Magna Scientia Advanced Biology and Pharmacy

eISSN: 2582-8363

Cross Ref DOI: 10.30574/msabp

Journal homepage: https://magnascientiapub.com/journals/msabp/

(Review Article)

Check for updates

Exploring the role of nanotechnology in aquaculture, including targeted drug delivery, water purification and feed enhancement

Francis Agbo Idoko [1], David Oche Idoko [2, *] and Adeyemo Catherine [3]

[1] *Department of Fisheries Technology, Bauchi State College of Agriculture, Bauchi, Nigeria.*
[2] *Department of Fisheries and Aquaculture, J.S Tarkaa University, Makurdi, Nigeria.*
[3] *Department of Business Administration, Ahmadu Bello University, Zaria, Nigeria.*

Magna Scientia Advanced Biology and Pharmacy, 2025, 14(02), 001-017

Publication history: Received on 26 December 2024; revised on 24 February 2025; accepted on 27 February 2025

Article DOI: https://doi.org/10.30574/msabp.2025.14.2.0019

Abstract

Nanotechnology is revolutionizing various sectors, including aquaculture, by offering innovative solutions to longstanding challenges. This paper explores the potential applications of nanotechnology in aquaculture, focusing on three critical areas: targeted drug delivery, water purification, and feed enhancement. Targeted drug delivery systems employing nanoparticles enable precise and efficient treatment of fish diseases, reducing the overuse of antibiotics and minimizing environmental impact. Advanced nanomaterials, such as nanofilters and photocatalysts, are transforming water purification practices, effectively removing contaminants and maintaining optimal water quality for aquatic organisms. Additionally, nano-enhanced feed formulations improve nutrient delivery, promote growth, and enhance the health of aquaculture species. While nanotechnology promises significant advancements, the paper also discusses associated challenges, including safety concerns, regulatory frameworks, and the cost-effectiveness of implementing nanotechnological solutions in commercial aquaculture. By highlighting these opportunities and obstacles, the study underscores the transformative potential of nanotechnology in fostering sustainable and efficient aquaculture practices.

Keywords: Nanotechnology; Drug delivery; Water purification; Nanofilters

1. Introduction

1.1. Overview of aquaculture as a growing industry and its challenges (disease, water quality, nutrition)

Aquaculture has experienced significant growth in recent years, becoming a vital component of global food production. In 2022, global fish farming production surpassed wild catch for the first time, with 94.4 million tonnes farmed compared to 91 million tonnes caught in open waters (Robertset al., 20234. This expansion is largely driven by the increasing demand for seafood and the need to alleviate pressure on overexploited wild fish populations (Roberts et al., 2024).

Despite its rapid development, the aquaculture industry faces several challenges that threaten its sustainability and productivity. Disease management remains a critical concern, as intensive farming practices can lead to the proliferation of pathogens, resulting in significant economic losses. For instance, bacterial infections are among the most common and devastating diseases affecting farmed fish, causing mortality rates of up to 100% (Austin & Austin, 2016).

Water quality is another pivotal issue in aquaculture systems. Maintaining optimal water conditions is essential for the health and growth of aquatic organisms (Idoko et al, 2024). Factors such as temperature fluctuations, pH levels, and the

* Corresponding author: David Oche Idoko.

accumulation of waste products can deteriorate water quality, leading to stress and increased susceptibility to diseases in farmed species (Yusuf et al., 2023).

Nutrition also poses a significant challenge. The formulation of balanced diets that meet the specific nutritional requirements of different species is crucial. Nutritional deficiencies or imbalances can lead to diseases, poor growth rates, and reduced product quality, ultimately affecting the industry's profitability and sustainability (Syanya et al., 2023).

Addressing these challenges is imperative for the continued growth and sustainability of the aquaculture industry. Implementing effective disease management strategies, ensuring rigorous water quality control, and developing nutritionally adequate feeds are essential steps toward achieving this goal (Yusuf et al., 2024).

1.2. Introduction to nanotechnology and its potential transformative impact on aquaculture

Nanotechnology, the manipulation of matter at the atomic and molecular scale, has emerged as a transformative force across various industries, including aquaculture. Its application in this sector offers innovative solutions to longstanding challenges, such as disease management, water quality maintenance, and nutritional optimization. By leveraging nanomaterials and Nano scale processes, aquaculture can achieve enhanced productivity and sustainability (Idoko et al., 2024).

One significant application of nanotechnology in aquaculture is the development of nanoparticle-based drug delivery systems. These systems enable targeted and controlled release of therapeutics, improving treatment efficacy and reducing environmental contamination. For instance, chitosan-based nanoparticles have been explored for delivering vaccines and antimicrobial agents to fish, offering a promising approach to disease control in aquaculture (Nasr-Eldahan et al., 2021).

Additionally, nanotechnology contributes to water purification in aquaculture systems. Nanomaterials, such as nanofilters and photocatalysts, can effectively remove pollutants, pathogens, and excess nutrients from water, thereby maintaining optimal conditions for aquatic organisms. The use of nanobubbles, which are ultra-fine bubbles of gas in water, has also been investigated for enhancing water quality and promoting fish health by increasing dissolved oxygen levels and reducing harmful microbial populations (Forood et al., 2024).

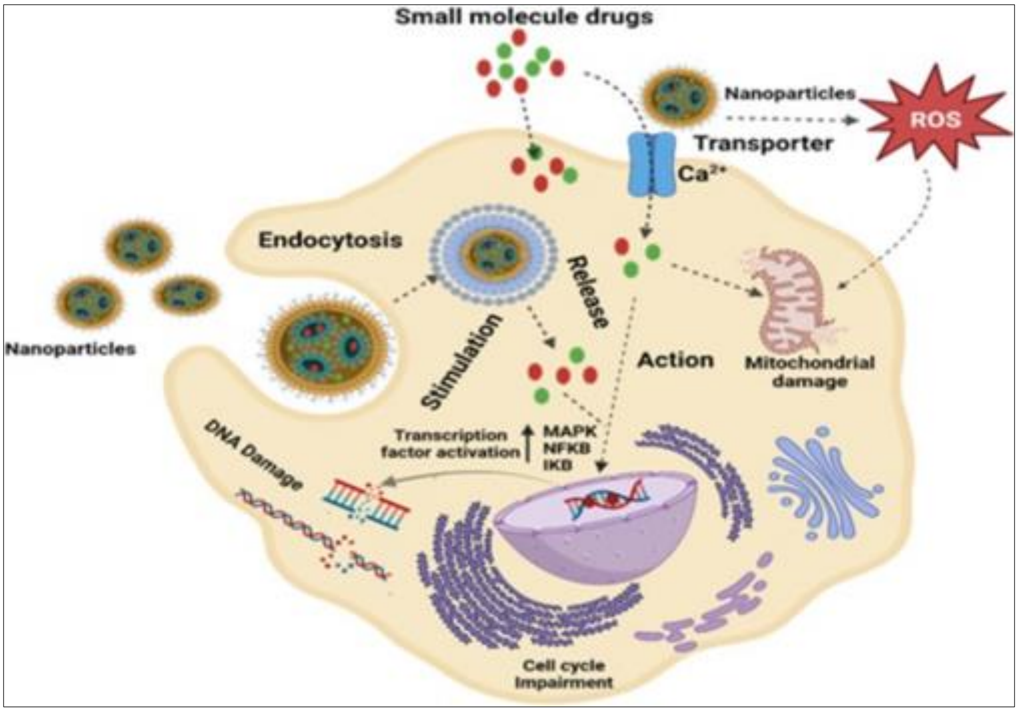

Figure 1 Nanoparticle-Enhanced Drug Delivery Mechanisms in Cellular Systems

Furthermore, nanotechnology plays a role in feed enhancement. Nano-encapsulation techniques can improve the bioavailability and stability of nutrients and supplements in aquafeeds, leading to better growth performance and feed utilization in farmed species. This approach not only enhances the nutritional value of the feed but also minimizes waste and environmental impact (Sarkar et al., 2022).

The integration of nanotechnology into aquaculture presents a promising avenue for addressing critical challenges in the industry. Through advancements in targeted drug delivery, water purification, and feed enhancement, nanotechnology has the potential to significantly improve the efficiency and sustainability of aquaculture practices (Idoko et al., 2024).

The image illustrates the beneficial cellular interactions of nanoparticles and small molecule drugs, showcasing advanced drug delivery pathways through endocytosis, transcription activation, and targeted cellular responses. This innovative approach represents significant advancements in therapeutic delivery systems.

1.3. Objectives of the review

The primary objective of this review is to examine the applications of nanotechnology within aquaculture, focusing on three critical areas: drug delivery, water purification, and feed enhancement. By analyzing recent advancements and current practices, this review aims to elucidate how nanotechnology can address prevalent challenges in aquaculture, thereby promoting sustainability and efficiency in the industry.

In the realm of drug delivery, nanotechnology offers innovative solutions for the targeted administration of therapeutics, enhancing treatment efficacy and minimizing environmental impact. Nanoparticles can be engineered to deliver drugs directly to specific sites within aquatic organisms, reducing the required dosage and mitigating side effects. This targeted approach is particularly beneficial in managing diseases prevalent in aquaculture settings, where traditional methods may fall short.

Water purification is another domain where nanotechnology demonstrates significant potential. Nanomaterials, such as nanofilters and photocatalysts, can effectively remove contaminants, including pathogens and excess nutrients, from aquaculture systems. This capability ensures optimal water quality, which is essential for the health and growth of cultured species. The application of nanotechnology in water treatment processes can lead to more efficient and sustainable aquaculture practices.

Furthermore, nanotechnology contributes to feed enhancement by improving the bioavailability and stability of nutrients. Nano-encapsulation techniques protect sensitive feed components from degradation, ensuring that essential nutrients are efficiently delivered to aquatic organisms. This enhancement not only promotes better growth performance but also reduces waste, contributing to the overall sustainability of aquaculture operations.

By exploring these applications, this review seeks to provide a comprehensive understanding of the transformative impact of nanotechnology on aquaculture, highlighting its potential to revolutionize industry practices and address existing challenges.

2. Nanotechnology in Targeted Drug Delivery

2.1. Current issues in disease management in aquaculture (antibiotic overuse, inefficiency).

Disease management in aquaculture faces significant challenges, particularly concerning the overuse and inefficiency of antibiotics. The widespread application of antibiotics to control bacterial infections has led to the emergence of antibiotic-resistant strains, rendering treatments less effective and posing substantial risks to both aquatic animal health and public health (Cabello et al., 2013).

The indiscriminate use of antibiotics in aquaculture has been linked to the development of resistant bacteria, which can transfer resistance genes to human pathogens, thereby compromising the efficacy of antibiotics in human medicine (Cabello et al., 2013). Additionally, antibiotic residues in aquaculture products raise food safety concerns, as they may contribute to the accumulation of resistance determinants in consumers (Done & Halden, 2015).

Table 1 Impact Analysis of Antibiotic Usage in Aquaculture: Challenges and Consequences

Impact Area	Challenges	Consequences	Mitigation Strategies
Animal Health	- Emergence of resistant bacterial strains -Reduced treatment effectiveness - Disease control difficulties	- Compromised animal health - Increased mortality rates - Treatment failure	- Development of vaccines -Implementation of probiotics - Enhanced biosecurity measures
Public Health	- Transfer of resistance genes to human pathogens - Antibiotic residues in food products - Accumulation of resistance determinants	- Reduced antibiotic efficacy in human medicine - Food safety risks - Health risks for consumers	- Improved monitoring systems - Stricter regulation of antibiotic use - Alternative treatment methods
Environmental	-Disruption of microbial communities - Ecological imbalance - Antibiotic accumulation in water	- Proliferation of opportunistic pathogens - Altered ecosystem dynamics - Long-term environmental damage	- Sustainable farming practices - Environmental monitoring - Reduced antibiotic dependency
Management	- Inefficient disease control - Overreliance on antibiotics - Cost implications	- Unsustainable operations - Economic losses - Regulatory compliance issues	- Disease prevention strategies - Alternative treatment development - Improved management practices

Furthermore, the environmental impact of antibiotic overuse is profound. Antibiotics introduced into aquatic environments can disrupt microbial communities and ecological balance, leading to unintended consequences such as the proliferation of opportunistic pathogens (Cabello et al., 2013). The inefficiency of current disease management practices necessitates the exploration of alternative strategies, including the development of vaccines, probiotics, and the implementation of improved biosecurity measures, to mitigate the reliance on antibiotics and enhance the sustainability of aquaculture operations (Done & Halden, 2015).

2.2. Role of Nanocarriers (e.g., liposomes, nanoparticles) in delivering therapeutics directly to target tissues.

Nanocarriers, such as liposomes and nanoparticles, have revolutionized the field of targeted drug delivery by enabling the direct transport of therapeutics to specific tissues. This precision enhances treatment efficacy while minimizing systemic side effects. Liposomes, which are spherical vesicles composed of lipid bilayers, can encapsulate both hydrophilic and hydrophobic drugs, protecting them from degradation and facilitating controlled release at the target site (Wikipedia, 2023). Their biocompatibility and ability to fuse with cellular membranes make them ideal candidates for delivering a wide range of therapeutic agents.

Nanoparticles, including polymeric nanoparticles and metallic nanocarriers, offer unique advantages in drug delivery applications. Their small size and modifiable surface properties allow for enhanced permeability and retention in target tissues, particularly in pathological areas with compromised vasculature, such as tumors (Idoko et al; 2024). By functionalizing the surface of these nanocarriers with specific ligands, it is possible to achieve active targeting, thereby increasing the concentration of the therapeutic agent at the desired site while reducing exposure to healthy tissues.

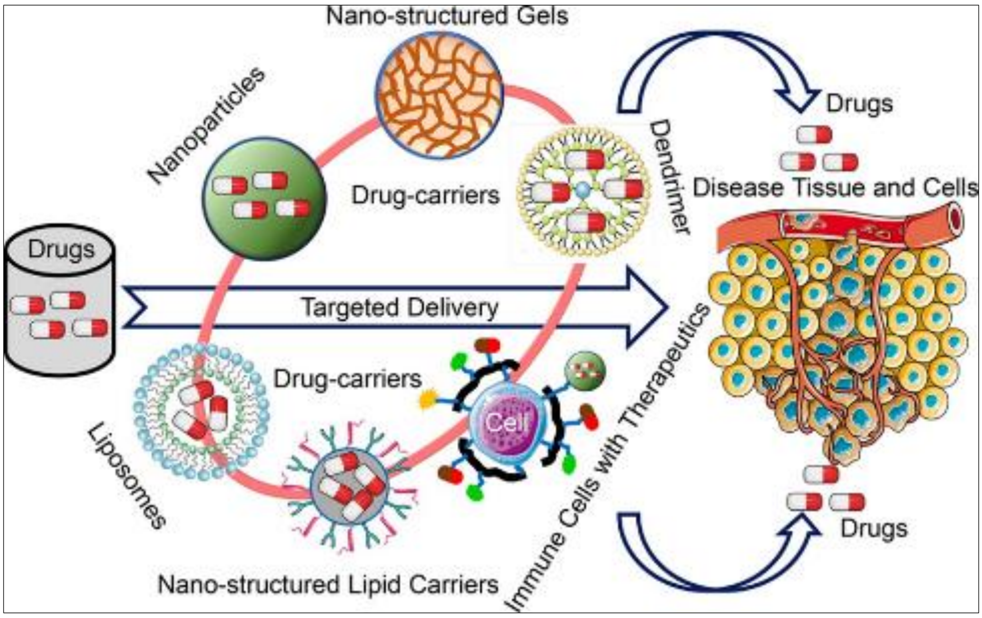

Figure 2 Enhanced Precision and Efficacy in Nanocarrier-Based Targeted Drug Delivery Systems (Majumder et al., 2019)

Nanocarriers, such as liposomes and nanoparticles, enhance targeted drug delivery by transporting therapeutics directly to diseased tissues, improving efficacy and reducing side effects while protecting drug stability

The utilization of nanocarriers in targeted drug delivery has been extensively studied in various medical applications, including oncology and infectious diseases. For instance, liposomal formulations of chemotherapeutic agents have demonstrated improved pharmacokinetics and reduced toxicity compared to conventional formulations (Aladetan et al, 2024). Similarly, nanoparticle-based delivery systems have shown promise in overcoming biological barriers and enhancing the therapeutic index of antimicrobial agents. These advancements underscore the potential of nanocarriers to transform therapeutic delivery by providing more effective and safer treatment options (Idoko et al., 2024).

2.3. Case studies or recent advancements in nano-drug delivery systems.

Table 2 Nanotechnology Applications in Aquaculture: Advancements and Benefits

Nano Application	Technology Used	Benefits	Impact
Drug Delivery Systems	- Liposomes - Nanoparticles - Nanocarriers	- Targeted delivery - Controlled release - Enhanced efficacy	- Reduced environmental impact - Improved treatment outcomes - More efficient drug administration
Nanovaccines	- Encapsulated antigens - Nanoparticle carriers - Sustained release systems	- Enhanced immune response - Better protection - Sustained effectiveness	- Improved disease management - Reduced infection rates - More effective vaccination
Nanoencapsulated Feeds	- Nutrient nanoparticles - Bioavailable compounds - Stabilized nutrients	- Improved nutrient stability - Enhanced bioavailability - Better growth performance	- Enhanced nutritional quality - Increased disease resistance - Improved sustainability

Recent advancements in nanotechnology have significantly enhanced drug delivery systems in aquaculture, offering innovative solutions to combat diseases and improve fish health. Nanocarriers, such as liposomes and nanoparticles, have been developed to encapsulate therapeutic agents, ensuring targeted delivery and controlled release within aquatic organisms. This approach not only increases the efficacy of treatments but also reduces the environmental impact associated with traditional drug administration methods (Idoko et al 2024).

A notable application of nanotechnology in aquaculture is the development of nanovaccines aimed at combating Aeromonas hydrophila infections. These vaccines utilize nanoparticles to encapsulate antigens, providing protection and facilitating sustained release, thereby enhancing the immune response in fish (Idoko et al., 2024). This strategy represents a significant advancement in disease management, offering a more efficient and environmentally friendly alternative to conventional vaccination methods.

Furthermore, the integration of nanotechnology into aquaculture has led to the creation of nanoencapsulated aquafeeds. These feeds incorporate nanoparticles to improve the bioavailability and stability of nutrients, promoting better growth performance and disease resistance in fish (Ali et al., 2023). The use of nanoencapsulated feeds exemplifies the potential of nanotechnology to enhance the nutritional quality of aquaculture products, contributing to the overall sustainability of the industry.

2.4. Benefits and limitations of nanotechnology in aquatic animal health.

Nanotechnology offers significant benefits in enhancing aquatic animal health, particularly through the development of nanoparticle-enhanced feeds. These feeds improve nutrient delivery, bolster immune responses, and exhibit antimicrobial properties, thereby promoting growth and reducing disease incidence in fish (Ali et al., 2023). Additionally, the incorporation of nanomaterials in aquaculture practices can lead to improved water quality and overall sustainability of the aquaculture environment (Abbas, 2021).

Table 3 Benefits and Limitations of Nanotechnology in Aquaculture: A Risk-Benefit Analysis

Aspect	Benefits	Limitations	Research Needs
Animal Health	- Enhanced nutrient delivery - Improved immune response - Better growth performance - Reduced disease incidence	- Potential toxicity risks - Unknown long-term effects - Bioaccumulation concerns	- Long-term health impact studies - Toxicity assessments - Bioaccumulation research
Environmental Impact	- Improved water quality - Enhanced sustainability - Better feed efficiency	-Ecological impact uncertainties -Environmental accumulation - Ecosystem disruption risks	- Ecological impact studies - Environmental monitoring methods - Ecosystem effect assessments
Implementation	- Advanced feed formulation - Disease management tools - Sustainable practices	- Limited risk assessment data - Regulatory challenges - Implementation uncertainties	- Safety protocol development - Regulatory framework studies - Implementation guidelines
Resource Management	- Enhanced feed efficiency - Improved resource utilization - Better production outcomes	- Cost considerations - Technical limitations - Resource allocation challenges	- Cost-benefit analyses - Technical feasibility studies - Resource optimization research

However, the application of nanotechnology in aquaculture is not without limitations. Concerns have been raised regarding the potential toxicity of nanomaterials to aquatic organisms and the surrounding environment. The introduction of nanoparticles may lead to bioaccumulation and unforeseen ecological impacts, necessitating comprehensive risk assessments before widespread adoption (Abbas, 2021). Furthermore, the long-term effects of nanomaterials on fish health and the environment remain under-researched, highlighting the need for further studies to ensure safe and effective implementation (Ali et al., 2023).

While nanotechnology presents promising advancements for improving aquatic animal health through enhanced nutrition and disease management, it is imperative to address the associated environmental and health risks. A balanced approach that includes thorough research and regulation is essential to harness the benefits of nanotechnology in aquaculture while mitigating potential drawbacks (Aladetan et al., 2024).

2.5. Nanotechnology in Water Purification

2.5.1. Challenges of maintaining water quality in aquaculture systems (pollutants, ammonia, and pathogens).

Maintaining optimal water quality in aquaculture systems is essential for the health and productivity of aquatic organisms. However, several challenges persist, notably the accumulation of pollutants, elevated ammonia levels, and the proliferation of pathogens.

Pollutants in aquaculture environments often originate from external sources such as contaminated water supplies, excessive feeding practices, overstocking, and the use of antibiotics and chemicals. These factors contribute to the degradation of water quality, adversely affecting fish health and growth.

Ammonia, a toxic nitrogenous compound, poses a significant threat in aquaculture systems. It is primarily produced through the excretion of waste by aquatic animals and the decomposition of organic matter. High concentrations of ammonia can impair fish gill function, reduce oxygen-carrying capacity, and lead to increased mortality rates. Overcrowded and poorly maintained systems are particularly susceptible to ammonia buildup, necessitating regular monitoring and effective filtration to mitigate its impact.

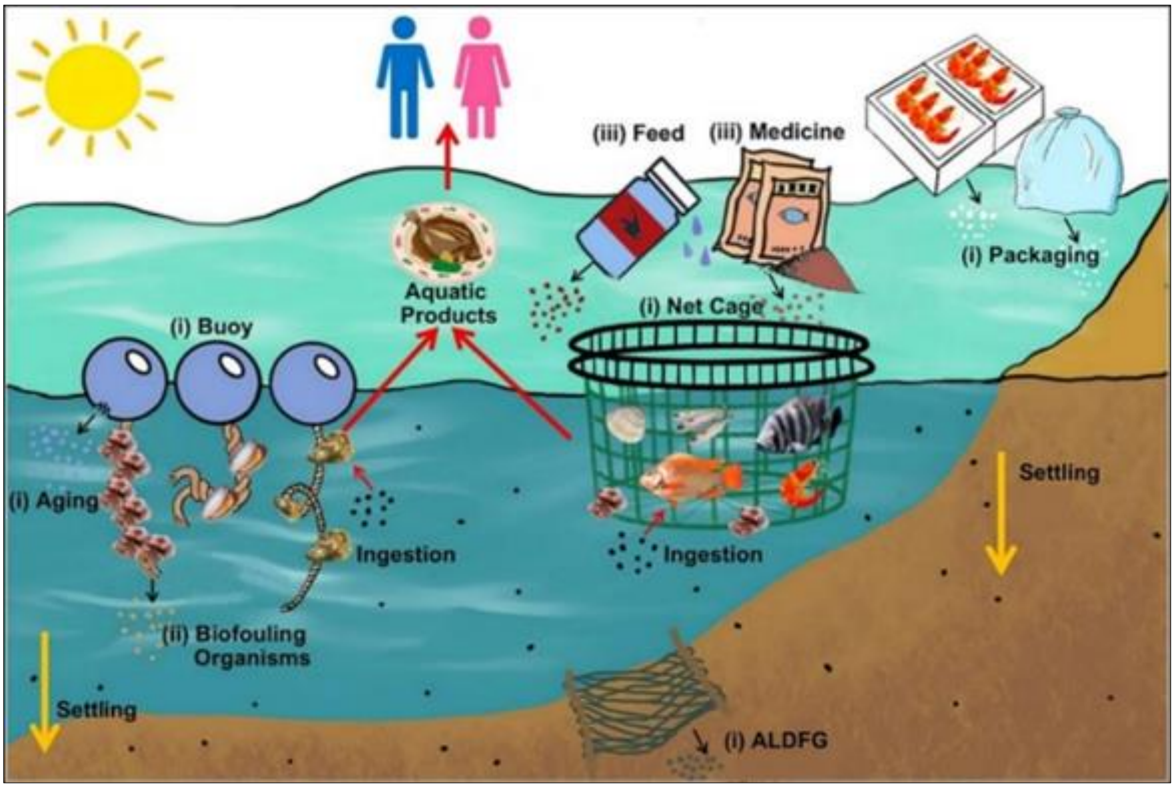

Figure 3 Environmental Challenges and Waste Management in Aquaculture System (Drizo & Shaikh, 2023)

The diagram illustrates challenges in aquaculture, including pollutant accumulation, biofouling, ammonia buildup, and pathogen proliferation, which threaten aquatic health and productivity, emphasizing the need for sustainable water quality management practices.

Pathogens, including bacteria, viruses, and parasites, thrive in compromised water conditions, leading to disease outbreaks that can devastate aquaculture operations. Factors such as poor water quality, high stocking densities, and inadequate biosecurity measures exacerbate the risk of pathogen proliferation. Implementing comprehensive water quality management practices is crucial to control and prevent the spread of infectious agents in aquaculture systems.

Addressing these challenges requires a multifaceted approach, including regular water quality assessments, appropriate system design, and the implementation of best management practices to ensure a sustainable and productive aquaculture environment.

2.6. Application of nanomaterials for water purification (e.g., nanofilters, photocatalysts, and adsorbents).

Nanotechnology has emerged as a transformative approach in enhancing water purification processes within aquaculture systems. The utilization of nanomaterials, such as nanofilters, photocatalysts, and adsorbents, offers innovative solutions to address water quality challenges by effectively removing contaminants and pathogens. Nanofilters, incorporating materials like carbon nanotubes and nanofibers, provide superior filtration capabilities due to their high surface area and porosity. These filters can efficiently remove a wide range of pollutants, including heavy metals and organic compounds, thereby improving water quality in aquaculture environments (Oladipo et al., 2020).

Photocatalysts, particularly those based on titanium dioxide (TiO_2) nanoparticles, have demonstrated significant potential in degrading organic pollutants and inactivating microorganisms under light irradiation. The photocatalytic activity of TiO_2 facilitates the breakdown of harmful substances, contributing to the maintenance of a healthier aquatic environment (Oladipo et al., 2020).

Nanoadsorbents, such as graphene oxide and carbon nanotubes, exhibit exceptional adsorption properties, enabling the removal of contaminants like dyes, heavy metals, and other pollutants from water. Their high adsorption capacity and selectivity make them valuable tools in water purification efforts within aquaculture systems (Idoko et al., 2020).

The integration of these nanomaterials into water treatment protocols presents a promising avenue for enhancing the efficiency and effectiveness of water purification in aquaculture. However, it is crucial to conduct comprehensive assessments of their environmental impact and long-term sustainability to ensure safe and responsible application.

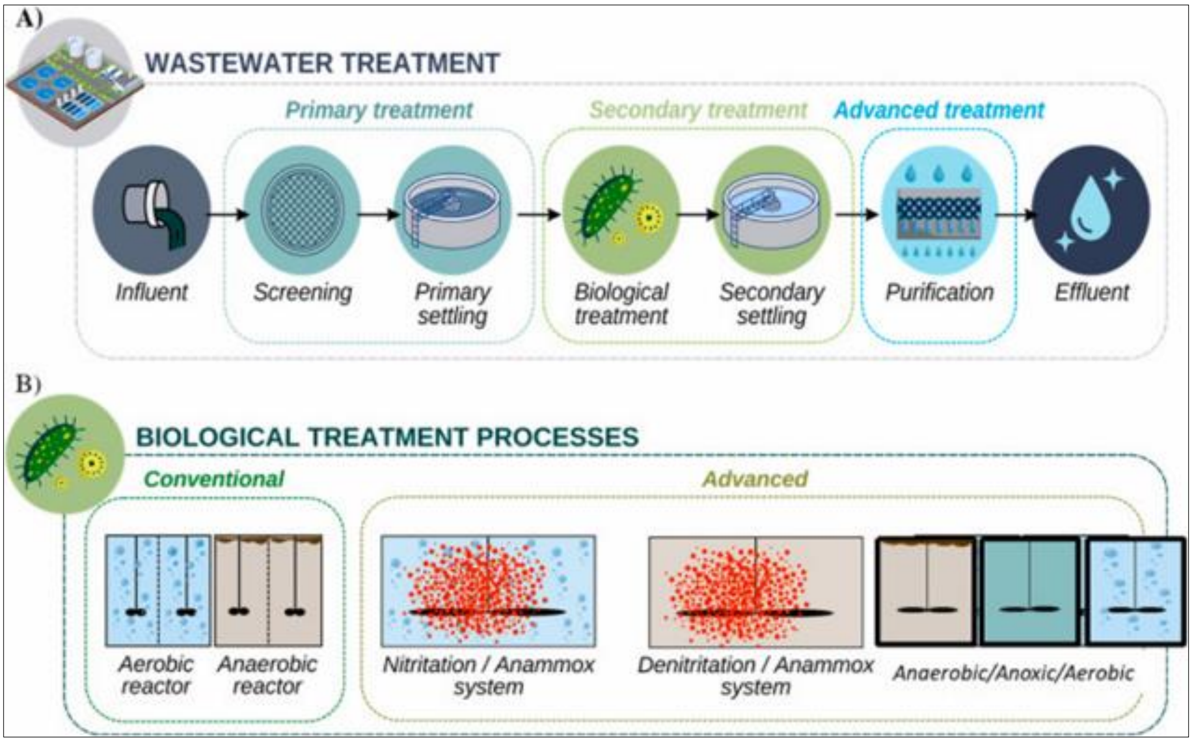

Figure 4 Advancements in Wastewater Treatment Processes for Sustainable Water Management (Joseph et al., 2023). The diagram highlights progressive wastewater treatment methods, emphasizing advanced biological processes that utilize innovative technologies like nanotechnology, ensuring efficient contaminant removal and sustainable aquaculture water management

2.6.1. Examples of successful implementation of nano-based water treatment technologies.

Nanotechnology has significantly advanced water purification techniques, introducing nanomaterials such as nanofilters, photocatalysts, and adsorbents that enhance the efficiency of contaminant removal. Nanofilters, utilizing materials like carbon nanotubes (CNTs) and nanofibers, offer superior filtration capabilities due to their high surface area and porosity. These filters effectively remove a wide range of pollutants, including heavy metals and organic compounds, thereby improving water quality (Oladipo et al., 2020).

Table 4 Key nanomaterials and their roles in water purification

Nanomaterial Type	Components	Properties	Applications
Nanofilters	Carbon nanotubes (CNTs), nanofibers	High surface area, enhanced porosity	Removal of heavy metals and organic compounds, superior filtration capabilities
Nanoadsorbents	Graphene oxide, CNTs	High adsorption capacity, selective binding	Removal of dyes, heavy metals, and various pollutants from water
Photocatalysts	Titanium dioxide (TiO_2) nanoparticles	Photocatalytic activity under light irradiation	Degradation of organic pollutants, inactivation of microorganisms
Integration Systems	Combined nanomaterial technologies	Enhanced efficiency, comprehensive treatment capability	Complete water purification protocols with improved effectiveness

Nanoadsorbents, such as graphene oxide and CNTs, exhibit exceptional adsorption Photocatalysts, particularly titanium dioxide (TiO_2) nanoparticles, have demonstrated significant potential in degrading organic pollutants and inactivating microorganisms under light irradiation. The photocatalytic activity of TiO_2 facilitates the breakdown of harmful substances, contributing to the maintenance of a healthier aquatic environment (Oladipo et al., 2020).

Properties, enabling the removal of contaminants like dyes, heavy metals, and other pollutants from water. Their high adsorption capacity and selectivity make them valuable tools in water purification efforts (Idoko et al., 2024).

The integration of these nanomaterials into water treatment protocols presents a promising avenue for enhancing the efficiency and effectiveness of water purification. However, it is crucial to conduct comprehensive assessments of their environmental impact and long-term sustainability to ensure safe and responsible application.

2.7. Potential environmental implications of using nanomaterials in aquatic systems.

The application of nanomaterials in aquatic systems, particularly for water purification, has garnered significant attention due to their unique physicochemical properties. However, concerns have been raised regarding their potential environmental implications. Nanoparticles can undergo transformations such as dissolution, releasing potentially toxic components into the environment. Additionally, they may aggregate with other nanoparticles (homoaggregation) or with natural mineral and organic colloids (heteroaggregation), altering their fate and potential toxicity in aquatic ecosystems (Maurer-Jones et al., 2013).

The interactions between nanomaterials and natural organic matter can modify surface charge and mobility, influencing their bioavailability and toxicity to aquatic organisms. For instance, the presence of natural organic matter may enhance the stability of nanoparticles, increasing their persistence in the environment and potential for bioaccumulation (Maurer-Jones et al., 2013). Furthermore, studies have indicated that certain nanomaterials, such as metal oxide nanoparticles, can adversely affect aquatic life, including algae, daphnia, and fish, leading to concerns about their ecological impact (Keller, 2010).

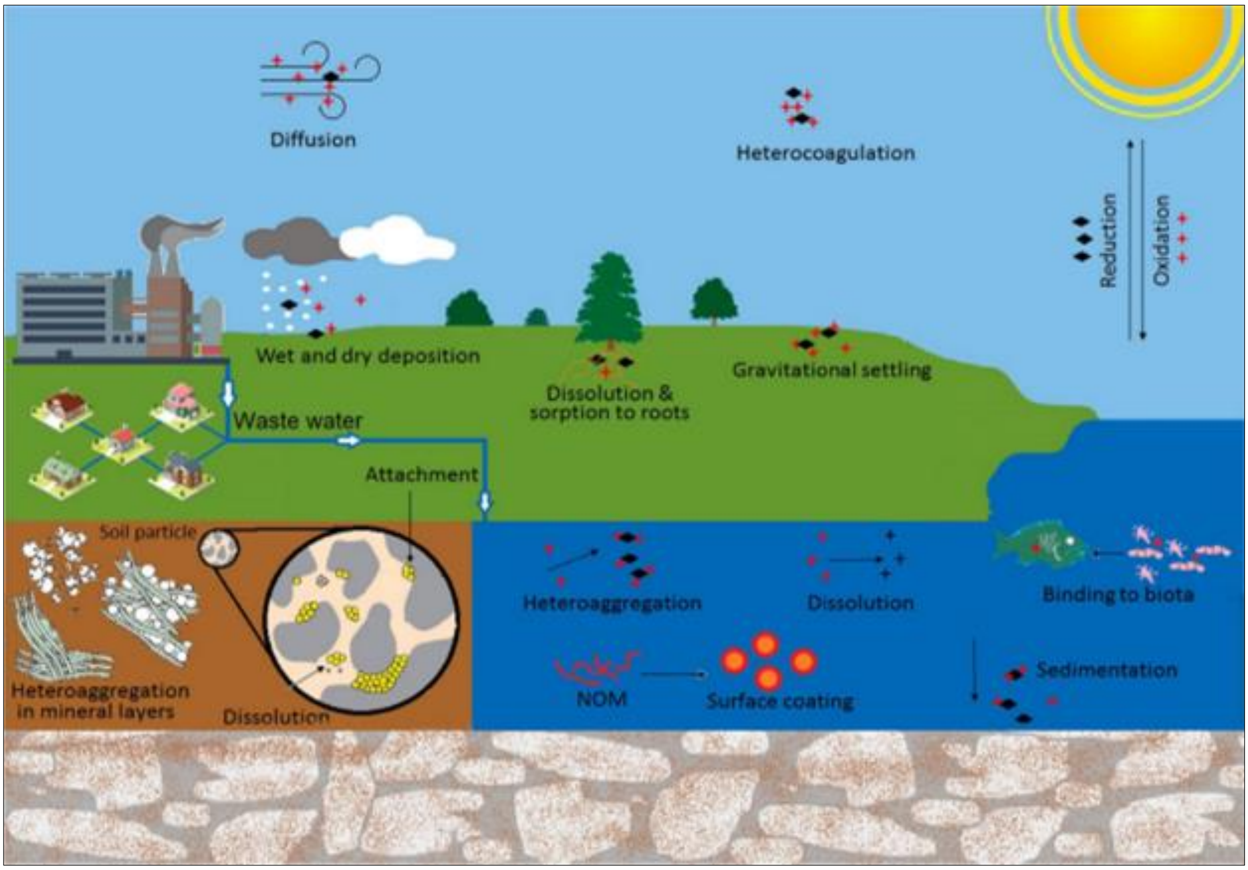

Figure 5 Environmental Fate and Transport of Nanoparticles in Aquatic Systems (Rex et al 2023)
This image illustrates various transformation processes of nanoparticles in aquatic environments, including diffusion, heterocoagulation, dissolution, and binding to biota. These processes, along with interactions with natural organic matter (NOM) and surface coating, influence their environmental impact and potential toxicity. Given these potential risks, it is imperative to conduct comprehensive assessments of the environmental fate, behavior, and toxicity of nanomaterials before their widespread application in aquatic systems. Such evaluations are essential to ensure that the benefits of nanotechnology in water purification do not come at the expense of aquatic ecosystem health

3. Nanotechnology in Feed Enhancement

3.1. Limitations of traditional aquafeeds (nutritional losses, digestibility issues).

Traditional aquafeeds, primarily composed of fishmeal and fish oil, face several limitations that impact their efficiency and sustainability in aquaculture. One significant issue is the presence of antinutritional factors in plant-based ingredients used as fishmeal alternatives. Compounds such as phytate can impede nutrient absorption, leading to reduced growth rates and feed efficiency in fish (Oladipo et al., 2020).

Additionally, the high fiber content in certain plant-derived feedstuffs contributes to digestibility challenges. Fish lack the necessary enzymes to break down complex fibers, resulting in increased fecal waste and diminished nutrient uptake. For instance, the inclusion of distiller's dried grains with solubles (DDGS) in fish diets has been associated with elevated fecal losses due to indigestible fiber components (Gatlin et al., 2007).

Moreover, the substitution of fish oil with terrestrial plant oils in aquafeeds can alter the fatty acid composition of the feed, potentially affecting fish health and the nutritional quality of the final product. While plant oils are more sustainable, they often lack essential long-chain omega-3 fatty acids present in fish oil, which are crucial for optimal fish growth and human health benefits (Idoko et al., 2022).

Addressing these limitations is essential for the advancement of sustainable aquaculture practices. Ongoing research focuses on improving the nutritional profiles of plant-based ingredients, enhancing digestibility through processing techniques, and ensuring that alternative lipid sources meet the essential fatty acid requirements of cultured species (Ezeamii et al., 2024).

3.2. Development of nano-encapsulated nutrients and supplements for improved bioavailability.

The development of nano-encapsulated nutrients and supplements has emerged as a promising strategy to enhance the bioavailability of bioactive compounds. Nanoencapsulation involves enclosing nutrients within nanometer-sized carriers, which can improve their solubility, stability, and absorption in the gastrointestinal tract. This technique has been particularly effective for hydrophobic compounds, such as certain vitamins and phytochemicals, which typically exhibit low bioavailability due to poor water solubility (Ndlovu et al., 2020).

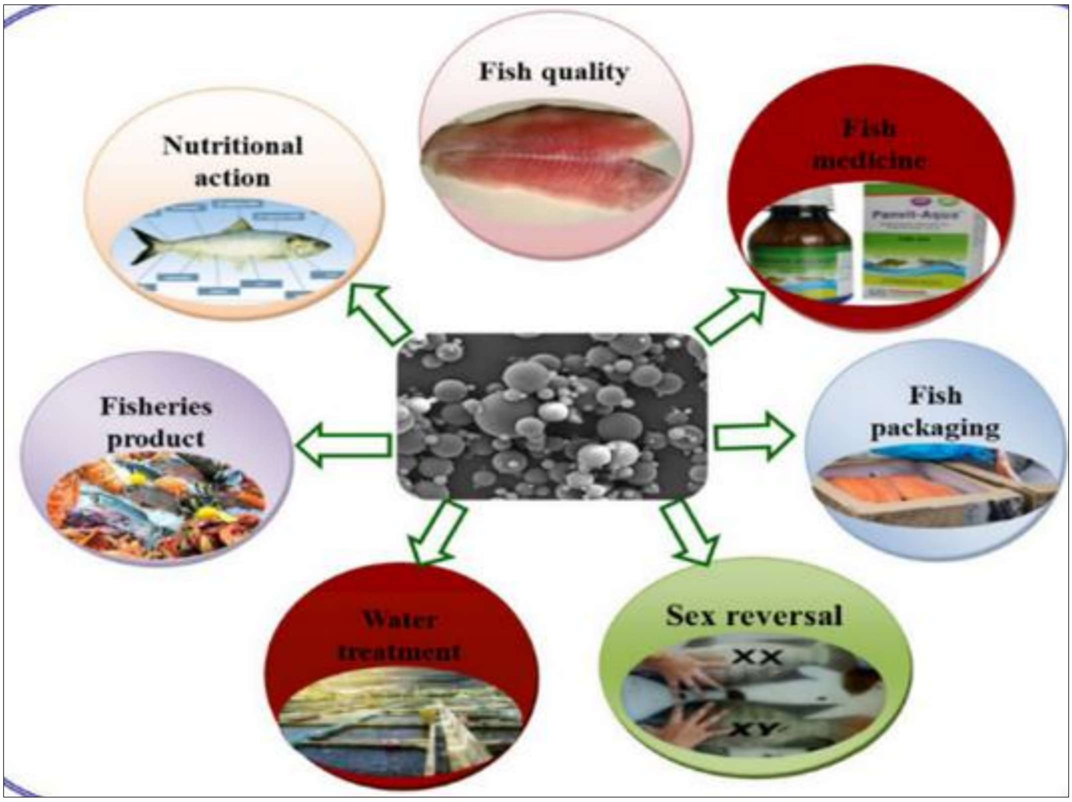

Figure 6 Applications of Nanoencapsulation in Aquaculture Industry (Ahmed et al., 2024). The figure illustrates various applications of nanoencapsulation technology in aquaculture, showcasing its role in fish nutrition, quality enhancement, medicine delivery, packaging, water treatment, and sex reversal, with the central SEM image showing nanoparticles

Nanoparticles can improve the bioavailability of micronutrients, for example, vitamin B12, vitamin A, folic acid, and iron. However, toxicity associated with nanoparticle-based delivery systems is still a major concern (Ndlovu et al., 2020).

In the context of aquaculture, nanoencapsulation has been applied to enhance the delivery of nutrients in fish feed. By encapsulating essential nutrients within nanoparticles, it is possible to improve their stability and absorption in the digestive systems of farmed fish, leading to better growth performance and health outcomes (Idoko et al., 2021). This approach also allows for the controlled release of nutrients, ensuring a sustained supply that aligns with the metabolic needs of the fish.

Despite these advantages, it is crucial to consider the potential toxicity associated with nanoparticle-based delivery systems. Ensuring the safety of nano-encapsulated nutrients requires thorough evaluation of their interactions within biological systems and the environment. Ongoing research aims to address these concerns by developing biocompatible and biodegradable nanocarriers that minimize adverse effects while maximizing the benefits of enhanced nutrient delivery.

3.3. Role of nanotechnology in enhancing feed efficiency and reducing waste

Nanotechnology has emerged as a transformative tool in aquaculture, significantly enhancing feed efficiency and reducing waste. By incorporating nanoparticles into fish feed, nutrient delivery systems are improved, leading to better absorption and utilization by aquatic organisms. This enhancement not only promotes growth but also minimizes the amount of unutilized feed, thereby reducing environmental pollution (Idoko et al., 2023).

One notable application is the use of nanoencapsulation techniques, which protect sensitive nutrients and ensure their targeted release within the digestive tract of fish. This controlled release mechanism ensures a steady supply of nutrients, optimizing feed conversion ratios and minimizing nutrient losses. Consequently, there is a reduction in waste output, which is beneficial for maintaining water quality in aquaculture systems (Francis et al., 2024).

Additionally, nanotechnology facilitates the incorporation of bioactive compounds with immune-boosting and antimicrobial properties into fish diets. These nanoparticle-enhanced feeds can improve fish health, reduce the reliance on antibiotics, and decrease the incidence of diseases. The overall effect is an increase in feed efficiency and a reduction in waste, contributing to more sustainable aquaculture practices (Idoko et al., 2024).

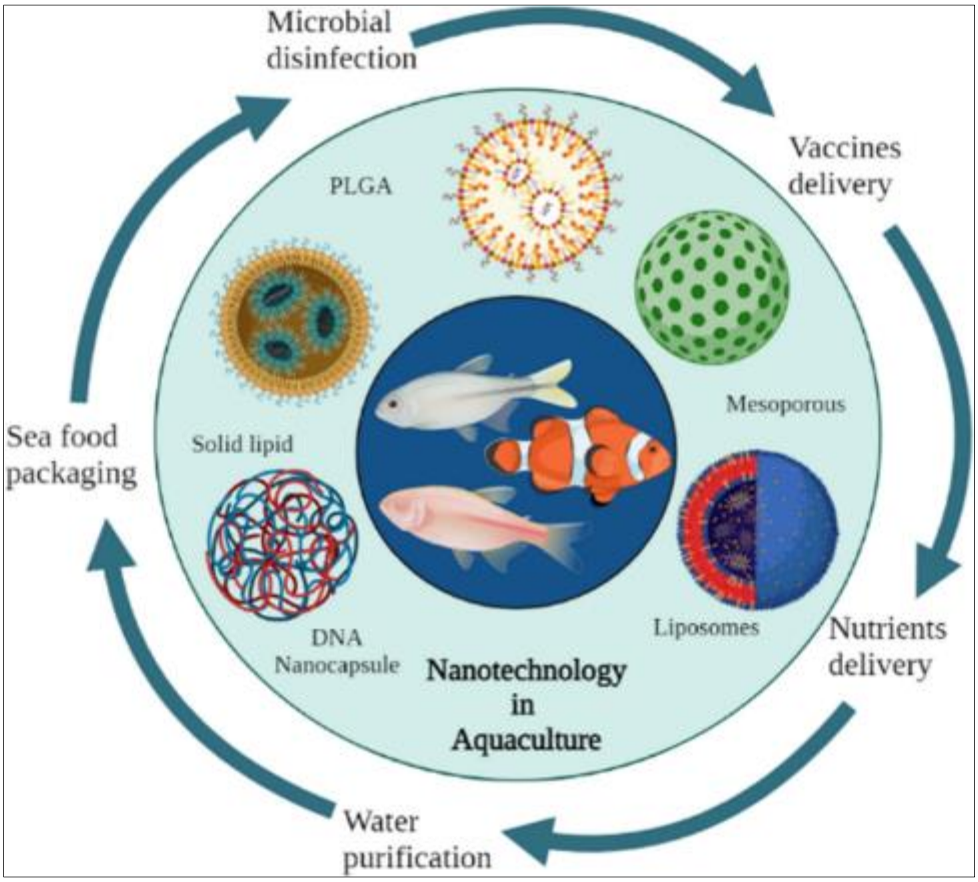

Figure 7 Diverse Applications of Nanotechnology in Aquaculture

Figure 7: illustrates various nanocarrier systems (PLGA, lipids, mesoporous materials, liposomes, DNA nanocapsules) and their applications in aquaculture, including vaccine delivery, nutrient transport, water purification, and seafood packaging for enhanced industry sustainability.

3.4. Emerging trends and innovations in nano-based aquafeeds.

Nanotechnology is revolutionizing aquaculture by introducing innovative approaches to enhance feed efficiency and promote sustainable practices. One emerging trend involves the incorporation of nanoparticles as feed additives to improve nutrient absorption and overall fish health. For instance, selenium nanoparticles have been shown to enhance growth performance and antioxidant status in crucian carp (Carassius auratus), indicating their potential as effective dietary supplements in aquafeeds (El Basuini et al., 2016).

Table 5 Nanotechnology Applications in Aquafeed Enhancement

Technology Type	Components	Benefits	Species/Application Examples
Nanoparticle Feed Additives	Selenium nanoparticles	Enhanced growth performance, improved antioxidant status	Crucian carp (Carassius auratus)
Nanoencapsulation	Bioactive compounds, essential oils	Protected nutrient delivery, controlled release, improved bioavailability	Various fish species, enhanced immune response and growth
Chitosan-based Systems	Chitosan nanocarriers	Antimicrobial properties, improved vitamin and mineral delivery	Reduced antibiotic need, enhanced feed utilization
Nutraceutical Delivery	Vitamins, minerals, essential oils	Improved bioavailability, enhanced immune response	Multiple species, sustainable aquaculture practices

Another innovation is the development of nanoencapsulation techniques for delivering bioactive compounds in aquafeeds. Nanoencapsulation protects sensitive nutrients from degradation and ensures their controlled release within the digestive tract, thereby improving bioavailability and efficacy. This method has been applied to incorporate essential oils and other nutraceuticals into fish diets, enhancing immune responses and growth rates in various species (Akbari et al., 2017).

Additionally, the use of chitosan nanoparticles in feed formulations has gained attention due to their biocompatibility and antimicrobial properties. Chitosan-based nanocarriers can effectively deliver vitamins and minerals, improving feed utilization and reducing the need for antibiotics in aquaculture systems. This approach not only promotes fish health but also addresses concerns related to antibiotic resistance and environmental impact (Gómez-Estaca et al., 2015).

4. Future Prospects and Challenges

4.1. Opportunities for scaling up nanotechnology applications in aquaculture

Nanotechnology offers promising opportunities for scaling up applications in aquaculture to address critical challenges and enhance productivity sustainably. By leveraging advanced materials and systems at the nanoscale, aquaculture can achieve improved water quality management, optimized nutrient delivery, and effective disease control. A significant advantage of nanotechnology is its scalability in integrating innovative solutions such as nanofilters for water purification, nanoencapsulated feed additives, and nanocarriers for targeted drug delivery. Scaling up these technologies can improve the operational efficiency of large aquaculture systems, enabling them to meet the growing global demand for seafood.

The scalability of nanotechnology in aquaculture depends on advancements in manufacturing techniques and cost-efficiency. For instance, large-scale production of nanofilters or photocatalytic materials can enhance their affordability and accessibility for aquaculture enterprises. Similarly, the development of cost-effective nanoencapsulation methods for vitamins and minerals can reduce feed waste and improve fish health at commercial levels. Government policies and public-private partnerships can also play a crucial role in promoting the adoption of nanotechnology in aquaculture, ensuring regulatory compliance and supporting research initiatives to address potential risks.

While opportunities for scaling up nanotechnology applications are vast, addressing environmental and ethical concerns remains essential. Research into the long-term impacts of nanoparticles on aquatic ecosystems and human health is critical to ensure sustainable development. Furthermore, fostering collaboration between academia, industry, and policymakers can drive innovation and ensure the responsible implementation of nanotechnology in aquaculture systems.

4.2. Potential risks, ethical concerns, and regulatory considerations

The integration of nanotechnology in aquaculture presents potential risks, ethical concerns, and regulatory challenges that must be carefully addressed to ensure its sustainable application. One significant risk is the environmental impact of nanoparticles, particularly their potential to accumulate in aquatic ecosystems and disrupt ecological balance. Studies have highlighted the potential toxicity of certain nanomaterials to aquatic organisms, which can have cascading effects on the food chain. Furthermore, the persistence of nanoparticles in water bodies may contribute to long-term environmental degradation, raising concerns about their use without proper mitigation strategies.

Ethical considerations also arise in the application of nanotechnology in aquaculture, particularly in the context of consumer safety and transparency. Ensuring that nanomaterials used in aquaculture do not pose health risks to humans is paramount. Ethical dilemmas may also stem from the unequal access to advanced nanotechnology solutions, potentially widening the gap between developed and developing nations in terms of aquaculture productivity. Transparent labeling and public awareness campaigns are essential to build consumer trust and address concerns regarding the adoption of nanotechnology in food systems.

Regulatory frameworks for nanotechnology in aquaculture are still in their infancy, requiring comprehensive guidelines to govern its development and application. Current regulations often lag behind technological advancements, creating gaps in the oversight of nanoparticle production, usage, and disposal. Effective regulatory measures must include risk assessment protocols, environmental monitoring, and international collaboration to harmonize standards. Policymakers must balance fostering innovation while ensuring the safety of aquatic ecosystems and consumers, making evidence-based regulations a critical priority.

4.3. Research gaps and future directions for integrating nanotechnology in sustainable aquaculture practices

The integration of nanotechnology in sustainable aquaculture presents a promising avenue for enhancing productivity, efficiency, and environmental sustainability. However, significant research gaps hinder its full realization. One critical area requiring attention is the long-term environmental impact of nanomaterials. While studies have demonstrated the efficacy of nanoparticles in applications such as drug delivery and water purification, there remains limited understanding of their biodegradability, persistence, and potential toxicity in aquatic ecosystems. Addressing these gaps is vital to ensuring that nanotechnology solutions do not inadvertently harm marine and freshwater environments.

Another key research gap lies in optimizing the design and functionality of nanomaterials for specific aquaculture applications. The development of targeted delivery systems, such as nano-encapsulated feed supplements or therapeutics, requires a deeper understanding of nanoparticle interactions with biological systems in fish and shellfish. Furthermore, scaling up production while maintaining cost-effectiveness remains a challenge, as many nanotechnology solutions are currently prohibitively expensive for widespread adoption in commercial aquaculture. Future research must prioritize cost-effective and scalable nanotechnology solutions to ensure their accessibility and adoption across diverse aquaculture settings.

Additionally, there is a pressing need for comprehensive regulatory frameworks and standardized testing protocols to evaluate the safety and efficacy of nanotechnology in aquaculture. Current regulations often lack specificity regarding the use of nanomaterials, leading to uncertainties in their application. Future research should focus on developing robust guidelines for risk assessment and environmental monitoring, fostering international collaboration to harmonize standards. The integration of stakeholder perspectives, including policymakers, industry leaders, and consumers, is crucial to aligning research efforts with societal and environmental needs.

4.4. Potential and challenges of nanotechnology in transforming aquaculture

Nanotechnology holds transformative potential for aquaculture by addressing critical challenges such as disease management, water quality, and feed efficiency. The application of nanomaterials, including nanoparticles and nano-encapsulated nutrients, has demonstrated considerable efficacy in delivering targeted therapeutics, purifying water, and enhancing feed bioavailability. These advancements can significantly improve the sustainability and productivity of aquaculture systems, catering to the rising global demand for aquatic products while reducing environmental impact. Furthermore, innovations such as nanofilters and photocatalysts provide sustainable solutions for water purification, ensuring the health and growth of aquatic organisms in intensive farming systems.

Despite its promise, the integration of nanotechnology in aquaculture faces significant challenges. Environmental concerns, particularly the potential toxicity and persistence of nanomaterials in aquatic ecosystems, remain a critical area requiring further investigation. Inadequate regulatory frameworks and the high cost of nanotechnology implementation also hinder its widespread adoption, especially in small-scale aquaculture operations. Addressing these challenges necessitates multidisciplinary research efforts to optimize nanomaterial design, evaluate long-term environmental impacts, and develop cost-effective and scalable solutions.

While nanotechnology offers significant opportunities to revolutionize aquaculture, its successful integration requires addressing environmental, economic, and regulatory challenges. A collaborative approach involving researchers, policymakers, and industry stakeholders is essential to harness its potential responsibly. By prioritizing sustainability and safety, nanotechnology can play a pivotal role in transforming aquaculture into a more efficient and eco-friendly industry capable of meeting future demands.

5. Conclusion

Nanotechnology represents a transformative frontier for aquaculture, offering innovative solutions for disease management, water quality enhancement, and improved feed efficiency through applications like targeted nanoparticles and nano-encapsulated nutrients; however, significant challenges remain regarding environmental safety, regulatory frameworks, and implementation costs, particularly for small-scale operations. The successful integration of these technologies into sustainable aquaculture practices requires a coordinated multidisciplinary approach involving researchers, policymakers, and industry stakeholders to develop environmentally responsible, economically viable solutions that can meet growing global demand for aquatic products while minimizing ecological impacts and ensuring the long-term health of aquatic ecosystems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abbas, W. T. (2021). Advantages and prospective challenges of nanotechnology applications in fish cultures: a comparative review. Environmental Science and Pollution Research, 28(7), 7669-7690.

[2] Ahmed, M. T., Ali, M. S., Ahamed, T., Suraiya, S., & Haq, M. (2024). Exploring the aspects of the application of nanotechnology system in aquaculture: a systematic review. Aquaculture International, 1-30.

[3] Aladetan, J. B., Idoko, F. A., & Bamigwojo, O. V. (2024). Mathematical approaches to fisheries quota management: ensuring sustainable practices in U.S. commercial fishing. World Journal of Advanced Research and Reviews, 24(1), 1019-1053.

[4] Austin, B., & Austin, D. A. (2016). Bacterial fish pathogens: disease of farmed and wild fish. Springer.

[5] Bellanthudawa, B. K. A., Nawalage, N. M. S. K., Handapangoda, H. M. A. K., Suvendran, S., Wijayasenarathne, K. A. S. H., Rathnasuriya, M. L. D., ... & Perera, I. J. J. U. N. (2023). A perspective on biodegradable and non-biodegradable nanoparticles in industrial sectors: applications, challenges, and future prospects. Nanotechnology for Environmental Engineering, 8(4), 975-1013.

[6] Cabello, F. C., Godfrey, H. P., Tomova, A., Ivanova, L., Dölz, H., Millanao, A., & Buschmann, A. H. (2013). Antimicrobial use in aquaculture re-examined: its relevance to antimicrobial resistance and to animal and human health. Environmental microbiology, 15(7), 1917-1942.

[7] Castada, H. Z., Mirondo, R., Sigurdson, G. T., Giusti, M. M., & Barringer, S. (2017). Deodorization of garlic odor by spearmint, peppermint, and chocolate mint leaves and rosmarinic acid. LWT, 84, 160-167.

[8] Drizo, A., & Shaikh, M. O. (2023). An assessment of approaches and techniques for estimating water pollution releases from aquaculture production facilities. Marine Pollution Bulletin, 196, 115661.

[9] Ezeamii, G. C., Idoko, F. A., & Ojochogwu, O. J. (2024). Biosensors and technological advances in monitoring marine pollution in the USA. Global Journal of Engineering and Technology Advances, 20(3).

[10] Forood, A. M. K., Osifuwa, A. D., Idoko, J. E., Oni, O., Ajaelu, C. S., & Idoko, F. A. (2024). Advancements in health information technology and their role in enhancing cancer care: Innovations in early detection, treatment, and data privacy. GSC Advanced Research and Reviews, 21(1), 228-241.

[11] Gatlin III, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., ... & Wurtele, E. (2007). Expanding the utilization of sustainable plant products in aquafeeds: a review. Aquaculture research, 38(6), 551-579.

[12] Gómez-Estaca, J., López de Lacey, A., Gómez-Guillén, M. C., López-Caballero, M. E., & Montero, P. (2009). Antimicrobial activity of composite edible films based on fish gelatin and chitosan incorporated with clove essential oil. Journal of Aquatic Food Product Technology, 18(1-2), 46-52.

[13] Hashempour-Baltork, F., Jannat, B., Dadgarnejad, M., Mirza Alizadeh, A., Khosravi-Darani, K., & Hosseini, H. (2023). Mycoprotein as chicken meat substitute in nugget formulation: Physicochemical and sensorial characterization. Food Science & Nutrition, 11(7), 4289-4295.

[14] Idoko, A. F., Garba, A. M., & Mukhtar, A. H. (2018). Determination of common external parasites of Clarias gariepinus and Oreochromis niloticus in Bauchi metropolis. International Journal of Fisheries and Aquatic Studies, 6(6).

[15] Idoko, A. F., Garba, A. M., & Mukhtar. (2022). Comparative analysis of some plants protein sources on the growth performance of Clarias gariepinus juveniles. International Journal of Applied Research and Technology, 11(1), 61-65.

[16] Idoko, A. F., Garba, A. M., & Mukhtar. (2022). Comparative analysis of the physico-chemical parameters of ground and surface water across three sites in Makurdi metropolis, Benue State. International Journal of Applied Research and Technology, 11(1), 38-52.

[17] Idoko, A. F., Garba, A. M., & Mukhtar. (2022). Determination of varying inclusion levels and incubation period of Baker's Yeast (Saccharomyces cerevisae) and cassava on the floatability and stability of formulated fish diet. International Journal of Applied Research and Technology, 11(2), 11-15.

[18] Idoko, A. F., Garba, A. M., & Mukhtar. (2022). Growth enhancement of catfish fed with formulated diet containing probiotics (Lactobacillus spp.). International Journal of Applied Research and Technology, 11(1), 53-60.

[19] Idoko, D. O. Ugoaghalam, U. J., Babalola, A., & Oyebanji, S. O. (2024). A comprehensive review of combating EDoS attacks in cloud services with deep learning and advanced network security technologies including DDoS protection and intrusion prevention systems. Global Journal of Engineering and Technology Advances, 2024, 20(03), 006–033.

[20] Idoko, D. O. Ugoaghalam, U. J., Babalola, A., & Oyebanji, S. O. (2024). A comprehensive review of combating EDoS attacks in cloud services with deep learning and advanced network security technologies including DDoS protection and intrusion prevention systems. Global Journal of Engineering and Technology Advances, 2024, 20(03), 006–033.

[21] Idoko, D. O., Adenyi, M., Senejani, M. N., Erondu, O. F., & Adeyeye, Y. (2024). Nanoparticle-Assisted Cancer Imaging and Targeted Drug Delivery for Early-Stage Tumor Detection and Combined Diagnosis-Therapy Systems for Improved Cancer Management. International Journal of Innovative Science and Research Technology. Volume 9, Issue 11, November-2024. ISSN No:- 2456-2165.

[22] Idoko, D. O., Agaba, J. A., Nduka, I., Badu, S. G., Ijiga, A. C. & Okereke, E. K, (2024). The role of HSE risk assessments in mitigating occupational hazards and infectious disease spread: A public health review. Open Access Research Journal of Biology and Pharmacy, 2024, 11(02), 011–030.

[23] Idoko, D. O., Danso, M. O., Olola T. M, Manuel, H. N. N., & Ibokette, A. I. (2024). Evaluating the ecological impact of fisheries management strategies in Georgia, USA: A review on current practices and future directions. Magna Scientia Advanced Biology and Pharmacy, 2024, 12(02), 023–045.

[24] Idoko, F. A., Aladetan, J. B., & Bamigwojo, O. V. (2024). Mathematical models for sustainable fisheries management in US waters: Balancing economic growth and conservation. Magna Scientia Advanced Biology and Pharmacy, 13(1).

[25] Idoko, F. A., Ezeamii, G. C., & Ojochogwu, O. J. (2024). Green chemistry in manufacturing: Innovations in reducing environmental impact. World Journal of Advanced Research and Reviews, 23(3), 2826-2841.

[26] Joseph, T. M., Al-Hazmi, H. E., Śniatała, B., Esmaeili, A., & Habibzadeh, S. (2023). Nanoparticles and nanofiltration for wastewater treatment: From polluted to fresh water. Environmental Research, 117114.

[27] Keller, A. A., Wang, H., Zhou, D., Lenihan, H. S., Cherr, G., Cardinale, B. J., ... & Ji, Z. (2010). Stability and aggregation of metal oxide nanoparticles in natural aqueous matrices. Environmental science & technology, 44(6), 1962-1967.

[28] Khan, S. K., Dutta, J., Ahmad, I., Rather, M. A. (2024). Nanotechnology in aquaculture: Transforming the future of food security. Food Chemistry: X, 24, 101974.

[29] Majumder, J., Taratula, O., & Minko, T. (2019). Nanocarrier-based systems for targeted and site specific therapeutic delivery. Advanced drug delivery reviews, 144, 57-77.

[30] Maurer-Jones, M. A., Gunsolus, I. L., Murphy, C. J., & Haynes, C. L. (2013). Toxicity of engineered nanoparticles in the environment. Analytical chemistry, 85(6), 3036-3049.

[31] Nasr-Eldahan, S., Nabil-Adam, A., Shreadah, M. A., Maher, A. M., & El-Sayed Ali, T. (2021). A review article on nanotechnology in aquaculture sustainability as a novel tool in fish disease control. Aquaculture International, 29, 1459-1480.

[32] Nasr-Eldahan, S., Nabil-Adam, A., Shreadah, M. A., Maher, A. M., & El-Sayed Ali, T. (2021). A review article on nanotechnology in aquaculture sustainability as a novel tool in fish disease control. Aquaculture International, 29, 1459-1480.

[33] Olmez-Hanci, T., Arslan-Alaton, I., & Dursun, D. (2014). Investigation of the toxicity of common oxidants used in advanced oxidation processes and their quenching agents. Journal of hazardous materials, 278, 330-335.

[34] Randhawa, P., Marshall, F., Kushwaha, P. K., & Desai, P. (2020). Pathways for sustainable urban waste management and reduced environmental health risks in India: winners, losers, and alternatives to waste to energy in Delhi. Frontiers in Sustainable Cities, 2, 14.

[35] Randhawa, P., Marshall, F., Kushwaha, P. K., & Desai, P. (2020). Pathways for sustainable urban waste management and reduced environmental health risks in India: winners, losers, and alternatives to waste to energy in Delhi. Frontiers in Sustainable Cities, 2, 14.

[36] Rex M, C., Anand, S., Rai, P. K., & Mukherjee, A. (2023). Engineered nanoparticles (ENPs) in the aquatic environment: an overview of their fate and transformations. Water, Air, & Soil Pollution, 234(7), 462.

[37] Roberts, S., Jacquet, J., Majluf, P., & Hayek, M. N. (2024). Feeding global aquaculture. Science advances, 10(42), eadn9698.

[38] Sarkar, B., Mahanty, A., Gupta, S. K., Choudhury, A. R., Daware, A., & Bhattacharjee, S. (2022). Nanotechnology: A next-generation tool for sustainable aquaculture. Aquaculture, 546, 737330.

[39] Sarkar, B., Mahanty, A., Gupta, S. K., Choudhury, A. R., Daware, A., & Bhattacharjee, S. (2022). Nanotechnology: A next-generation tool for sustainable aquaculture. Aquaculture, 546, 737330.

[40] Sharjeel, M., Ali, S., Summer, M., Noor, S., & Nazakat, L. (2024). Recent advancements of nanotechnology in fish aquaculture: an updated mechanistic insight from disease management, growth to toxicity. Aquaculture International, 1-38.

[41] Sharjeel, M., Ali, S., Summer, M., Noor, S., & Nazakat, L. (2024). Recent advancements of nanotechnology in fish aquaculture: an updated mechanistic insight from disease management, growth to toxicity. Aquaculture International, 1-38.

[42] Sørensen, M., Berge, G. M., Reitan, K. I., & Ruyter, B. (2016). Microalga Phaeodactylum tricornutum in feed for Atlantic salmon (Salmo salar)—Effect on nutrient digestibility, growth and utilization of feed. Aquaculture, 460, 116-123.

[43] Syanya, F. J., Litabas, J. A., Mathia, W. M., & Ntakirutimana, R. (2023). Nutritional fish diseases in aquaculture: A human health hazard or mythical theory: An overview. European Journal of Nutrition & Food Safety, 15(8), 41-58.

[44] Yusuf, F. M., Umi, W. A., Ramli, N. M., & Harun, R. (2024). Water quality management in aquaculture. Cambridge Prisms: Water, 2, e8.