AgriCos e-Newsletter
ISSN: 2582-7049
AgriCos e-Newsletter
Open Access Multidisciplinary Monthly Online Magazine
Volume: 06 Issue: 04 April 2025 Article No: 14

Nano-Encapsulated Diets in Aquaculture: Advancing Nutrition and Sustainability

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SUMMARY

Aquaculture is a rapidly expanding industry which is crucial to global food security and economic development. The aquafeed sector is very crucial; however, the reliance on traditional feed ingredients such as fishmeal and soy present significant sustainability challenges. Nanotechnology, particularly nanoencapsulation, offers potential solutions to enhance feed sustainability. Nanoencapsulation involves the encapsulation of nutrients, bioactive compounds, or pharmaceuticals within nanoparticles, thereby improving their stability, bioavailability and controlled release. This technology provides distinct advantages in aquaculture, including enhanced nutrient absorption, growth promotion and improved disease resistance in aquatic species. Various nanomaterials, such as nanoparticles, nano emulsions and nanocomposites are being developed to optimize feed formulations and mitigate the environmental impacts of aquaculture. Additionally, green synthesis methods are being investigated as sustainable, non-toxic alternatives for nanoparticle production. Despite the promising benefits, challenges such as consumer acceptance, nanoparticle stability, safety and environmental concerns must be addressed. In conclusion, nano encapsulation offers significant potential for advancing sustainable aquaculture practices by optimizing nutrient digestibility, minimizing waste and improving the health & productivity of farmed fish.

INTRODUCTION

Aquaculture is the fastest-growing sector in the food industry, currently contributing to over 50% of global seafood production for consumption (FAO, 2024). It plays a crucial role in food security and economic development. As the sector expands and demands for nutritious food rise, it is essential for aquaculture to adopt sustainable practices. The aquafeed industry is key to meeting the growing aquatic animal feed needs. However, aquaculture's rapid growth increases feed demand, which is the largest variable cost. This raises sustainability concerns, particularly due to the industry's reliance on traditional feed ingredients like fishmeal and soy products. Achieving sustainability requires exploring alternative feed sources and improving the efficiency of existing ingredients. Nanotechnology is increasingly being explored in aquaculture for its potential to enhance sustainability by developing innovative aquafeed formulations that address environmental challenges linked to conventional feed. Feed additives have long been used in the industry to improve the nutritional quality of feed, promote better growth, strengthen disease resistance, and improve the overall health of farmed animals. The use of nanoparticles as feed additives in aquaculture presents new opportunities to further improve the benefits of aquaculture feed. Nanoelements have the potential to enhance protein stability, which can positively impact biological functions such as digestion, metabolism, and nutrient absorption. These properties of nanomaterials offer transformative potential, not only by optimizing food production processes and increasing efficiency but also by creating new functional foods with superior qualities. This advancement promises to improve the nutritional value, safety, and overall quality of food products, representing a significant step toward meeting the changing demands of consumers and ensuring better food production standards, while enhancing dietary quality and reducing the environmental impacts of aquaculture.

Nanoencapsulation

Nanoencapsulation is a technique that involves enclosing nutrients, bioactive substances, or medications in nanoparticles, which range in size from 1 to 1000 nanometers (nm). This process offers several benefits, such as improved stability of sensitive compounds, controlled release of encapsulated substances, and enhanced bioavailability, ensuring that the nutrients are more efficiently absorbed. The nanoparticles act as a protective shield, preventing degradation caused by environmental elements like light, heat, or oxygen. Additionally, nanoencapsulation can be used for targeted delivery, providing more precise control over the distribution and utilization of the encapsulated material.

Common methods include:

Emulsion-Based Methods: In this technique, nutrients are enclosed in droplets of emulsion stabilized by surfactants or polymers, offering protection against degradation.

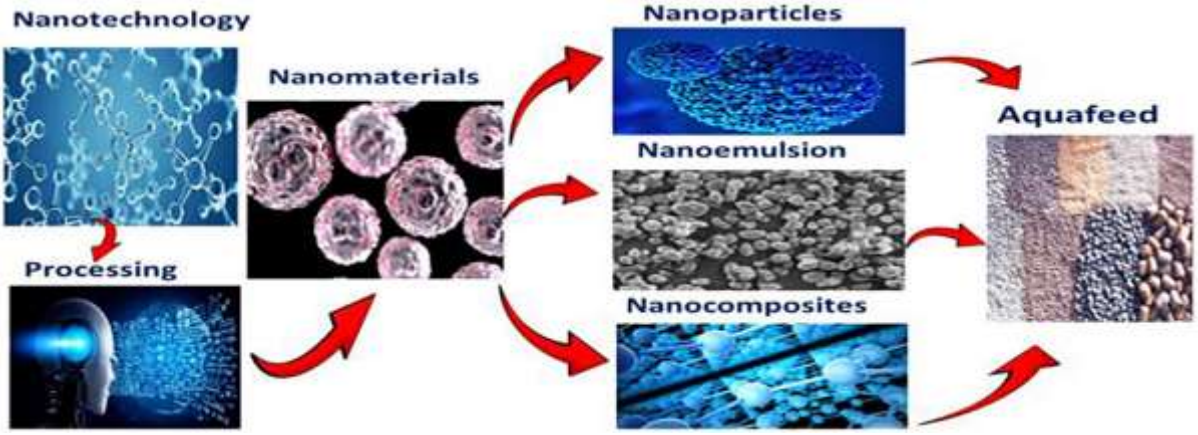
Coacervation: Oppositely charged polymers form capsules around the nutrients, allowing for precise control over capsule size and the release of the encapsulated substances.

Spray Drying: Nutrients are dissolved or dispersed in a liquid, atomized into droplets, and rapidly dried into solid particles, which improves their stability and bioavailability.

These techniques are essential in developing specialized fish feed, ensuring the efficient delivery and absorption of nutrients within the fish's digestive system.

Material selection

Three key nanomaterials - nanoparticles, nanoemulsions, and nanocomposites—produced through nanotechnology have demonstrated potential for improving formulated diets in aquaculture. Each of these nanomaterials can be used for distinct purposes.



Source: Mitra et al., 2025

Nanoparticles enhance aquaculture sustainability by improving nutrient absorption throughout the digestive tract. They can encapsulate essential nutrients like vitamins, minerals, and fatty acids, protecting them from degradation and ensuring targeted delivery. This approach optimizes feeding, metabolism, and growth while reducing environmental impact. Nanoparticle-encapsulated nutrients and bioactive compounds have been shown to improve growth and health in fish, offering more efficient nutrient uptake than traditional feed formulations.

Nanoemulsions produced through nanotechnology are stable oil-in-water suspensions that enhance the bioavailability of lipophilic compounds. They can be used to coat feed pellets, acting as carriers for bioactive components, protecting them from degradation, and improving essential oils' bioavailability and antimicrobial activity. This improves the shelf life and palatability of the feed, ensuring a consistent nutrient supply to aquatic organisms.

Nanocomposites are emerging as a new class of materials with the potential to address water pollution. Made from natural biopolymers like lipids, proteins, and polysaccharides, they are eco-friendly, non-carcinogenic, and edible. These properties make them an alternative to petrochemical-based plastics. In aquaculture, nanocomposites enhance nutrient delivery and bioavailability in aquafeed, increasing feed consumption by aquatic animals and thereby reducing waste and pollution.

Organic Nanoparticles: Lipid-based and polymer-based nanoparticles are used in fish feed for nutrient encapsulation. Lipid nanoparticles offer controlled release, while polymer nanoparticles allow customization of release profiles.

Biopolymers: Natural biopolymers like chitosan and gelatin are used in nanoencapsulation for fish feed. They are biodegradable, biocompatible, and can provide additional health benefits to fish.

Hybrid Nanoparticles: Hybrid nanoparticles, made from inorganic and organic materials, enhance nutrient stability, controlled release, and bioavailability in fish feed.

Inorganic Nanoparticles: Inorganic nanoparticles like metal oxides (e.g., zinc oxide, titanium dioxide) and silica are valued in fish feed nanoencapsulation for their stability and controlled release. These nanoparticles can be modified with a high surface area to improve nutrient encapsulation and delivery efficiency.

Delivery of feed

Delivery systems for feed supplements and nutraceuticals use various methods, such as nanoemulsions, surfactant micelles, emulsion micelles, emulsion bilayers, and reverse micelles. Advanced nano-enabled systems

offer several benefits, including reduced risk of nutrient leaching into water, lower dosage requirements, protection against oxidation and interactions with feed ingredients, enhanced efficacy of antioxidants and preservatives, improved bioavailability of active components, and better chemical stability. These systems also ensure stability under mechanical, thermal, and pH conditions, prolonged protection during storage, and extended shelf life. As a result, nanotechnology provides a promising method for encapsulating essential nutrients in animal feed, optimizing their delivery and effectiveness.

Bioavailability

Nanoencapsulation significantly improves the bioavailability and absorption of nutrients in fish feed by protecting the encapsulated nutrients from degradation. This process helps maintain nutrient stability during storage and passing through the digestive system, ensuring effective delivery to target tissues.

Impact on Nutrient Stability: Nanoencapsulation creates a protective barrier around nutrients, safeguarding them from environmental factors like oxygen, moisture, and light, which could otherwise cause degradation. This protection helps maintain their bioactivity and nutritional value.

Shielding from Degradation: Nanoencapsulation helps prevent the enzymatic breakdown of nutrients in the digestive system. Creating a barrier against enzymes ensures controlled, sustained nutrient release, improving absorption efficiency.

Controlled Release of Nutrients: Beyond physical protection, nanoencapsulation enables the gradual and controlled release of nutrients, optimizing their delivery and absorption in the gut.

Absorption

Nanoencapsulation enhances nutrient solubility and absorption in fish, improving bioavailability and protecting nutrients from degradation.

Boosting Nutrient Solubility: Nanoencapsulation increases the solubility and dispersibility of hydrophobic nutrients, making them more easily absorbed in the digestive system.

Promoting Efficient Nutrient Absorption: It improves nutrient absorption by modifying properties like size and charge, and protects nutrients from enzymatic degradation, allowing for controlled release and better absorption.

Mechanism

Nanoencapsulation provides innovative strategies for precisely delivering nutrients and bioactive compounds in fish feed, enhancing their absorption and effectiveness.

Targeted Delivery Mechanisms: Attaching ligands like peptides or antibodies to nanoparticles directs nutrients to specific receptors in the fish digestive tract, improving their bioavailability and bioactivity.

pH-Sensitive Release: Nanoencapsulation can be engineered to release nutrients at specific sites in response to pH changes in the digestive system. This ensures nutrients are protected in the stomach and released in the intestine for optimal absorption.

Adhesive Release System: Mucoadhesive nanoparticles cling to the mucus layer in the gastrointestinal tract, extending their residence time and facilitating better contact between the nutrients and absorptive surfaces, which enhances nutrient absorption.

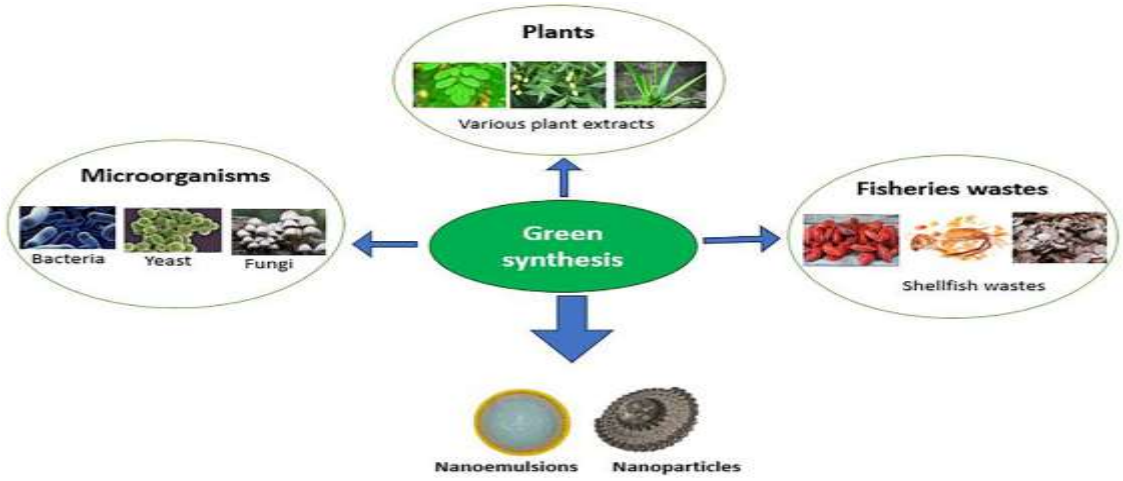
Examples

In recent years, there has been growing interest in studying dietary feed additives containing nanoparticles of selenium, manganese, zinc, iron, gold, copper, magnesium, nano-encapsulated ascorbic acid and chitosan. These additives offer multiple benefits for aquatic animals, surpassing conventional feed formulations in terms of enhanced growth performance and health.

Green Synthesis

Nanoparticles for feed formulations can be produced through eco-friendly methods like green synthesis. Green synthesis is a sustainable and environmentally friendly approach that uses microorganisms, such as bacteria, fungi, yeast, and plants, to safely produce various compounds. These organisms have long been utilized for their ability to convert inorganic metallic ions into metal nanoparticles. Plants, algae, fungi, bacteria, and viruses have all been used to produce low-cost, energy-efficient, and non-toxic nanomineral particles. Microorganisms, with their lipid-based amphipathic membranes, interact with their environment, triggering oxidation-reduction processes that accelerate nanoparticle production. As a result, green synthesis offers a sustainable and efficient method for generating nanoparticles suitable for aquafeed.

In addition to green synthesis methods, other promising approaches include nano emulsions and the use of fisheries waste. Nano emulsions are crucial in the development of edible films, offering potential for innovative feed solutions. Researchers are exploring these methods for sustainable and effective aquafeed production.



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Prospects

- Cost-effective disease management
- Enhanced growth and immune function
- Improved nutrient utilization
- Sustainable aquaculture practices
- Environmental benefits by reducing feed loss and nutrient leaching
- Tailored nutrition for different species and life stages

Challenges

- Consumer acceptance
- Nano particle stability
- Environmental impact
- Safety and toxicological concerns
- Regulatory changes
- Cost of production

CONCLUSION

Nanoencapsulation technology offers great potential for enhancing fish nutrition and promoting sustainable aquaculture. By encapsulating nutrients, bioactive compounds, and antioxidants, it improves nutrient stability, solubility, and absorption. This technology provides advantages such as controlled nutrient release, protection from degradation, and targeted delivery. Overcoming the limitations of traditional feed additives, nano-encapsulated nutrients can boost growth performance, feed efficiency, and immune response in farmed fish.

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