NANOTECHNOLOGY FOR SUSTAINABLE DEVELOPMENT IN FISHERIES AND AQUACULTURE: A COMPREHENSIVE REVIEW

Abstract

This review presents an overview and analysis of potential uses of nanotechnology in the fishery and aquaculture domains, while also investigating their potential for advancing sustainable development in these industries. A comprehensive overview will be provided, highlighting the various applications of nanotechnology and elucidating their biological effects on fish, as well as their influence on the productivity of the aquaculture sector. Furthermore, this chapter will delve into the current state and prospects of nanotechnology in areas such as fish feed formulation, packaging, storage, materials for aquaculture manufacturing such as fishing containers, water quality monitoring, and fish medicines delivery by ensuring a thorough exploration of these subjects.

Keywords: Nanotechnology, Aquaculture, Fishery, Sustainable development.

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I. INTRODUCTION

Aquaculture, the fastest-growing sector, is essential to fulfill the demand for animal proteins, fats, and other micronutrients. However, aquaculture's tremendous growth potential is being hampered by various factors such as water scarcity, pollution, and climate change. There is a lot of potential for nanotechnology as an effective tool in various aspects of aquaculture like fish breeding, fish diet, genetics of fishes, fish pathology, and maintenance of ecological quality. Particularly the use of nanoelement-enriched feed has been shown to purposefully enhance fish growth, while novel nanomaterials are being used in aquatic systems to remove pollutants and reduce treatment costs. The use of materials at the nanoscale is known as nanotechnology, which leads to the development of novel products and processes with a wide range of social benefits. [1]. Man-made nanomaterials are also known as engineered nanomaterials and range is < 100 nm [2,3]. NMs have a primary size in the range of 1–100 nm [4]. NMs can be formed into a variety of shapes, such as nanofilms, nanowires, nanotubes, and NPs, which can be spherical or rod-shaped. The incorporation of manufactured NMs into products can take place in a variety of ways, including as surface coatings, laminates, or materials dispersed throughout a product's matrix [5,6].

Nanotechnology has great potential for a variety of disciplines, including physics, chemistry, and biology, because of its wide range of potential applications. Nanotechnology's interdisciplinary nature is evident in both the aquaculture and agricultural industries. The highly integrated fish farming sector is one of the best industries for incorporating and marketing nanotechnological products [7]. This field utilizes nanomaterials, nanosensors, DNA nano vaccines, fluorescent biological labels for drug delivery, gene delivery, DNA structure probing, pathogen detection, and the separation and purification of biological molecules and cells. Additionally, nanotechnology finds expanding applications in aquaculture, fish biotechnology, fish genetics, fish reproduction, and fish health management. In the fish processing industry, the application of nanotechnology enables the rapid detection of fish bacteria in packaging, enhances flavour intensity, and improves the colour quality [8]. It is a rapidly growing industry that holds immense economic value, amounting to billions of dollars. The field offers numerous potential societal benefits across various domains and the existing advancements in nanotechnology can be applied to the fisheries and aquaculture sectors, introducing innovative solutions to the fishery industry. [9, 10]. The application of nanomaterials has made a significant contribution to the fishery sector which has increased the production capacity of the sector in a sustainable manner. Scientists believe that if farmers use such applications properly then they can produce more than the old methods and become economically self-sufficient. Our world is becoming increasingly populated and food shortages are becoming a major problem as people are running out of agricultural land and water. Therefore, production must be increased in the remaining areas.Various ongoing researches have shown that proper application of nanomaterials has benefited various aspects of fish farming, for example, fish medicine, disease control, fishing gear application, etc. In addition, nanomaterials have been found to be beneficial in fish preservation, packaging, etc. This chapter aims to provide a comprehensive overview of the emerging field of nanotechnology and its potential contributions to the sustainable development of fisheries and aquaculture. The review also addresses the current state of research and development in nanotechnology for fisheries and aquaculture, highlighting recent advancements, successful case studies, and ongoing challenges. It underscores the need for interdisciplinary collaboration, knowledge sharing, and policy support to facilitate the responsible and sustainable integration of nanotechnology into these industries. Figure 1 illustrates the diverse applications of nanotechnology in the aquaculture and fishery industries.

Figure 1: Showing various applications of nanotechnology in fisheries and aquaculture.

II. NANOTECHNOLOGY IN AQUACULTURE AND FISHERY

1. **Water Quality Management:** Non-contaminated water with the ideal range of water quality parameters, such as pH, dissolved oxygen, ammonia, etc., is crucial for the productive fish culture system. Nanotechnology has numerous applications which have a significant impact on water filtration and purification, water quality monitoring, and fish health diagnostics [11]. Nanotechnology also offers cost-effective, high-performance in wastewater treatment, pond sterilisation, aquatic disease detection, and their control [12-14]. Different nanotechnology-based techniques are employed to treat wastewater, desalinate seawater, and purify contaminated water. Nano-adsorption processes are utilized to eliminate pollutants, nano-photocatalysis is employed to break down contaminants, nanosensors are used to detect pollutants, and various membrane technologies, including nanofiltration, are employed [15, 16]. Moreover, by lowering the costs and toxic side effects of conventional disinfectants, nanotechnology can increase the disinfection efficiency of water sources [12], and numerous antimicrobial nanomaterials could play a part in disinfection and microbial control [17]. The carbon nanotubes can be used to absorb industrial wastewater that contains toxic dyes, nitro and amino compounds, and heavy metals like zinc, copper, arsenic, and chromium [18]. It is possible to use the antimicrobial qualities of NMs like nano titania and nano silver [19] to lessen the accumulation of bacteria in the aquaculture system. The use of nanotechnology in water purification as antibacterial nanomaterials (NMs) are used to eliminate pathogens, thereby ensuring water safety and preventing the proliferation of harmful microorganisms [17]. A nanoscale powder made of iron can be utilised as a valuable tool for cleaning up contaminants such as trichloroethane, carbon tetrachloride, polychlorinated biphenyls, and dioxins to simpler carbon compounds that are less harmful, paving the way for nano-aquaculture [8]. The chitosan nanoparticles are used as adsorbents to remove heavy metals, from clays like kaolinite, bentonite, and montmorillonite [20, 21].

2. **Fish Food and Packaging Industry:** The food industry already employs nanotechnology in various ways. [22, 23]. The nanopolymers and coatings could be used to fortify food packaging and safeguard delicate fish fillets [24.]. Antibacterial nanocoatings and transparent polymer films can be used to prevent oxygen from entering the bodies of fish and shellfish because they have a limited shelf life. In contrast to some conventional plastics [25], nano packaging can be made from natural nanoscale polymers like cellulose and starch or chitosan particles as they are likely to be biodegradable. [24]. Due to microbial activity, fresh fish products spoil, so antimicrobial and antifungal surfaces can be used for packaging to reduce spoilage [24, 26] e.g the antibacterial properties of nanosilver are very well-known. [19]. Nanotechnology has the potential in identifying gases emitted from deteriorating fish fillets, including carbon dioxide, which can be crucial for ensuring the freshness of the fish [27]. For the preservation of flavour and quality of fish oil, nanoencapsulation techniques used maltodextrin in combination with surface-active biopolymers like starch or whey protein concentrate [28]. Nanoencapsulation methods can be employed to safeguard fish oil and improve its durability throughout the processing and storage stages. The preservation of fish can be achieved by utilizing Nano Ice infused with antimicrobial properties, incorporating silver nanoparticles synthesized through biological processes for increased biocompatibility rather than relying on chemical means. Additionally, exploring further applications of nanoparticle-impregnated ice in the realm of food packaging is worth investigating [29].

   Besides other applications, the use of Nanomaterials in aquafeeds has potential benefits. Micronutrients or other unstable ingredients can be delivered to fish by using methods of nanotechnology in an efficient way [30-32]. On examining the effects of different selenium nanoparticles and selenomethionine on the growth performance of crucian carp. As a result, in comparison to the control group, the groups treated with selenium nanoparticles and selenomethionine showed significantly higher relative growth rates (RGRs) and final weights. Scientists from the Russian Academy of Sciences discovered that when young carp and sturgeon were fed iron nanoparticles, their growth rates increased (30% and 24%, respectively) [33]. Using nanodevice in seawater shrimp aquaculture could increase the shrimp survival rate, and yield [34]. Additionally, nano supplementation can reduce oxidative stress and increase the productivity of fish and livestock [35]. Nanotechnology provides various protection and packaging methods to ensure product safety by preventing enzymatic and microbial spoilage in seafood [36, 37]. The use of Se nanoparticles in fisheries and livestock enhances development, immunomodulation, reproduction, digestion, and toxicity concentration in comparison to other forms of Se [38].

3. **Nanotechnology in Fish Health Management:** The disease is a major constraint in the aquaculture industry, causing farmers to lose millions of dollars each year around the globe. Nanotechnological applications in fish health management include the use of antibacterial surfaces in the aquaculture system, the effective nano-delivery of veterinary medicines in fish food using porous nanostructures, and nanosensors for detecting pathogens in the water. There is a significant emphasis on utilizing nanoparticles as additives and effective carriers in the advancement of fish vaccines as nanoparticles possess the ability to enhance the relative surface area and quantum size effects. Nanotechnological methods can deliver fish vaccines effectively and nanosensors can

detect various pathogens, with electrical nanosensors can detect individual virus particles [39].

4. **Nanomedicine in Aquaculture:** Nanomedicine, an emerging field within nanotechnology, has considerable prospects for monitoring and improving fish health. By utilizing nanomaterials in drug delivery systems, like those employed in human medicine, it becomes possible to deliver to the fish as well [40]. The solid core drug delivery systems (SCDDS) entail enclosing a solid nanoparticle with a fatty acid shell to ensure drug retention within the system [41]. Various researchers have found that using synthetic polymers to encapsulate antigens in live delivery systems, such as carbon nanotubes, alginate nanoparticles, nanoliposomes, and chitosan nanoparticles, enhances antigen uptake and increases the production of antibodies in fish [42-45]. The nanotechnological approaches aid in drug stability, release control, and efficient drug delivery. Nanoparticles, due to their small size, can be taken up by various intracellular trafficking pathways such as phagocytosis and endocytosis, facilitating antigen uptake and presentation to immune cells.[46-49]. The chitosan nanoparticles make excellent drug delivery systems as they are non-toxic, biocompatible, and biodegradable polymers that are easily excreted by the kidney [50]. Additionally, they release medications gradually and sustainably as they are mucoadhesive [51]. Numerous diseases in the aquaculture sector result in significant yearly losses [52], and the Nano-biosensor may make it easier to detect low concentrations of pathogens like viruses, bacteria, parasites, and pollutants. Gold nanoparticles are one of the most used particles in diagnostics and are appropriate for use in a variety of methods [53-54]. *Escherichia coli* and *Salmonella typhi* were both susceptible to the bactericidal properties of gold nanoparticles supported on zeolite [55]. Gold nanoparticles have been found to have fungicidal activity against Candida species. Smaller gold nanoparticles had stronger antifungal effects, and their efficacy was size-dependent [56,57]. Like the pharmaceutical antifungal Amphotericin B, silver nanoparticles have high inhibitory effects against Candida species [58,59]. It has also been observed that silver nanoparticles have antifungal activity against dermatophytes [60]. Antibacterial and antifungal properties are present in zinc oxide nanoparticles and they can prevent the growth of a variety of bacteria and are used in fish medicine [61, 62]. Silver nanoparticles are a type of nano-antibacterial agent that works against bacteria through a variety of mechanisms, enabling them to evade bacterial resistance [63]. The antibacterial efficacy of silver nanoparticles against multi-drug resistant bacterial isolates is high [64]. For quick and accurate disease diagnosis, nanoparticles have been used; this field of detection is known as nanodiagnostics [65].

5. **Reproductive Effectiveness:** The fishes fed with selenium nanoparticle-supplemented [Se-N] plant protein [PP]-rich diets had higher spermatozoa density, spermatozoa motility, and highest spermatozoa with straight movement than fish fed fish meal [FM]-based diets without Se-N. Furthermore, males fed a Se-N-supplemented diet had a lower percentage of spermatozoa with pendulum-like motility. The longevity of spermatozoa motility was greater in a PP-rich diet supplemented with Se-N than in an FM-based diet. Further research revealed a negative correlation between dietary Se-N and sperm pendulum movement, suggesting that dietary Se in A. arabicus was essential for male fertility [66]. The dietary Se deficiency can decrease sperm motility by causing morphological changes and abnormal chromatin condensation, which ultimately results in fertilisation failure [67]. nanotechnology can be used to detect sexual maturity which is

helpful in animal breeding as real-time measurement of changes in the level of estradiol in the blood is possible. In this process, a nanotube is fixed beneath the skin of the targeted species as nanotubes can bind and detect the estradiol antibody at track sexual maturity [68]. A Radio Frequency ID [Rfid] chip integrated with a nanoscale component can be utilised as a tracking tool as well as a tool for the observation of fish metabolism, swimming patterns, and feeding behaviour [7]

6. **Nanomaterials in Fishing Gears and Crafts:** Nanotechnology provides an abundance of new building materials, textiles, fabrics, and electronic devices. Any material that can increase the strength of fish cage construction without adding weight would be advantageous for aquaculture engineering [69]. Traditional mooring lines can be strengthened by weaving CNT fibers into the strands of the rope and increasing tensile strength as CNT fibers are light and strong in nature. The antibacterial properties NMs can also be used to prevent the biofouling of marine structures [70]. Previously, copper [Cu] has been used in fishery engineering, particularly in aquaculture cages or seines [71,72]. Cu/polymer nanocomposites offer an effective solution for anti-fouling purposes because of their cost-effectiveness and impressive performance. By integrating copper nanoparticles (CuNP) into the polymer, the material's strength and ability to withstand high temperatures are enhanced, and it gains inherent antiseptic and antibacterial qualities [73-77]. Additionally, antibacterial coatings are used on the sides of fish tanks and water pipes to prevent biofouling. The application of biosensors improves microbial control in aquaculture systems. The carbon nanotube-based biosensors can detect even trace amounts of pathogens in water and food, including bacteria, viruses, parasites, and heavy metals. On the other hand, Nano colloidal silver functions as a catalyst and can successfully target a wide range of bacteria, fungi, parasites, and viruses by limiting the activity of their metabolic enzymes [78]. Biofouling is the accumulation of unwanted bacteria, invertebrates, and algae which is a major problem in fisheries that can be controlled by incorporating metal oxide nanoparticles such as ZnO, CuO, and SiO2 into coatings or paints [8, 9, 79, 80]. The processing industry and exporters can use a Radio Frequency ID (Rfid) chip integrated with a nanoscale component as a tracking tool to monitor the source and track the delivery status of their aqua product until it reaches the market [7].

III. CONCLUSION

Nanotechnology has significantly advanced aquaculture and fisheries, revolutionizing the diagnosis and treatment of genetic disorders in fishes, and enabling precise eradication of pathogens even at low densities, protecting aquatic populations from disease outbreaks. It has facilitated the rapid detection of heavy metal contamination in water and food sources, ensuring the safety of ecosystems and fish for consumption. Nanotechnology also enhances fish’s nutrient absorption, leading to increased production and better health. Moreover, it plays a crucial role in filtration systems for remediating contaminated water, maintaining a sustainable environment, and contributing to controlled breeding techniques. Additionally, nanotechnology prevents bio-fouling agents, protecting fish habitats and infrastructure. As an evolving field, it promises even more unexplored applications to enhance productivity, sustainability, and overall aquatic ecosystem health. As a relatively nascent field, nanotechnology continues to offer promising potential in aquaculture and fisheries. Many more applications are yet to be explored, promising further innovations that can address challenges and improve the overall productivity, sustainability, and health of aquatic ecosystems and the fisheries industry.

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