Application of Nanotechnology in Fisheries and Aquaculture

Neha Rani, Sangeeta Kumari and Mamta Singh*
College of Fisheries, Kishanganj (Bihar Animal Sciences University),
DKAC Campus, Arrabari, Kishanganj-855107
Corresponding Author: mamta0131@gmail.com

Introduction

In recent years, aquaculture has become one of the fastest-growing food industries in the world. It plays a significant role in meeting the growing demand for high-quality animal proteins. But meeting the demand sustainably is a big challenge. To achieve the global fish production goal of >180MMT by 2025, the efficiency and sustainability of the fish production system need to be maximized. The main challenges faced by the aquaculture industry are habitat loss, environmental degradation, chemical contamination, disease outbreaks, and inefficient feed utilization. These factors altogether cause heavy losses to the aquaculture industry and are major roadblocks in achieving the global fish production goal. To address these issues, a lot of work has been done to use scientific and technological advancements in aquaculture. Among various approaches used for sustainable and efficient fish production, nanotechnology has been recognized as a highly effective and innovative approach. It covers almost all the fields of aquaculture like fish nutrition, genetic engineering, reproduction, drug delivery, pathogen detection, disease prevention, biodiversity monitoring, food processing and quality assurance, environmental safety, and water remediation. The nanotechnology application in fisheries and aquaculture can improve the productivity, sustainability, and overall health of aquatic species. As the demand for fish is rising globally, fisheries scientists are taking advantage of nanotechnology as a solution for improving fish stock quality, breeding success, disease prevention, treatment of pollutants, and microbial disinfection as nanotechnology offers a wide range of potential applications to address these challenges. This article focused on the application of nanotechnology in fisheries and aquaculture as well as the potential health and environmental risks associated with this technology.

Nanotechnology and its application in fisheries and aquaculture: Nanotechnology is a field focused on the study and manipulation of materials and systems at the nanoscale i.e. 1-100 nm. Nanoparticles are of various dimensions like zero-dimension, one-dimension, two-dimensions, and three-dimensions and they could be synthesized by arranging atom by atom or converting large materials to nanoscale. The main types of nanomaterials include nano-metals, metal oxides, carbon nanotubes, carbon spheres, quantum dots, nanoceramics, and nanoshells. Nanotechnology has a broad range of applications in aquaculture and holds the potential to revolutionize the industry. The primary uses of nanotechnology in fisheries and aquaculture are outlined below.

Fish Breeding and Reproduction

Use of (1) nanoparticles during sperm cryopreservation, (2) nano-encapsulation of essential nutrients for brooders and larvae, (3) nanocarrier targeted delivery of gonadotropin-releasing hormone (GnRH) analogues for induced spawning as ovulation, (4) biocompatible nano sensors to monitor fish behaviour, providing valuable data to optimize breeding conditions and improve reproduction outcomes, and (5) nanoparticle targeted delivering of reproductive hormones in gonads for fertility improvement are some of the applications of nanotechnology that increase the chance of successful fertilization and improves breeding efficiency. The use of nanoparticles like silver (AgNPs), gold (AuNPs), and zinc oxide (ZnO NPs) enhances sperm viability and motility during cryopreservation. These nanoparticles reduce oxidative stress and protect spermatozoa from cryo-damage, thereby improving post-thaw fertilization success.

Delivery of nutrients for fish growth

Nutrients in the form of nanoparticles can enhance the growth rate of aquaculture species compared to conventional feed due to their ability to increase nutrient absorption in the digestive tract. Significant improvement was observed in previous studies conducted on sturgeon, carp, gilthead seabream, red sea bream, freshwater prawn, rainbow trout, and Nile tilapia using micronutrient coated nanoparticles like nano selenium, nano zinc, nano iron, nano manganese, nano gold, and nano cooper. Nanoparticles also improve the shelf life, bioavailability, and absorption of natural bioactive compounds including hydrophobic ones. In addition to improving the stability and bioavailability of food ingredients, it can also alter the physical properties of fish feed of food pellets like maintaining feed integrity in water for a longer duration which minimizes feed wastage. Incorporation of nano-sized nutrients such as iron, calcium, and phosphorus in fish diets enhances reproductive performance by improving overall health, gonadal development, and spawning success. Newly hatched larvae require precise nutrition for survival. Nano-sized protein and lipid formulations improve nutrient bioavailability, supporting higher survival rates and growth.

Drug and vaccine delivery for health management

Nanotechnology provides novel prospects related to disease diagnosis and health management in aquaculture. Coating solid nanoparticles by the fatty acid shell offers an innovative solution for the efficient delivery of thermolabile drugs. The use of poriferous nanomaterials for the controlled release of drugs is also employed by the pharmaceutical industry. Nonencapsulated vaccines are used in fishes to induce immune response in some fishes like nano vaccines against different pathogens in carp (rohu), Japanese flounder, and rainbow trout. Chitosan-coated mucoadhesive nano vaccine showed promising results in tilapia against columnaris disease.

Pathogen detection and microbial disinfection

Several nano biosensors are developed to detect the very low concentration of a wide range of pathogens like parasites, bacteria, and viruses. In aquaculture, disease symptoms appear very late which significantly compromises its management and causes economic losses. Nanoparticle-based sensor holds the potential to overcome this challenge through early detection and eradication of pathogens. Highly sensitive carbon nanotube-based sensors are used to detect traces of pathogens, heavy metals, and pH changes in aquaculture systems. It is feasible to detect a single virus particle by electric nano sensors. Metal nanoparticles like silver, titanium, and copper are used against pathogens with different modes of action. They generally disrupt the cell wall and cell membrane in bacteria or ion transports across membranes. Titanium dioxide nanoparticles are reported to kill a wide range of bacteria, filamentous and unicellular fungi, algae, protozoa, and viruses. Ginger and neem nanoparticles showed antibacterial and immunomodulatory activity in carp.

Environmental safety and water remediation

Nanomaterials with high photo-catalysis and absorption efficiency can solve the problem of water pollution in aquaculture systems. Graphene nanosheets and graphene oxide are capable of removing heavy metals and organic compounds from water. Iron nanoparticles are reported to break down polychlorinated biphenyls and dioxins into less toxic carbon compounds. Nano-sensors can optimize fish culture conditions by detecting pollutants, monitoring oxygen levels, and tracking water quality. Advanced filtration systems incorporating nanomaterials effectively maintain optimal water quality, reducing stress and mortality rates in fish. Considering another dimension of nanotechnology in water remediation, nanobubble technology holds great promise. In nanobubbles technology nanobubbles are nanoscopic gaseous (typically air) cavities in aqueous solutions that can change the normal characteristics of water. It is an on-shore gas transfer mechanism that creates ultra-fine bubbles of less than one micrometer. They are about 1 million times smaller than ordinary bubbles as a result of their size, nanobubbles have no natural buoyancy. Nanobubbles remain within the water column for extended periods, providing direct oxygenation of the water. Nanobubbles are negatively charged and attract positively charged organic matter in the water column which leads to the inactivation of heavy metals, pollutants, and dangerous cyanotoxins, and maintains desirable water quality conditions.

Genetic engineering or improvement of aquatic species

Nanotechnology can be used for genetic improvement of fish by facilitating more efficient gene delivery methods, allowing for precise manipulation of fish DNA using nano-sized carriers, which can potentially enhance traits like growth rate, disease resistance, and environmental adaptability in aquaculture practices. Nanotechnology can be used to selectively deliver genes to control the sex of fish populations, allowing for better management of aquaculture operations.

Seafood processing

Nanotechnology plays a significant role in food processing and packaging industry. The use of nanomaterials provided several desired properties like oxygen depletion, antimicrobial activity, detection of pathogens, toxins, and hazardous chemicals, improved shelf life, etc. Essential oil-encapsulated nanomaterials like solid lipid nanoparticles, biodegradable nanoparticles, and nanotubes are commonly used in the fish food processing industry. Silver nanoparticles have been used to reduce the microbial load in seafood. The use of nanofilms as packaging materials is becoming very popular. Nano emulsions and nanoliposomes with essential oils have also been used in seafood packaging.

Challenges and prospects

While nanotechnology holds immense promise in aquaculture, several challenges must be addressed i.e. (1) Toxicological concerns: long-term effects of nanoparticles on fish health and aquatic ecosystems remain under investigation, (2) Regulatory frameworks: lack of standardized regulations for nanoparticle usage in aquaculture raises concerns about safety and environmental impact, and (3) Cost, scalability, and accessibility: high production costs and limited accessibility hinder large-scale adoption of nanotechnology in aquaculture. The feasibility of scaling up nanotechnology applications and ensuring their cost-effectiveness is still uncertain. As research progresses, nanotechnology is expected to be widely adopted, offering innovative solutions to increase productivity, improve sustainability, and meet the global demand for fish. Future advancements in nanotechnology could revolutionize the aquaculture industry by addressing challenges like disease prevention, reproductive efficiency, and environmental optimization.

Conclusion

Nanotechnology is revolutionizing fisheries and aquaculture by enhancing gamete quality, optimizing hormonal control, improving disease management, and ensuring better nutrition and water quality. While challenges persist, continued advancements and responsible implementation can pave the way for more efficient and sustainable aquaculture practices. With proper regulation and ethical considerations, nanotechnology will play a crucial role in meeting the increasing global demand for fish production while minimizing environmental impact.

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