenomethionine) on growth performance, muscle composition and glutathione peroxidase enzyme activity of crucian carp (*Carassius auratus gibelio). Aquaculture*, 291: 78-81.

[53] M¨uhling, M., Bradford, A., Readman, J. W., Somerfield, P. J. and Handy, R. D. (2009). An investigation into the effects of silver nanoparticles on antibiotic resistance of naturally occurring bacteria in an estuarine sediment. *Mar Environ Res*, 68, 278 –283.

[54] Ye, S., Jin, W., Huang, Q., Hu, Y., Shah, B. R., Li, Y., & Li, B. (2016). Development of Mag-FMBO in clay-reinforced KGM aerogels for arsenite removal. *International Journal of Biological Macromolecules*, 87, 77–84. https://doi.org/10.1016/j.ijbiomac.2016.01.087

[55] Liu, L., Cui, Z., Ma, Q., Cui, W., & Zhang, X. (2016). One-step synthesis of magnetic iron–aluminum oxide/graphene oxide nanoparticles as a selective adsorbent for fluoride removal from aqueous solution. *RSC Advances*, 6(13), 10783–10791.

[56] Motamedi, E., Talebi-Atouei, M., & Kassaee, M. Z. (2014). Comparison of nitrate removal from water via graphene oxide coated Fe, Ni and Co nanoparticles. *Materials Research Bulletin*, 54, 34–40. https://doi.org/10.1016/j.materresbull.2014.02.019

[57] Atchudan, R., Edison, T. N. J. I., Perumal, S., Karthikeyan, D., & Lee, Y. R. (2017). Effective photocatalytic degradation of anthropogenic dyes

using graphene oxide grafting titanium dioxide nanoparticles under UV-light irradiation. *Journal of Photochemistry and Photobiology A: Chemistry*, 333, 92–104. https://doi.org/10.1016/j.jphotochem.2016.10.021

[58] Hu, C., Lu, T., Chen, F., & Zhang, R. (2013). A brief review of graphene–metal oxide composites synthesis and applications in photocatalysis. *Journal of Chinese Advanced Materials and Society*, 1 (1), 21–39. https://doi.org/10.1080/22243682.2013.771917

[59] Foster, H. A., Ditta, I. B., Varghese, S., & Steele, A. (2011). Photocatalytic disinfection using titanium dioxide: Spectrum and mechanism of antimicrobial activity. *Applied Microbiology and Biotechnology*, 90(6), 1847–1868. https://doi.org/10.1007/s00253- 011-3213-7

[60] Majumder, D., & Dash, G. (2017). Application of nanotechnology in fisheries and aquaculture. *Everyman Sci,* 51(6), 358–364. Retrieved from http://www.sciencecongress.nic.in/pdf/e-book/Feb17-March17.pdf. (Accessed 16 December 2021)

[61] Rajeshkumar S, Venkatesan C, Sarathi M ,Sarathbabu V, Thomas J, Anver Basha K, Sahul and Hameed A.S. (2009). Oral delivery of DNA construct using chitosan nanoparticles to protect the shrimp from white spot syndrome virus (WSSV). *Fish & Shellfish Immunology, 26:* 429-437.

[62] Stromme, M., Brohede, U., Atluri, R. and Garcia-Bennett, A. E. (2009). Mesoporous silica- based nanomaterials for drug delivery: evaluation of structural properties associated with release rate. Wiley Interdisciplinary *Rev Nano medicine Nano biotechnology*, 1, 140–148.

[63] Liu X., Gao H., Xiao N., Liu Y., Li J., Li L. Outer membrane protein U (OmpU) mediates adhesion of *Vibrio mimicus* to host cells via two novel N-terminal motifs. *PLoS ONE.* 2015;10:e0119026. https://doi.org/10.1371/journal.pone.0119026.

[64] Dash P., Yadav S.K., Garg L.C., Dixit A., Sahoo P.K. Post-challenge immune gene expression profiling in rohu, *Labeo rohita* vaccinated with modified adjuvant-based *Aeromonas hydrophila* outer membrane protein R formulation. *Vet. Arh.* 2017;87:607–622. https://doi.org/10.24099/vet.arhiv.160430.

[65] Guo Z., Lin Y., Wang X., Fu Y., Lin W., Lin X. The protective efficacy of four iron related recombinant proteins and their single-walled carbon nanotube encapsulated counterparts against *Aeromonas hydrophila* infection in zebrafish. *Fish Shellfish Immunol.* 2018;82:50–59. https://doi.org/10.1016/j.fsi.2018.08.009.

[66] Vijayakumar S., Vaseeharan B., Malaikozhundan B., Gobi N., Ravichandran S., Karthi S., Ashokkumar, B., Sivakumar N. A novel antimicrobial therapy for the control of *Aeromonas hydrophila* infection in aquaculture using marine polysaccharide coated gold nanoparticle. *Microb. Pathog.* 2017;110:140–151. https://doi.org/10.1016/j.micpath.2017.06.029.

[67] Dubey S., Avadhani K., Mutalik S., Sivadasan S.M., Maiti B., Paul J., Girisha S.K., Venugopal M.N., Mutoloki S., Evensen Ø., et al. *Aeromonas hydrophila* OmpW PLGA nanoparticle oral vaccine shows a dose-dependent protective immunity in rohu (*Labeo rohita*) *Vaccines.* 2016;4:21. https://doi.org/10.3390/vaccines4020021.

[68] Tomlinson E, and Rolland A.P, (1996). Controllable gene therapy pharmaceutics of non-viral gene delivery systems. *Journal of Controlled Release*, 1: 357-372.

[69] Roy K, Mao HQ, and Leong KW, (1997). DNA-chitosan nanospheres: Transfection efficiency and cellular uptake. *Proceedings of the Controlled Release Society*, 24: 673-674.

[70] Murata J, Ohya Y, and Ouchi T. (1998). Design of quaternary chitosan conjugate having antennary galactose residues as a gene delivery tool. *Carbohydrate Polymers*, 32 (2): 105-109.

[71] Mitchell, J. and Trivedi, V. (2010). Pharmaceutical nanomaterials: The preparation of solid core drug delivery systems (SCDDS*). J Pharm Pharmacol*, 62, 1457–1458.

[72] FOE (Friends of the Earth) (2008). Out of the laboratory and onto our plates: Nanotechnology in food and agriculture. [http://www.foe.org/]

[73] Can E, Kizak V, Kayim M, Can S.S, Kutlu B, Ates M, Kocabasl M, Demirtas N (2011). Nanotechnological applications in aquaculture-seafood industries and adverse effects of nanoparticles on environment. J *Mater Sci Eng* 5:605–609.

[74] Aitken, R. J., Chaudhry, M. Q., Boxall, A. B. A. and Hull, M. (2006). Manufacture and use of nanomaterials: current status in the UK and global trends. *Occup Med (Lond*), 56, 300–306.

[75] Chang, C. C., Hsu, I. K., Aykol, M., Hung, W. H., Chen, C. C. and Cronin, S. B. (2010). A new lower limit for the ultimate breaking strain of carbon nanotubes. *ACS Nano*, 4, 5095–5100.

[76] Chae, H. G. and Kumar, S. (2006). Rigid-rod polymeric fibers. *J Appl Polymer Sci*, 100, 791–802.

[77] Moore, M. N. (2006). Do nanoparticles present ecotoxicological risk for the health of the aquatic environment. *Environment International*, 32, 967–976. https://doi.org/ 10.1016/j.envint.2006.06.014

[78] Shah, B. R., & Mraz, J. (2019). Advances in nanotechnology for sustainable aquaculture and fisheries. *Reviews in Aquaculture*, 1–18. https://doi.org/10.1111/raq.12356

[79] Majumder, D., & Dash, G. (2017). Application of nanotechnology in fisheries and aquaculture. *Everyman Sci*, 51(6), 358–364. Retrieved from http://www.sciencecongress.nic.in/pdf/e-book/Feb17-March17.pdf. (Accessed 16 December 2021).

[80] Meghani, N., Dave, S., & Kumar, A. (2020). Introduction to nanofood. In U. Hebbar, S. Ranjan, N. Dasgupta, and R. Kumar Mishra (Eds.), Nano-food engineering. *Food engineering Series. Cham: Springer*. https://doi.org/10.1007/978-3-030-44552-2_1.

[81] Vicari, T., Dagostim, A. C., Klingelfus, T., Limberger-Galvan, G., Sampaio-Monteiro, P., da Silva-Pereira, L., Silva-de Assis, H. C., & Cestari, M. M. (2018). Co-exposure to titanium dioxide nanoparticles (NpTiO2) and lead at environmentally relevant concentrations in the Neotropical fish species *Hoplias intermedius*. *Toxicology Reproductive*, 5, 1032–1043. https://doi.org/10.1016/j.toxrep.2018.09.001

[82] Omosanya T.A., Yekeen T.A. , Fawole O.O., Azeez M.A., Lateef A. and Ajala O.O. 2021. Applications and Benefits of Dietary Nanoparticles in Aquaculture: A Review. Stnanomat Journal. *Vol 2, Issue 1, Article number: 13 (Oct, 2021)* https://doi.org/10.48187/stnanomat.2021.2.010

[83] Li, H., Zhang, J., Wang, T., Luo, W., Zhou, Q., Jiang, G. (2008). Elemental selenium particles at nano-size (Nano-Se) are more toxic to Medaka (*Oryzia slatipes*) as a consequence of hyper-accumulation of selenium, a comparison with sodium selenite. *Aquaculture toxicology*. 89:251-256 https://doi.org/10.1016/j.aquatox.2008.07.008.

[84] Lee, B., Duong, C.N., Cho, J., Lee, J., Kim, K., Seo, Y. (2012). Toxicity of citrate-capped silver nanoparticles in common carp (Cyprinus carpio). *BioMedical Resources International* 2012: 1–14. https:// doi.org/10.1155/2012/262670

[85] Connolly, M., Fernandez, M., Conde, E., Torrent, F., Navas, J.M., Fernandez-Cruz, M.L. (2016). Tissue distribution of zinc and subtle oxidative stress effects after dietary administration of ZnO nanoparticles to rainbow trout. *Science of the Total Environment* 551: 334–343.

[86] Chupani, L., Niksirat, H., Valset, J., Stara, A., Hrdilova, S., Kolark, J (2018). Chronic dietary toxicity of Zinc oxide nanoparticles in common carp (*Cyprinus carpio* L.): Tissue accumulation and physiological responses. *Journal of ecotoxicology and environmental safety*. 147:110-116. https://doi.org/10-1016/j.ecoenv.2017.08.024

[87] Afifi, M., Saddick, S., Abu Zinada, O.A. (2016). Toxicity of silver nanoparticles on the brain of *Oreochromis* niloticus and *Tilapia zillii.* Saudi Journal of Biological Sciences 23: 754–760. https://doi.org/10.1016/j.sjbs.2016.06.008

[88] Yalsuyi, A.M., Vajargah, M.F. (2017). Acute toxicity of silver nanoparticles in Roach (*Rutilus rutilus*) and Goldfish (*Carassius auratus*). *Journal of Environmental Treatment and Technology* 5: 1–4. https://ww.researchgate.netpublication/313694874

[89] Bello, D., and Leong, D. T. (2017). A decade of nanotoxicology: Assessing the impact on human health and the environment. *NanoImpact,* 7, 15–16. https://doi.org/ 10.1016/j.impact.2017.04.001

[90] Handy, R., von der Kammer, F., Lead, J., Hassellov, M., Owen, R., & Crane, M. (2008). The ecotoxicology and chemistry of manufactured nanoparticles. *Ecotoxicology*, 17, 287–314. https://doi.org/10.1007/s10646-008-0199-8

[91] Khosravi-Katuli, K., Prato, E., Lofrano, G., Guida, M., Vale, G., and Libralato, G. (2017). Effects of nanoparticles in species of aquaculture interest. Environmental Science & Pollution Research, 24 (21), 17326–17346. https://doi.org/10.1007/s11356-017- 9360-3

[92] Ramsden, C. S., Smith, T. J., Shaw, B. S., and Handy, R. D. (2009). Dietary exposure to titanium dioxide nanoparticles in rainbow trout, *(Oncorhynchus mykiss*): No effect on growth, but subtle biochemical disturbances in the brain. *Ecotoxicology,* 18, 939–951. https://doi.org/10.1007/s10646-009-0357-7

[93] Shaw, B., and Handy, R. D. (2011). Physiological effects of nanoparticles on fish: A comparison of nanometals versus metal ions. *Environment International*, 37(6), 1083–1097. https://doi.org/10.1016/j.envint.2011.03.009.