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Nanoencapsulation of Nutrients in Fish Feed: Enhancing Bioavailability, Absorption, and Health Benefits for Farmed Fish

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ABSTRACT: Nanoencapsulation has emerged as a promising strategy for improving the delivery and efficacy of nutrients in fish feed. This review aims to provide a comprehensive analysis of the impact of nanoencapsulation on the bioavailability, absorption, and health benefits of nutrients in farmed fish. By encapsulating essential nutrients such as vitamins, minerals, omega-3 fatty acids, and antioxidants within nanoparticles, researchers have sought to optimize nutrient utilization, enhance fish growth, boost immune response, reduce oxidative stress, and improve disease resistance. The studies reviewed herein demonstrate the tremendous potential of nanoencapsulation to address challenges associated with nutrient degradation, limited bioavailability, and inefficient absorption in conventional fish feed formulations. Furthermore, the review highlights the mechanisms underlying the improved bioactivity of nano-encapsulated nutrients, including protection against degradation, targeted delivery to specific tissues, and enhanced cellular uptake. However, considerations regarding nanoparticle toxicity, environmental impact, and regulatory guidelines warrant further investigation to ensure the safe and sustainable implementation of nanoencapsulation technology in aquaculture practices. Overall, the findings reviewed here indicate that nanoencapsulation holds great promise for advancing fish feed formulations, promoting the health and productivity of farmed fish, and contributing to the sustainable growth of the aquaculture industry.

Keywords: Nanoencapsulation, nutrients, fish feed, bioavailability, absorption, health benefits, farmed fish, growth, immune response, oxidative stress, disease resistance, aquaculture, sustainability.

INTRODUCTION

Aquaculture, the farming of aquatic organisms, has become essential in meeting the increasing global demand for seafood. However, the successful producing healthy and high-quality farmed fish relies heavily on the nutrition provided through fish feed. Optimal feed formulations are crucial to support farmed fish's growth, development, and overall health (Bureau *et al*., 2017). Therefore, continuous advancements in fish feed technology are essential to maximize feed efficiency, nutrient utilization, and the overall performance of aquaculture systems.

In recent years, nanotechnology has emerged as a promising approach in various fields, including aquaculture. Nanoencapsulation, a key application of nanotechnology, involves the packaging of nutrients within nanoparticles to enhance their stability, bioavailability, and targeted delivery (García-Orue *et al*., 2020; Venkatesan *et al*., 2021). This technology offers unique advantages in improving the efficacy of nutrient delivery in fish feed formulations, potentially revolutionizing the aquaculture industry.

Nanoencapsulation provides a protective coating to encapsulated nutrients, shielding them from degradation during feed processing, storage, and digestion (Choi *et al*., 2021; Bharathiraja *et al*., 2020). The encapsulated nutrients are effectively preserved, maintaining their bioactivity and nutritional value until they are released at the desired site of action within the fish. Furthermore, the nanoscale size of the particles enhances solubility and absorption of nutrients in the fish's gastrointestinal tract, ensuring optimal utilization of these essential components (Hu *et al*., 2020; Pradhan *et al*., 2021).

The targeted delivery capabilities of nanoencapsulation enable the efficient delivery of nutrients to specific tissues or cells within the fish's body. Functionalized nanoparticles can be designed to interact selectively with certain organs or physiological processes, allowing for site-specific nutrient delivery (Li *et al*., 2021; Nguyen *et al*., 2020). This targeted approach minimizes nutrient wastage and enhances their bioavailability, leading to improved growth performance, immune function, and overall health of farmed fish.

As the potential benefits of nanoencapsulation in fish feed become increasingly evident, research efforts have intensified, exploring various encapsulation materials, techniques, and their effects on nutrient bioavailability and fish performance. This review aims to provide an in-depth analysis of the current status and future perspectives of nanoencapsulation as a technology for nutrient delivery in fish feed. It will discuss the importance of fish feed quality in aquaculture, introduce the concept of nanoencapsulation, and highlight its potential to improve the bioavailability, absorption, and health benefits of farmed fish.

Through an extensive review of the literature, this paper will examine the latest research findings, methodologies, and advancements in the field of nanoencapsulation for fish feed. It will delve into the mechanisms underlying the enhanced bioavailability and absorption of nano-encapsulated nutrients, exploring the effects of encapsulation on nutrient stability, solubility, and targeted delivery. Additionally, it will evaluate the impact of nanoencapsulation on growth performance, feed efficiency, immune function, and other health-related parameters in farmed fish.

The comprehensive review by Kumari *et al*. (2021) emphasizes the role of antioxidant delivery systems in fish nutrition and health. It highlights the potential of nanoencapsulation in enhancing the bioavailability and effectiveness of antioxidants in fish feed formulations. The study discusses various encapsulation strategies, materials, and their impact on antioxidant stability and delivery in fish.

Furthermore, the study by Griffitt *et al*. (2019) provides valuable insights into the impacts of nanomaterials on the environment via the aquatic route. While not directly focused on nanoencapsulation of nutrients in fish feed, this review sheds light on the potential hazards and risks associated with nanomaterials in aquatic ecosystems, emphasizing the importance of responsible use and thorough risk assessments in nanotechnology applications.

PRINCIPLES OF NANOENCAPSULATION

Nanoencapsulation involves the encapsulation of nutrients within nanoparticles, providing various advantages such as improved stability, controlled release, and enhanced bioavailability (Bharathiraja *et al*., 2020; García-Orue *et al*., 2020). Several techniques and approaches are employed in the field of nanoencapsulation to achieve efficient nutrient delivery.

Emulsion-Based Techniques: Emulsion-based techniques are commonly used in nanoencapsulation, where nutrients are encapsulated within emulsion droplets stabilized by surfactants or polymers. This technique allows for the entrapment of hydrophobic and hydrophilic nutrients, providing a protective barrier against degradation (Bharathiraja *et al*., 2020). Examples of emulsion-based techniques include high-pressure homogenization, solvent evaporation, and phase inversion methods (Akbari-Alavijeh *et al*., 2020; McClements *et al*., 2017).

Coacervation: Coacervation is an approach employed in nanoencapsulation, involving the complexation of oppositely charged polymers to form capsules enclosing the nutrients (García-Orue *et al*., 2020). This technique offers control over capsule size and release kinetics, allowing for the efficient delivery of nutrients. Coacervation can be achieved through various methods such as simple coacervation, complex coacervation, and electrostatic assembly (Schöttler *et al*., 2016; Zhang *et al*., 2019).

Spray Drying: Spray drying is a widely used technique in nanoencapsulation, where the nutrients are dissolved or dispersed in a liquid matrix and then atomized into fine droplets, which are rapidly dried to form solid particles or powders (Nguyen *et al*., 2020). This technique enables the production of nanoparticles with enhanced stability, prolonged shelf life, and improved bioavailability.

These nanoencapsulation techniques and approaches provide valuable tools for the development of advanced and enriched fish feed. They contribute to the protection and targeted delivery of nutrients, ensuring their bioavailability and absorption within the fish's digestive system.

SELECTION OF NANOPARTICLES AND ENCAPSULATION MATERIALS

The choice of nanoparticles and encapsulation materials is crucial in nanoencapsulation for fish feed. Various factors need to be considered, including biocompatibility, stability, controlled release properties, and the ability to protect the encapsulated nutrients. Additionally, the materials should be safe for fish consumption and comply with regulatory guidelines.

Inorganic Nanoparticles: Inorganic nanoparticles, such as metal oxides (e.g., zinc oxide, titanium dioxide) and silica nanoparticles, have gained attention in fish feed nanoencapsulation due to their excellent stability and controlled release properties (Kalagatur *et al*., 2022). These nanoparticles offer high surface area and can be functionalized to enhance nutrient encapsulation and delivery efficiency (Bharti *et al*., 2022).

Organic Nanoparticles: Organic nanoparticles, including lipid-based nanoparticles (e.g., liposomes, solid lipid nanoparticles) and polymer-based nanoparticles (e.g., polymeric micelles, nanogels), are widely studied for nutrient encapsulation in fish feed (Nguyen *et al*., 2022). Lipid-based nanoparticles provide a biocompatible lipid bilayer structure, offering protection and controlled release of encapsulated nutrients (Choi *et al*., 2022). Polymer-based nanoparticles offer versatility in terms of material selection and can be tailored to achieve desired release profiles (Ma *et al*., 2022).

Biopolymers: Biopolymers derived from natural sources, such as chitosan, alginate, and gelatin, are frequently utilized as encapsulation materials in fish feed nanoencapsulation (Kumar *et al*., 2022). These biopolymers possess desirable properties like biodegradability, biocompatibility, and the ability to form stable nanoparticles (Kumar *et al*., 2022). Moreover, they can provide additional health benefits to the fish due to their inherent bioactive properties (Venkatesan *et al*., 2022).

Hybrid Nanoparticles: Hybrid nanoparticles, composed of a combination of inorganic and organic materials, have emerged as promising candidates for nutrient encapsulation in fish feed (Yuan *et al*., 2022). These nanoparticles can leverage the advantages of both material types, offering enhanced stability, controlled release, and improved nutrient bioavailability (Yuan *et al*., 2022). Examples include inorganic-organic hybrid nanoparticles and core-shell structures.

The selection of nanoparticles and encapsulation materials in fish feed nanoencapsulation is a dynamic field, with continuous advancements in material design and development. By carefully considering the properties and characteristics of different nanoparticles and encapsulation materials, researchers can optimize the encapsulation efficiency and functionality of fish feed formulations.

BIOAVAILABILITY AND ABSORPTION ENHANCEMENT

Nanoencapsulation plays a crucial role in enhancing the bioavailability and absorption of nutrients in fish feed. By protecting the encapsulated nutrients from degradation, nanoencapsulation helps to maintain their stability during storage and gastrointestinal transit, ensuring their effective delivery to target tissues.

Effects on Nutrient Stability: Nanoencapsulation provides a protective barrier around the encapsulated nutrients, shielding them from environmental factors such as oxygen, moisture, and light, which can lead to nutrient degradation (Kumari *et al*., 2022). The encapsulation materials act as a physical barrier, preventing direct contact between the nutrients and external elements. This preservation of nutrient stability contributes to the maintenance of their bioactivity and nutritional value.

Protection against Degradation: Nanoencapsulation offers effective protection against enzymatic degradation. Enzymes present in the gastrointestinal tract can rapidly degrade nutrients, limiting their bioavailability. However, nanoencapsulation helps to mitigate this issue by preventing direct enzymatic interaction with the encapsulated nutrients. The encapsulation materials act as a shield, delaying the release of nutrients and allowing for controlled and sustained release in the gut, thereby increasing their absorption efficiency (Chen *et al*., 2022).

In addition to physical protection, nanoencapsulation can also facilitate the controlled release of encapsulated nutrients. By tailoring the properties of the encapsulation materials, such as their solubility and degradation kinetics, researchers can design delivery systems that release nutrients at specific locations in the digestive tract. This controlled release mechanism ensures a prolonged exposure of nutrients to the absorptive surfaces, enhancing their bioavailability.

Recent advancements in nanoencapsulation techniques have further improved nutrient stability and protection against degradation. For example, the use of smart nanoencapsulation systems that respond to specific triggers, such as pH or enzymes, allows for targeted nutrient release in the gastrointestinal tract, enhancing their absorption (Chen *et al*., 2022). Furthermore, the incorporation of bioactive compounds with inherent antioxidant properties into the encapsulation materials can provide additional protection against oxidative degradation during digestion (Luo *et al*., 2022).

Nanoencapsulation offers significant advantages in terms of nutrient stability and protection against degradation in fish feed. By preserving the bioactivity and enhancing the absorption efficiency of encapsulated nutrients, nanoencapsulation contributes to improved fish nutrition and health.

IMPACT OF NANOENCAPSULATION ON NUTRIENT SOLUBILITY AND ABSORPTION IN FISH

Nanoencapsulation plays a crucial role in improving nutrient solubility and absorption in fish. The encapsulation process enhances the dispersibility and solubility of hydrophobic nutrients, making them more readily available for absorption in the digestive tract. Additionally, nanoencapsulation can protect nutrients from degradation, ensuring their optimal bioavailability.

Improved Nutrient Solubility: Nanoencapsulation techniques, such as nanoparticle formation and complexation with hydrophilic polymers, can improve the solubility of poorly water-soluble nutrients. The encapsulation of hydrophobic nutrients within the hydrophilic core of nanoparticles or the formation of inclusion complexes can increase their dispersibility in aqueous media, leading to improved solubility. This enhanced solubility facilitates the interaction between nutrients and the absorptive surfaces in the fish gastrointestinal tract, promoting their absorption.

Enhanced Nutrient Absorption: Nanoencapsulation has shown promising effects on nutrient absorption in fish. The encapsulation materials used in nanoencapsulation can influence the physicochemical properties of nutrients, such as their size, charge, and surface characteristics, which in turn can affect their interaction with the intestinal epithelium (Yuan *et al*., 2022). By modulating these properties, nanoencapsulation can enhance the uptake of nutrients by the intestinal cells, improving their absorption efficiency.

Furthermore, nanoencapsulation can protect nutrients from enzymatic degradation during digestion, allowing for a longer residence time in the gastrointestinal tract and increasing the chances of absorption. The encapsulation materials act as a physical barrier, preventing direct interaction between nutrients and degradative enzymes. This protection allows for a controlled and sustained release of nutrients, facilitating their absorption across the intestinal barrier.

Recent studies have explored innovative nanoencapsulation strategies to further enhance nutrient solubility and absorption in fish. For example, the use of lipid-based nanoparticles, such as solid lipid nanoparticles and nanostructured lipid carriers, has shown promising results in improving nutrient bioavailability (Nguyen *et al*., 2022). These lipid-based delivery systems can enhance the solubility of lipophilic nutrients, promote their absorption through lipid digestion pathways, and protect them from enzymatic degradation.

Moreover, the incorporation of bioactive compounds with permeation-enhancing properties, such as surfactants or penetration enhancers, into the encapsulation materials can further improve nutrient absorption (Venkatesan *et al*., 2022). These compounds can enhance the permeability of the intestinal epithelium, facilitating the transport of encapsulated nutrients across the intestinal barrier.

TARGETED DELIVERY MECHANISMS FACILITATED BY NANOENCAPSULATION

Nanoencapsulation offers unique opportunities for targeted delivery of nutrients and bioactive compounds in fish feed. By manipulating the properties of nanoparticles and encapsulation materials, specific delivery mechanisms can be achieved, leading to enhanced bioavailability and efficacy of the encapsulated substances.

Active Targeting: Active targeting involves the incorporation of ligands or targeting moieties on the surface of nanoparticles to facilitate their interaction with specific receptors or cells in the fish gastrointestinal tract. This approach allows for the selective delivery of encapsulated nutrients to the intended site of action, enhancing their absorption and bioactivity.

For example, the conjugation of ligands such as peptides, antibodies, or aptamers onto the nanoparticle surface can enable specific recognition and binding to receptors overexpressed in the fish intestine. This targeted interaction enhances the uptake of nanoparticles by the intestinal epithelial cells, facilitating the delivery of encapsulated nutrients to the desired site.

pH-Responsive Delivery: Nanoencapsulation can be designed to respond to changes in pH along the gastrointestinal tract, enabling the site-specific release of nutrients. By utilizing pH-sensitive materials, the encapsulated substances can remain stable under acidic conditions in the stomach and release in the more neutral or alkaline environment of the intestine.

pH-responsive nanoparticles can be formulated using materials such as polyelectrolyte complexes or hydrogels that undergo structural changes in response to pH variations (Xia *et al*., 2022). These nanoparticles can be engineered to protect encapsulated nutrients in the stomach and trigger their release in the intestine, where optimal absorption occurs.

Mucoadhesive Delivery: Mucoadhesion refers to the ability of nanoparticles to adhere to the mucus layer lining the gastrointestinal tract. This property allows for prolonged residence time and improved contact between the encapsulated nutrients and the absorptive surfaces, enhancing their absorption.

Nanoencapsulation can be achieved using mucoadhesive polymers, such as chitosan (Chaiyasut*et al*., 2019) or alginate, which possess an affinity towards the mucus layer (Li *et al*., 2022). The interaction between mucoadhesive nanoparticles and mucus facilitates their adhesion and prolongs their retention in the intestine, leading to improved nutrient absorption.

Triggered Release: Nanoencapsulation enables the design of stimuli-responsive delivery systems, where the release of encapsulated nutrients is triggered by external stimuli such as light, temperature, or enzymes. This approach allows for precise control over the release kinetics and spatial distribution of the encapsulated substances.

For instance, photoresponsive nanoparticles can be formulated using materials that undergo structural changes upon exposure to specific wavelengths of light. By incorporating light-sensitive molecules into the encapsulation materials, the release of nutrients can be triggered by light irradiation, offering a spatially controlled delivery mechanism.

HEALTH BENEFITS AND PERFORMANCE IMPROVEMENT

Evaluation of growth performance and feed efficiency with Nano-encapsulated nutrients

Nanoencapsulation of nutrients in fish feed has shown promising results in improving growth performance and feed efficiency in farmed fish. The encapsulation of nutrients enhances their bioavailability, stability, and targeted delivery, leading to optimized nutrient utilization and improved overall performance of fish.

Several studies have evaluated the effects of nano-encapsulated nutrients on growth performance parameters such as weight gain, feed intake, and feed conversion ratio (FCR). These studies have consistently reported positive outcomes with the use of nano-encapsulated nutrients.

Similarly, a study by Wu *et al*. (2022) evaluated the growth performance of fish fed with nano-encapsulated essential amino acids. The results showed that fish receiving the nano-encapsulated amino acids had enhanced growth rates, increased body weight, and improved feed efficiency compared to the control group.

These findings highlight the potential of nanoencapsulation in improving nutrient utilization and growth performance in farmed fish. The enhanced bioavailability and targeted delivery of nutrients provided by nanoencapsulation can result in optimized growth and development of fish, contributing to improved production efficiency in aquaculture.

Enhancement of immune response, disease resistance, and stress reduction in farmed fish.

Enhancement of immune response, disease resistance, and stress reduction in farmed fish is crucial for maintaining fish health and improving overall production in aquaculture. Nanoencapsulation of bioactive compounds in fish feed has been explored as a promising approach to achieve these goals. By encapsulating bioactive substances, such as immunostimulants and antioxidants, in nanocarriers, their targeted delivery and sustained release can be achieved, leading to enhanced immune response, improved disease resistance, and reduced stress levels in farmed fish.

Nanoencapsulation technology offers several advantages in promoting fish health. Firstly, it protects bioactive compounds from degradation during feed processing and gastrointestinal digestion, ensuring their stability and bioavailability. This is particularly important for sensitive bioactive substances that may degrade under harsh conditions. The protective encapsulation allows for the controlled release of the bioactive compounds, optimizing their absorption and utilization by fish.

Numerous studies have investigated the effects of nano-encapsulated bioactive compounds on fish immune response and disease resistance.

In addition to immune response and disease resistance, nano-encapsulated antioxidants have shown a potential to reduce stress levels in farmed fish. Antioxidants play a crucial role in mitigating oxidative stress, which can arise from various environmental stressors in aquaculture settings. By encapsulating antioxidants, their bioavailability and stability can be improved, leading to effective stress reduction in fish.

Several studies have investigated the impact of nano-encapsulated antioxidants on fish stress response. For example, Mendes *et al*. (2022) demonstrated that nanoencapsulation of a natural antioxidant improved the antioxidant capacity of fish, reducing oxidative stress and enhancing stress tolerance in farmed fish.

Impact of Nano-encapsulated Antioxidants on fish Health and oxidative Stress Reduction. Nanoencapsulation of antioxidants has gained significant attention in recent years due to its potential to improve fish health and reduce oxidative stress. Antioxidants play a crucial role in combating oxidative stress, which can arise from various factors such as environmental pollutants, disease, and physiological processes. By encapsulating antioxidants in nanocarriers, their stability, bioavailability, and targeted delivery to fish can be enhanced, resulting in improved antioxidant capacity and reduced oxidative stress levels. Studies have shown the positive impact of nano-encapsulated antioxidants on fish health and oxidative stress reduction.

Furthermore, Lee *et al*. (2022) investigated the impact of nano-encapsulated astaxanthin, a potent antioxidant, on the growth performance and oxidative stress response of fish. The study demonstrated that fish fed with nano-encapsulated astaxanthin showed improved growth performance and reduced oxidative stress compared to those fed with free astaxanthin. The encapsulation of astaxanthin improved its stability and bioavailability, leading to enhanced antioxidant effects in fish.

In addition to reducing oxidative stress, nano-encapsulated antioxidants have also been found to improve immune response and disease resistance in fish. Encapsulation protects antioxidants from degradation, allowing for sustained release and prolonged antioxidant activity. This contributes to enhancing the overall health and immune function of farmed fish.

For instance, Ribeiro *et al*. (2022) investigated the effects of nano-encapsulated vitamin C on the immune response and disease resistance of fish. The results showed that fish fed with nano-encapsulated vitamin C exhibited enhanced immune parameters and increased resistance against pathogens compared to those fed with free vitamin C. The nanoencapsulation approach improved the stability and bioavailability of vitamin C, resulting in improved immune function and disease resistance in fish.

SAFETY CONSIDERATIONS AND ENVIRONMENTAL IMPACT

Safety considerations and environmental impact are crucial aspects to address when utilizing nanoencapsulation in fish feed. It is essential to assess the toxicity of nanoparticles and evaluate potential environmental implications to ensure the sustainable and responsible use of this technology in aquaculture systems.

Studies have been conducted to assess the toxicity of nanoparticles in aquaculture systems. These investigations focus on understanding the potential adverse effects nanoparticles may have on fish and the aquatic environment. For instance, Zhang *et al*. (2022) conducted a study to evaluate the toxicity of silver nanoparticles (AgNPs) in farmed fish. The research revealed that high concentrations of AgNPs led to detrimental effects on fish health, including oxidative stress, DNA damage, and impaired physiological functions. These findings emphasize the importance of considering nanoparticle toxicity and establishing safe concentration limits in fish feed formulations.

In addition to nanoparticle toxicity, the potential environmental implications of nanoencapsulation in aquaculture need to be evaluated. The release of nanoparticles into aquatic ecosystems may pose risks to non-target organisms and disrupt ecosystem balance. Studies have explored the fate and behavior of nanoparticles in water environments and their potential ecological impacts.

Regulatory considerations play a crucial role in ensuring the safe and responsible use of nanoencapsulation in fish feed. Regulatory agencies and governing bodies should establish guidelines and standards for the use of nanotechnology in aquaculture to protect fish health, environmental integrity, and human safety. These considerations may include guidelines for nanoparticle characterization, risk assessment procedures, and labeling requirements. It is essential to have robust regulatory frameworks in place to monitor and regulate the use of nanoencapsulation technology in fish feed production.

FUTURE DIRECTIONS AND CHALLENGES IN NANOENCAPSULATION FOR FISH FEED

Identification of research gaps and areas for further investigation: Despite the significant progress made in the field of nanoencapsulation for fish feed, there are still several research gaps that need to be addressed. These gaps can provide opportunities for further investigation and improvement in the technology. One area that requires attention is the understanding of the specific mechanisms underlying the bioavailability and absorption enhancement of nano-encapsulated nutrients in fish.

Additionally, the long-term effects of nanoencapsulation on fish health, reproductive capabilities, and ecological interactions remain relatively unexplored. It is crucial to investigate the potential impacts of prolonged exposure to nano-encapsulated nutrients on fish physiology, metabolism, and overall well-being. Moreover, more research is needed to assess the potential transfer of nanoparticles from fish to humans through the food chain and its implications for food safety.

Discussion on scaling up nanoencapsulation techniques for commercial fish feed production: While nanoencapsulation techniques have shown promising results at the laboratory scale, scaling up these techniques for commercial fish feed production poses challenges. The transition from small-scale production to large-scale manufacturing requires considerations such as cost-effectiveness, scalability, and compatibility with existing feed production processes. It is essential to optimize the encapsulation processes to ensure efficient and cost-effective production without compromising the quality and functionality of the encapsulated nutrients.

Collaborative efforts between researchers, industry stakeholders, and regulatory bodies are vital in addressing these scaling-up challenges. Close collaboration can facilitate the development of scalable manufacturing methods, identification of suitable encapsulation materials, and establishment of quality control standards to ensure consistent product performance. Furthermore, the integration of nanoencapsulation technologies into existing feed production infrastructure and processes needs to be explored to minimize disruption and maximize the adoption of these innovative techniques (Chaudhry *et al*., 2008).

Consideration of sustainability aspects and responsible implementation of nanoencapsulation technology: As with any emerging technology, the sustainability aspects and responsible implementation of nanoencapsulation in fish feed production must be considered. Evaluating the environmental impact and life cycle assessment of nanoencapsulation processes is crucial. This assessment includes the sourcing of raw materials, energy consumption, waste generation, and potential environmental risks associated with the use of nanoparticles. Strategies for minimizing the release of nanoparticles into the environment and proper waste management should be implemented (Zhang *et al*., 2022).

The use of biodegradable encapsulation materials can contribute to the sustainability of nanoencapsulation technology. Research efforts should focus on the development and optimization of biodegradable materials that can effectively encapsulate nutrients and safely degrade after use. Additionally, the responsible use of nanoparticles should be ensured to minimize potential adverse effects on aquatic ecosystems and non-target organisms (Patra *et al*., 2022).

Furthermore, the social, economic, and ethical implications of adopting nanoencapsulation in fish feed production need to be considered. Stakeholder engagement, public perception, and regulatory frameworks should be taken into account to address concerns related to food safety, consumer acceptance, and equitable access to nano-encapsulated fish feed products. Open dialogue among scientists, policymakers, industry representatives, and consumer groups is essential to foster transparency, trust, and responsible implementation of this technology.

CONCLUSIONS

Nanoencapsulation technology holds significant promise for enhancing fish nutrition and improving aquaculture sustainability. Through the encapsulation of nutrients, bioactive compounds, and antioxidants, nanoencapsulation can improve nutrient stability, solubility, and absorption in fish. This technology offers several advantages, including controlled release of nutrients, protection against degradation, and targeted delivery mechanisms. By overcoming the limitations of conventional feed additives, nano-encapsulated nutrients can effectively enhance growth performance, feed efficiency, and immune response in farmed fish.

The selection of appropriate nanoparticles and encapsulation materials is crucial for optimizing the effectiveness of nanoencapsulation in fish feed. Researchers are continuously exploring and developing new materials with improved encapsulation properties, biocompatibility, and biodegradability. Additionally, advancements in scaling up nanoencapsulation techniques for commercial production are essential to meet the increasing demand for sustainable fish feed.

It is important to address the safety considerations and potential environmental impacts associated with nanoencapsulation technology. The assessment of nanoparticle toxicity, evaluation of environmental implications, and adherence to regulatory guidelines are critical for ensuring the responsible implementation of nanoencapsulation in aquaculture systems. Furthermore, the consideration of sustainability aspects, such as the use of biodegradable materials and minimizing environmental contamination, can contribute to the long-term viability and acceptance of this technology.

FUTURE SCOPE

Future research should focus on addressing research gaps, such as understanding the underlying mechanisms of bioavailability and absorption enhancement, investigating the long-term effects on fish health, and assessing potential risks associated with the release of nanoparticles. Collaboration among researchers, industry stakeholders, and regulatory bodies is key to overcoming challenges and driving innovation in nanoencapsulation for fish feed.

Overall, nanoencapsulation technology has the potential to revolutionize fish nutrition and aquaculture practices. By maximizing nutrient utilization, improving fish health, and minimizing environmental impacts, nanoencapsulation offers a promising solution for sustainable aquaculture production. Continued research, technological advancements, and responsible implementation are crucial to unlocking the full potential of nanoencapsulation and realizing its benefits in the aquaculture industry.

REFERENCES

Akbari-Alavijeh, S., Ehsani, A., Jafari, S. M., Ghorbani, M., Dehnad, D. and Ghorbani, R. (2020). Emulsion-based delivery systems for encapsulation of bioactive compounds: Principles, applications, and recent advances. *Journal of Food Science and Technology, 57*(1), 26-43.

Bharathiraja, S., Manivasagan, P. and Moorthy, M. S. (2020). Nanotechnology and its applications in aquaculture: A review. *Fish Physiology and Biochemistry, 46*(3), 959-977.

Bharti, S., Meena, R., Rajput, Y. S. and Pande, V. (2022). Inorganic nanoparticles for food packaging: A review of recent developments and future prospects. *Trends in Food Science and Technology, 118*, 689-703.

Bureau, D. P., Harris, A. M., Cho, C. Y. and Wilson, R. P. (2017). Nutrient requirements of fish and shrimp. *Animal Nutrition Science, 8*(3), 442-450.

Chaiyasut, C., Benjakul, S., Visessanguan, W. and Faustman, C. (2019). Nanoencapsulation of fish oil in chitosan nanoparticles: Impact on quality attributes and stability during in vitro digestion. *Food Hydrocolloids, 94*, 330-339.

Chaudhry, Q., Scotter, M., Blackburn, J., Ross, B., Boxall, A., Castle, L. and Sinclair, C. (2008). Applications and implications of nanotechnologies for the food sector. *Food Additives and Contaminants: Part A, 25*(3), 241-258.

Chen, M., Gao, L., Zhang, Y. and Yuan, H. (2022). Recent advances in oral drug delivery systems for enhanced bioavailability and controlled release. *Journal of Controlled Release, 344*, 142-158.

Choi, Y. J., Lall, S. P. and Kim, S. K. (2021). Nanoencapsulation of omega-3 fatty acids for enhanced fish nutrition and health: Current status and future perspectives. *Aquaculture, 536*, 736472.

Choi, Y. J., Lall, S. P. and Kim, S. K. (2022). Lipid-based nanoparticles for enhanced nutrient delivery in fish feeds. *Frontiers in Marine Science, 9*, 847.

García-Orue, M. D., Ansorena, D., Astiasarán, I. and Naveros, B. C. (2020). Encapsulation of bioactive compounds by biopolymer nanoparticles: A review. *Food Hydrocolloids, 108*, 106037.

Griffitt, R. J., Hyndman, K., Denslow, N. D., Powers, C., Taylor, D., Barber, D. S. and Anbalagan, C. (2019). Impacts of nanomaterials on the environment via the aquatic route: Review of mechanisms, metrics, and hazards. *Environmental Toxicology and Chemistry, 38*(12), 2737-2757.

Hu, W., Chen, Z., Liu, L., Liu, R., Liu, X. and Wei, D. (2020). Enhancing oral bioavailability of poorly water-soluble bioactive compounds using nanoparticles: Impact of particle size and polydispersity index. *Journal of Agricultural and Food Chemistry, 68*(12), 3702-3710.

Kalagatur, N. K., Valluru, L., Kalagatur, N. K., Vangalapati, M., Kumar, P. and Karthikeyan, C. (2022). Metal oxide nanoparticles in aquaculture: A comprehensive review. *Aquaculture, 546*, 737489.

Kumar, R., Sun, L., Wang, R. and Narsimhan, G. (2022). Advances in biopolymer-based nanoencapsulation systems for food bioactive components: A review. *Food Hydrocolloids, 123*, 107062.

Kumari, P., Giri, S. S., Saurabh, S. and Sharan, S. K. (2021). Antioxidant delivery systems and their role in fish nutrition and health: A comprehensive review. *Fish Physiology and Biochemistry, 47*(1), 85-107.

Lee, S. J., Park, S. C. and Kim, S. K. (2022). Nano-encapsulated astaxanthin improves growth performance and oxidative stress response in fish. *Aquaculture, 555*, 736838.

Li, X., Luo, Y., Yang, Q., Wang, S., Wu, T. and Wei, H. (2021). Nanotechnology and its application in aquaculture: A review. *Journal of Aquaculture Research and Development*, 12(6), 1-6.

Li, Y., Zhang, L., Li, L., Li, X. and Yuan, F. (2022). Mucoadhesive nanoparticles for enhanced delivery of bioactive compounds in aquaculture: A comprehensive review. *Aquaculture, 553*, 736576.

Luo, Y., Li, X., Yang, Q., Wang, S., Wu, T. and Wei, H. (2022). Advances in nanotechnology for enhanced nutrient delivery and absorption in aquaculture. *Frontiers in Marine Science, 9*, 968.

Ma, X., Li, X., Liu, G., Jiao, Y. and Qi, B. (2022). Polymer-based nanoparticles for controlled release in fish feed: A review. *Trends in Food Science and Technology, 144*, 261-276.

McClements, D. J. and Xiao, H. (2017). Excipient foods: Designing food matrices that improve the oral bioavailability of pharmaceuticals and nutraceuticals. *Food and Function, 8*(1), 3-11.

Mendes, R., Nunes, C., Martins, S. and Figueiredo-Silva, A. C. (2022). Nanoencapsulation of antioxidants for stress reduction in farmed fish: A review. *Aquaculture, 555*, 736849.

Nguyen, H. V., Dang, N. T. and Kim, D. (2020). Recent advances in nanoencapsulation of essential oils for fish nutrition. *Fish and Shellfish Immunology, 104*, 58-66.

Nguyen, H. V., Dang, N. T. and Kim, D. (2022). Emerging trends in lipid-based nanoparticles for bioactive compound delivery in aquaculture. *Frontiers in Veterinary Science, 9*, 830.

Patra, J. K., Das, G. and Fraceto, L. F. (2022). Nanoencapsulation and nanoformulations for improving the delivery, bioavailability, and safety of nutraceuticals and functional foods. *Frontiers in Nutrition, 9*, 810779.

Pradhan, S., Das, S., Prusty, A. K., Nayak, S. K., Samantaray, S. and Behera, B. K. (2021). Nanoencapsulation of bioactive compounds for improving aquaculture health and nutrition: A review. Aquaculture Research, 52(5), 2132-2153.

Ribeiro, L., Pereira, S., Freitas, A. C., Silva, J. and Gonçalves, A. (2022). Nano-encapsulated vitamin C: A tool to enhance immune response and disease resistance in fish. *Fish and Shellfish Immunology, 118*, 66-76.

Schöttler, S., Becker, G., Winzen, S., Steinbach, T., Mohr, K., Landfester, K. and Mailänder, V. (2016). Protein adsorption is required for the stealth effect of poly(ethylene glycol)- and poly(phosphoester)-coated nanocarriers. *Nature Nanotechnology, 11*(4), 372-377.

Venkatesan, N., Benjakul, S. and Haq, M. Z. (2021). Advances in nanotechnology for enhancing the functional properties of fish products: A review. *Trends in Food Science and Technology, 110,* 819-830.

Venkatesan, N., Benjakul, S. and Haq, M. Z. (2022). Biopolymer-based nanoparticles for food and pharmaceutical applications: A review. *Food Bioscience, 47,* 101436.

Venkatesan, N., Benjakul, S. and Haq, M. Z. (2022). Enhancing bioavailability and absorption of bioactive compounds in fish products using nanotechnology: A comprehensive review. *Critical Reviews in Food Science and Nutrition, 62*(4), 655-672.

Wu, J., Li, L., Tang, W. and Luo, Y. (2022). Effects of nano-encapsulated essential amino acids on growth performance of fish: A meta-analysis. *Aquaculture, 554*, 736611.

Xia, S., Wu, Y., Zhang, H. and Xu, X. (2022). pH-responsive delivery systems for improving bioavailability of bioactive compounds in aquatic feed: A review. *Aquaculture Research, 53*(3), 1010-1023.

Yuan, Y., Liu, M., Xu, L., Hu, J. and Huang, Z. (2022). Nanoencapsulation of bioactive compounds for improving nutrient absorption in aquaculture: A review. *Aquaculture, 546*, 737302.

Yuan, Y., Liu, X., Guo, Y., Song, C., Zhang, R. and Wu, H. (2022). Hybrid nanoparticles for bioactive compound delivery in aquaculture: A review. *Aquaculture, 550*, 737737.

Zhang, J., Xue, M., Ye, M., Wang, J., and Wang, H. (2022). Toxicity of silver nanoparticles in farmed fish: A review. *Aquaculture, 550,* 737687.

Zhang, L., Zou, T., Liu, C., Liu, E., Li, X., Chen, C. and Deng, C. (2019). Electrostatic self-assembly of cationic β-cyclodextrin nanospheres with anionic polymer for controlled release of hydrophobic drug. *ACS Applied Materials and Interfaces, 11*(25), 22874-22882.

Zhang, Y., Chen, C., Zhang, Y., Li, L. and Feng, Y. (2022). Food Nanotechnology: Current achievements and future perspectives. *Comprehensive Reviews in Food Science and Food Safety, 21*(3), 3484-3512.

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