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Nanotechnology in fisheries: Transforming aquaculture and sustainable harvesting

[1]Vipin Kumar Misra, [2]Sheetanshu Gupta, [3]Ankita Pandey, [4]Laksmi, [5]Yogesh Chadra Rikhri, [6]TS Mishra, [7]AN Tripathi [8]Sonmoina Bhuyan, [9]Mahesh Pathak and [10]Shikha Ahalawat

[1]KVK East Kameng, Arunachal Pradesh, India

[2]College of Food Technology, CAU, Imphal, Manipur, India

[3]RVSKVV-KVK Dhar, Madhya Pradesh, India

[4]RVSKVV-KVK Shivpuri, Madhya Pradesh, India

[5]RVSKVV-KVK Datiya, Madhya Pradesh, India

[6]KVK West Kameng, Arunachal Pradesh, India

[7]KVK Tawang, Arunachal Pradesh, India

[8]KVK Kamrup, AAU, Guwahati, Assam, India

[9]CPGS in Agriculture Sciences, CAU Umiam, Meghalaya, India

[10]Department of Zoology, COBS&H, CCS HAU, Hisar, Haryana, India

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Corresponding Author: Shikha Ahalawat

Abstract

Nanotechnology, with its potential to revolutionize various industries, has found a promising niche in fisheries and aquaculture. This review explores the multifaceted applications of nanotechnology in fisheries, shedding light on its transformative impacts. We delve into how nanomaterials, nanoparticles, and nanodevices are being harnessed to enhance water quality in aquaculture systems, boost fish health, optimize feed, and create advanced monitoring tools. The convergence of nanotechnology and fisheries has opened new avenues for sustainable practices, ranging from improved fish farming to eco-friendly fishing gear. However, this promising synergy also poses challenges, including environmental concerns and ethical considerations. As we navigate this emerging field, we identify future research directions and opportunities for harnessing nanotechnology's full potential in fisheries.

Keywords: Nanotechnology, fisheries, aquaculture, nanomaterials, sustainability, monitoring, fish health, eco-friendly, ethical considerations

1. Introduction

1.1 Background

Aquaculture and fisheries have long played pivotal roles in meeting the world's growing demand for seafood (FAO, 2020). However, these industries confront a plethora of challenges, including dwindling fish stocks, environmental degradation, and disease outbreaks (Pauly *et al*., 1998; Costello *et al*., 2020; Subasinghe *et al*., 2009) [35, 6, 41]. In this context, the marriage of nanotechnology with fisheries emerges as a potent solution, promising to address these challenges with unprecedented precision and efficiency.

The field of nanotechnology deals with materials, devices, and systems at the nanoscale, often working with particles measuring less than 100 nanometers (Nel *et al*., 2006) [34]. This scale provides unique properties, enabling scientists and engineers to design novel solutions to age-old problems. In fisheries, nanotechnology offers the potential to revolutionize practices, from aquaculture to sustainable harvesting, by harnessing these unique properties.

1.2 Significance of Nanotechnology in Fisheries

Nanotechnology's significance in fisheries extends across various dimensions:

- **Precision in Aquaculture:** Nanomaterials and nanoparticles are leveraged to enhance water quality, optimize fish feed, and improve disease management. These innovations drive higher yields, minimize resource consumption, and reduce environmental impacts (Qin *et al*., 2021; Kim *et al*., 2020) [36, 21].
- **Sustainable Harvesting:** Advanced nanomaterials and nanodevices play a pivotal role in crafting eco-friendly fishing gear, minimizing bycatch, and enhancing monitoring systems. This translates to more sustainable harvesting practices with reduced ecological footprints (Ramanan *et al*., 2019; Alam *et al*., 2018) [37, 3].
- **Environmental Stewardship:** The integration of nanotechnology in fisheries management extends to environmental monitoring and remediation. Nanosensors and nanoremediation strategies enable

real-time assessment and mitigation of environmental impacts (Liu *et al*., 2017; Fabrega *et al*., 2011) [29, 9].

As we embark on this exploration of nanotechnology's transformative potential in fisheries, it becomes evident that the applications extend far beyond technological innovation. They represent a paradigm shift towards sustainable, eco-conscious practices that are essential for preserving our marine ecosystems and ensuring a future where fisheries thrive in harmony with the environment.

2. Nanotechnology in Aquaculture

Nanotechnology has emerged as a game-changer in the field of aquaculture, offering innovative solutions to address longstanding challenges and revolutionize industry practices. In this section, we explore the multifaceted applications of nanotechnology in aquaculture, focusing on advancements in water quality management, monitoring, and remediation.

2.1 Improving Water Quality

Maintaining optimal water quality is paramount in aquaculture to ensure the health and productivity of aquatic species. Nanotechnology has introduced precision and efficiency into this critical aspect of aquaculture management.

2.1.1 Nanomaterials for Water Treatment

Nanomaterials have become pivotal in water treatment strategies for aquaculture systems. Nanoparticles like silver nanoparticles and carbon nanotubes possess exceptional adsorption and catalytic properties, facilitating the efficient removal of pollutants, heavy metals, and pathogens from water (Kim *et al*., 2019; Gogoi *et al*., 2020) [22, 15]. Nanostructured materials such as zeolites and magnetic nanoparticles are also employed for ion exchange and magnetic separation, further enhancing water quality (Ravishankar *et al*., 2010; Wang *et al*., 2021) [38, 45].

2.1.2 Monitoring and Remediation Using Nanosensors

Real-time monitoring of water parameters is critical for timely responses to changing conditions in aquaculture. Nanosensors, known for their precision and sensitivity, enable continuous monitoring of temperature, pH, oxygen levels, and the presence of harmful substances (Ivask *et al*., 2014; Gu *et al*., 2020) [19, 17]. Moreover, nanotechnology-driven remediation methods allow on-site treatment of water, mitigating the impact of pollutants and diseases (Liu *et al*., 2019; Li *et al*., 2021) [28, 25].

2.2 Enhancing Fish Health

Nanotechnology plays a pivotal role in enhancing the health and well-being of aquatic species in aquaculture settings. This section explores two critical aspects of fish health management: disease control and targeted drug delivery.

2.2.1 Nanoparticles in Disease Control

Nanoparticles have emerged as potent tools in the prevention and treatment of diseases in aquaculture. Metal nanoparticles, such as silver nanoparticles, exhibit remarkable antimicrobial properties, effectively combating bacterial and fungal infections in fish (Ma *et al*., 2016; Mohanta *et al*., 2020) [31, 32]. Additionally, nanoscale formulations of vaccines have demonstrated higher efficacy in bolstering the immune response, thereby reducing the susceptibility of fish to infections (Nayak *et al*., 2015; Abdelhamed *et al*., 2018) [33, 1]. The use of nanotechnology in disease control not only ensures the health of aquatic species but also minimizes the excessive use of antibiotics, mitigating the risk of antimicrobial resistance.

2.2.2 Nanoencapsulation for Drug Delivery

Nanoencapsulation technologies provide precise control over the delivery of therapeutic agents to fish. Encapsulation of drugs, probiotics, or essential nutrients within nanoparticles enables their targeted release, improving their bioavailability and efficacy (Table 1) (Lall *et al*., 2018; Ghosh *et al*., 2019) [24, 13]. This approach ensures that fish receive the necessary treatments while minimizing environmental dispersion and wastage, contributing to sustainable aquaculture practices.

Table 1: Nanoencapsulation Methods for Drug Delivery

Method	Description	Advantages
Liposomes	Lipid bilayer vesicles encapsulating drugs	Enhanced drug solubility
Polymeric Nanoparticles	Drug-loaded polymer particles	Controlled drug release, stability
Solid Lipid Nanoparticles	Lipid-based nanoparticles with a solid core	Improved drug stability
Nanoemulsions	Oil-in-water emulsions with nanoscale droplets	High drug loading, increased absorption
Dendrimers	Highly branched, tree-like molecules	Precise drug loading and targeting
Nanosuspensions	Submicron-sized drug particles in aqueous suspension	Enhanced drug dissolution
Carbon Nanotubes	Hollow, cylindrical carbon structures	High drug loading, unique properties
Protein Nanoparticles	Drug-loaded protein-based nanoparticles	Biocompatibility, targeted delivery

2.3 Optimizing Fish Feed

Nanotechnology has revolutionized the formulation of fish feed, allowing for precise control over nutrient delivery and uptake. Enhanced fish feed contributes to improved growth, development, and overall health of aquatic species.

2.3.1 Nanostructured Feed Additives

Nanostructured additives, such as liposomes and nanocapsules, serve as efficient carriers for nutrients and supplements in fish feed (Zhang *et al*., 2015; Sahu *et al*., 2017) [46, 39]. These nanoscale structures protect sensitive compounds from degradation, ensuring their delivery to fish with maximum effectiveness. Nanostructured feed additives enhance nutrient absorption, supporting healthy growth and development.

2.3.2 Controlled Nutrient Release Systems

Nanotechnology enables the development of controlled-release systems within fish feed. Nanoencapsulation of nutrients or growth-promoting agents allows for sustained release over time, matching the metabolic needs of fish (Karatas *et al*., 2019; Abdel-Tawwab *et al*., 2021) [20, 2]. This precise nutrient delivery enhances feed efficiency, reduces waste, and minimizes environmental impacts, promoting sustainable aquaculture.

Nanotechnology's influence in aquaculture extends beyond water quality management to revolutionize fish health management and optimize fish feed formulations, contributing to the overall sustainability and efficiency of the industry.

3. Nanotechnology in Sustainable Fishing

Nanotechnology is poised to transform sustainable fishing practices, revolutionizing both fishing gear and environmental monitoring for responsible fisheries management.

3.1 Advanced Fishing Gear

Nanomaterials are at the forefront of innovation in fishing gear design, offering remarkable properties that enhance sustainability.

3.1.1 Nanomaterials for Lightweight and Strong Equipment

Nanotechnology has opened new horizons for creating fishing equipment with unmatched properties. Carbon nanotubes and graphene-based materials are being employed in fishing gear, such as rods, reels, and lines (Lima, 2016) [26]. These nanomaterials are incredibly lightweight, while simultaneously exhibiting exceptional tensile strength. As a result, fishing gear made with these materials is not only robust but also minimizes the energy required for casting and retrieval, contributing to eco-friendly resource utilization (Table 2). Such lightweight gear not only reduces the physical strain on fishermen but also lowers the carbon footprint of fishing activities.

Table 2: Nanomaterials for Lightweight and Strong Equipment Preparation

Nanomaterial	Application	Advantages
Carbon Nanotubes	Fishing Rods	Exceptional strength-to-weight ratio
	Fishing Lines	Improved tensile strength and flexibility
Graphene	Fishing Rods	Ultra-lightweight, strong, and flexible
	Fishing Reels	Enhanced durability and reduced weight
Nanocomposites	Fishing Nets	Increased tensile strength and reduced weight
	Fishing Hooks	Improved durability and sharpness
Nanocoatings	Fishing Hooks	Enhanced corrosion resistance
	Fishing Blades	Reduced friction and increased sharpness

3.1.2 Smart Fishing Nets and Traps

Smart fishing nets and traps, featuring integrated nanoscale sensors, represent a significant advancement in sustainable fishing practices (Lai *et al*., 2019; Gokulakrishnan *et al*., 2021) [23, 16]. These intelligent nets can detect the size and species of caught fish in real-time. This technology enables selective harvesting, reducing bycatch and minimizing the ecological impact of fishing operations. By enhancing precision and decreasing waste, smart fishing gear aligns with sustainability principles, preserving marine ecosystems and resources.

3.2 Environmental Monitoring

Nanotechnology-based environmental monitoring tools offer unparalleled insights into aquatic ecosystems.

3.2.1 Nanosensors for Water Quality Assessment

Nanosensors are actively employed in aquatic environments to continuously assess water quality parameters, including pH, temperature, and pollutant levels (Sakthivel & Joseph, 2018; Liu *et al*., 2020) [40, 27]. These miniature sensors provide real-time data, enabling fishers and regulatory agencies to monitor aquatic ecosystems' health effectively. Rapid detection of changes in water quality supports informed decision-making and helps prevent environmental degradation, safeguarding the delicate balance of aquatic ecosystems.

3.2.2 Tracking Fish Movements with Nanotags

Nanotechnology facilitates the tagging and tracking of fish populations for research and conservation purposes (Brosnan *et al*., 2019; Waller *et al*., 2021) [5, 44]. Nanotags equipped with sensors enable scientists to monitor fish movements, migration patterns, and habitat preferences. This valuable data contributes to the development of sustainable fishing regulations, safeguarding critical spawning grounds and endangered species. By understanding fish behavior at a granular level, fisheries management can be optimized for both economic and ecological sustainability.

4. Challenges and Considerations

The application of nanotechnology in fisheries, while promising, introduces a set of significant challenges and considerations that necessitate careful attention to ensure the responsible and sustainable use of these advanced materials and technologies.

4.1 Environmental Concerns

Nanoparticle Release and Ecotoxicology

The release of nanoparticles into aquatic ecosystems is a central concern surrounding nanotechnology in fisheries. Nanoparticles can originate from various sources, including nanomaterials used in fishing gear, nanosensors employed for monitoring, and nanoparticle-based treatments. These particles, when released into aquatic environments, can interact with aquatic organisms, potentially leading to adverse effects on their health and behavior (Hund-Rinke *et al*., 2016) [18]. Understanding the ecotoxicology of nanoparticles is paramount to assessing their impact comprehensively.

Potential Risks in Aquatic Ecosystems

Beyond ecotoxicology, there is a broader concern about the potential risks nanotechnology poses to aquatic ecosystems. Alterations in the behavior, physiology, and life cycles of aquatic species could disrupt ecological balances. Nanoparticle contamination may also affect nutrient cycling and primary productivity in aquatic environments, influencing the entire food web. To manage these risks, long-term, ecosystem-level studies are essential (Gaiser *et al*., 2015) [12].

4.2 Ethical and Regulatory Issues

Responsible Nanotechnology in Fisheries

Ensuring the responsible use of nanotechnology in fisheries is an ethical imperative. Researchers, industry stakeholders, and policymakers must collaborate to establish ethical guidelines for the deployment of nanomaterials. This includes transparent reporting of research findings, ethical treatment of tagged fish in monitoring programs, and the responsible disposal of nanomaterial-based equipment (Arts *et al*., 2014) [4].

5. Regulatory Frameworks and Oversight

Robust regulatory frameworks are crucial to address the potential risks associated with nanotechnology in fisheries. Governments and international bodies should develop comprehensive regulations that cover the entire nanotechnology life cycle, from production to disposal. These regulations should include environmental impact assessments, safety standards, and mechanisms for continuous oversight (Tiede *et al*., 2016) [43]. Effective regulations are essential to reassure stakeholders that nanotechnology is being employed responsibly.

5.1 Sustainable Aquaculture

Nanotechnology for Precision Farming

The future of aquaculture lies in precision farming, where nanotechnology plays a pivotal role. Nanoscale sensors and monitoring systems enable real-time tracking of water quality parameters, feeding rates, and fish health (Duncan, 2011) [8]. These technologies will allow aquaculturists to optimize conditions for fish growth and minimize resource consumption. For instance, nanoparticles can be used to improve the efficiency of nutrient delivery to fish, ensuring that they receive the right nutrients at the right time. This precision in feeding can lead to healthier and more sustainable aquaculture practices.

Eco-friendly Aquaculture Practices

Nanotechnology is propelling the development of eco-friendly aquaculture practices. Nanoencapsulation of feed supplements and vaccines enhances nutrient absorption and disease resistance in farmed fish (Das, 2018) [7]. Furthermore, nanomaterial-based water treatment systems minimize environmental pollution and reduce the need for chemical additives. For example, nanoscale filtration systems can remove contaminants from water in an eco-friendly manner. These systems provide a sustainable approach to maintaining water quality in aquaculture facilities.

5.2 Eco-conscious Fishing

Minimizing Bycatch with Nanotechnology

One of the major challenges in fishing is bycatch, the unintentional capture of non-target species. Nanoscale modifications to fishing gear, such as selective nanocoatings on nets or traps, can reduce bycatch by repelling non-target species while attracting the desired catch (Fitzsimmons *et al*., 2014) [10]. This approach not only enhances the efficiency of fishing operations but also contributes to the conservation of vulnerable species.

Reducing Gear Impact on Marine Ecosystems

Nanotechnology enables the development of lightweight yet incredibly strong materials for fishing gear. These advanced materials significantly reduce the environmental impact of fishing operations by minimizing physical damage to marine ecosystems (Luo *et al*., 2016) [30]. Smart fishing nets equipped with nanosensors can further reduce the environmental footprint by providing real-time feedback on gear condition and integrity. Additionally, nanocoatings can make fishing gear resistant to biofouling, reducing the need for environmentally harmful antifouling agents.

5.3 Research Priorities

Exploring Novel Nanomaterials

The continuous exploration of novel nanomaterials is a research priority in the field of nanotechnology in fisheries. Researchers are investigating the potential of graphene-based nanocomposites, biodegradable nanoparticles, and sustainable nanocoatings for various applications in fisheries (Thapa *et al*., 2020) [42]. These materials hold promise for further enhancing the sustainability and efficiency of the industry. Moreover, the development of environmentally benign nanomaterials is essential to minimize potential ecological risks.

Long-term Environmental Impact Assessment

As nanotechnology becomes increasingly integrated into fisheries, it is imperative to conduct long-term environmental impact assessments. This research priority ensures that the benefits of nanotechnology are balanced against potential risks. Comprehensive studies on the persistence, fate, and effects of nanomaterials in aquatic ecosystems will guide responsible innovation (Giese *et al*., 2020) [14]. Additionally, monitoring programs should be established to track any unintended ecological consequences and adapt regulations accordingly.

6. Conclusion

6.1 Synthesis of Key Findings

In this comprehensive review, we have delved into the multifaceted applications of nanotechnology in fisheries, exploring its potential to revolutionize the aquaculture and fishing industries. Key findings underscore the versatility of nanomaterials in addressing pressing challenges, such as water quality management, disease control, and optimized nutrition in aquaculture. Additionally, nanotechnology exhibits promise in improving the sustainability and efficiency of fishing practices. These findings collectively illuminate the transformative power of nanotechnology in advancing fisheries management and production.

6.2 Nanotechnology as a Catalyst for Sustainable Fisheries
Nanotechnology emerges as a pivotal catalyst for achieving sustainability in fisheries. Its capacity to enhance water quality, mitigate disease outbreaks, and improve feed efficiency contributes significantly to the sustainable growth of aquaculture. Furthermore, the integration of nanomaterials in fishing gear design and environmental monitoring promotes eco-conscious fishing practices that minimize bycatch and reduce adverse impacts on marine ecosystems. The marriage of nanotechnology and fisheries science thus holds the potential to reconcile the ever-growing global demand for seafood with the imperative of preserving aquatic ecosystems.

6.3 Prospects and Future Research Directions
As we look to the future, several promising avenues beckon researchers and stakeholders alike. Firstly, continued exploration of novel nanomaterials and their tailored applications in fisheries remains an exciting prospect. In-depth studies on the long-term ecological impact of nanotechnology in aquatic environments will be imperative to ensure responsible and sustainable practices. Moreover, research efforts should extend to the development of standardized regulations and oversight frameworks to govern the use of nanomaterials in fisheries. These initiatives will collectively shape the future of nanotechnology in fisheries, with the ultimate goal of fostering sustainable practices and conserving our aquatic resources for generations to come.

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