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Nanotechnology's Voyage: Enriching Aquafeed with Nutraceuticals

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This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The integration of nutraceuticals into aquafeed presents a promising approach to enhancing the health and growth performance of aquatic species. However, the effectiveness of these bioactive compounds is often limited by their stability, bioavailability, and delivery efficiency. Nanotechnology is a key tool in modern agriculture, and agri-food nanotechnology is expected to become a major economic force in the near future. This field focuses on sustainability and protecting foods produced through agriculture, including crops for both human consumption and animal feed. Nanotechnology offers innovative solutions to these challenges by enabling the encapsulation and controlled release of nutraceuticals, thereby improving their stability and bioavailability. This abstract explores the potential of nanotechnology in the development of advanced aquafeeds enriched with nutraceuticals. Key areas of focus include the design and synthesis of nanocarriers, such as liposomes, nanoparticles, and nano-emulsions, tailored for aquatic environments. The benefits of using nanotechnology for nutraceutical delivery in aquafeed are discussed, including enhanced nutrient absorption, targeted delivery, and sustained release, which collectively contribute to

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improved health and productivity of farmed aquatic species. The abstract also highlights current research trends, challenges, and future prospects in the application of nanotechnology to aquafeed, underscoring its potential to revolutionize aquaculture nutrition and support sustainable aquaculture practices.

Keywords: Nanotechnology; aquafeed enrichment; nutraceutical incorporation; aquaculture enhancement; sustainable nutrition.

1. INTRODUCTION

Aquaculture, now the fastest-growing sector in global food production, finds itself at a critical crossroads. Its remarkable expansion brings with it the urgent need to balance growth with the imperative of ensuring the well-being of the species being cultivated. Traditionally, the focus of aquaculture nutrition has been on optimizing growth rates, a pursuit often achieved through the formulation of highly nutritious feeds. However, recent shifts in the industry underscore a profound change in perspective, one that places greater emphasis on safeguarding the health of cultured species and preventing diseases. This evolving approach acknowledges that sustainable development in aquaculture hinges not only on maximizing output but also on nurturing robust, disease-resistant stocks. Consequently, the aquafeed sector is witnessing a significant transformation, with a growing recognition that the feeds themselves can play a pivotal role in promoting health and bolstering immunity among aquatic organisms (Glencross et al. 2007). This paradigm shift represents a departure from viewing feeds merely as vehicles for delivering essential nutrients and instead positions them as key agents in safeguarding the well-being of aquaculture stocks.

The incorporation of health-promoting components into aquafeeds marks a departure from conventional practices. Beyond meeting basic nutritional requirements, these feeds are designed to confer additional benefits that fortify the overall health and resilience of cultured species. Ingredients such as prebiotics, probiotics, immunostimulants, and natural antioxidants are increasingly finding their way into feed formulations, offering a multifaceted approach to enhancing immunity, combating pathogens, and mitigating stress in aquaculture environments. This holistic approach to aquafeed formulation not only underscores the industry's commitment to sustainability but also underscores its recognition of the interconnectedness between animal health, environmental integrity, and long-term viability (Gatlin et al. 2007). By prioritizing the health and well-being of cultured species, aquaculture stakeholders are not only ensuring the continued growth of the sector but also laying the groundwork for a more resilient and sustainable future. In this way, the evolution of aquafeeds reflects a broader shift towards a more holistic and environmentally conscious approach to food production one that recognizes the intricate interplay between human activity and the natural world.

Nutraceuticals, a term coined by Stephen De Felice in 1989 from "nutrition" and "pharmaceutical," are gaining prominence in aquaculture for their potential to enhance health and disease resistance. These bioactive compounds can include vitamins, minerals, herbal extracts, and other naturally derived substances that offer physiological benefits to aquatic organisms (Ringo et al. 2016).

Nanotechnology, derived from the Latin word "nanus" meaning dwarf, involves manipulating matter at the nanoscale, typically less than 100 nanometres in size. This technology holds significant promise for transforming various aspects of aquaculture, including pathogen detection and control, water treatment, and nutrient delivery. The application of nanotechnology in aquafeed can improve the stability, bioavailability, and controlled release of nutraceuticals, thereby enhancing their effectiveness (Merrifield and Ringo 2014, Das et al. 2013).

Nanomaterials can be engineered to create delivery systems that protect sensitive nutraceutical compounds and ensure their targeted release within the digestive systems of aquatic species. This improves feed conversion rates and reduces waste, leading to more efficient and cost-effective aquaculture operations. Moreover, nanotechnology can enhance the shelf-life and stability of aquafeeds by encapsulating functional compounds and antimicrobial agents, thereby improving overall feed quality (Encarnação 2016, Handy and Shaw 2007).

This review aims to provide a comprehensive overview of the application of nanotechnology in incorporating nutraceuticals into aquafeed, highlighting current research trends, challenges, and future prospects. By exploring these innovative approaches, we can better understand how to enhance the health and productivity of farmed aquatic species through advanced nutritional strategies.

2. IMPORTANCE OF AQUAFEED

Aquaculture, the farming of aquatic organisms such as fish, crustaceans, molluscs, and aquatic plants, is a rapidly growing sector that plays a vital role in global food security and economic development. Central to the success of aquaculture is the provision of high-quality aquafeed, which is specifically formulated to meet the dietary needs of various aquatic species. The importance of aquafeed cannot be overstated, as it directly influences the growth, health, and sustainability of aquaculture operations.

2.1 Role of Aquafeed in Aquaculture

Aquafeed plays a crucial role in modern aquaculture, serving as the primary source of nutrition for farmed aquatic animals. Aquatic species have specific nutritional needs that must be met for optimal growth, reproduction, and health. Aquafeed formulations are designed to provide these essential nutrients in appropriate proportions, including proteins, lipids, carbohydrates, vitamins, and minerals. High-quality aquafeed supports the growth and development of farmed fish, shrimp, and other aquatic organisms. Proper nutrition ensures that animals reach market size efficiently and produce high yields (FAO 2022).

A well-balanced diet enhances the immune system of aquatic animals, making them more resistant to diseases and stress. Some aquafeed formulations also include additives like probiotics, prebiotics, and immunostimulants to further boost immune function. Efficient feed conversion is essential for sustainable aquaculture production. Aquafeed formulations aim to maximize feed conversion ratios (FCR), ensuring that a high percentage of ingested feed is converted into animal biomass. Sustainable aquafeed production involves minimizing environmental impact. This includes sourcing ingredients from responsibly managed fisheries and agricultural systems, reducing reliance on wild-caught fishmeal and fish oil, and minimizing waste and pollution associated with feed production and use.

Aquafeed typically represents a significant portion of production costs in aquaculture operations. Therefore, feed formulations must strike a balance between cost-effectiveness and nutritional quality to ensure profitability for farmers. Ongoing research and innovation in aquafeed development aim to improve feed efficiency, reduce environmental impact, and address specific nutritional requirements of different aquatic species. This includes exploring alternative protein and lipid sources, optimizing feed processing techniques, and incorporating advances in nutritional science (Tacon and Metian 2015). Overall, aquafeed is a critical component of modern aquaculture systems, playing a vital role in supporting the sustainable production of seafood to meet growing global demand.

2.2 Nutritional Requirements of Aquatic Species

The nutritional requirements of aquatic species vary depending on factors such as species, life stage, environment, and production goals. However, some general nutritional requirements common to many aquatic species include the following:

Proteins are essential for growth, tissue repair, reproduction, and immune function. Aquatic species require specific levels of dietary protein, which can vary based on factors such as species, life stage, and production system. Protein sources commonly used in aquafeed include fishmeal, soybean meal, poultry meal, and various plant and animal proteins (NRC 2011).

Lipids (fats and oils) are important energy sources for aquatic organisms, providing essential fatty acids, fat-soluble vitamins, and aiding in the absorption of fat-soluble nutrients. The optimal lipid requirements vary among species and life stages, and sources like fish oil, vegetable oils, and animal fats are commonly used in aquafeed formulations (NRC 2011).

While aquatic animals have lower carbohydrate requirements compared to terrestrial animals, carbohydrates still serve as a source of energy in aquafeeds. However, excessive carbohydrate levels can negatively impact digestibility and growth in some species. Common carbohydrate sources in aquafeed include grains, cereals, and plant by-products (NRC 2011).

Aquatic species require vitamins and minerals for various physiological functions, including metabolism, bone development, and immune function. Vitamin and mineral requirements vary widely among species, and deficiencies can lead to growth retardation, skeletal deformities, and increased susceptibility to diseases. Aquafeed formulations typically include premixes containing essential vitamins and minerals to meet these requirements (Tacon 1992).

Certain amino acids cannot be synthesized by aquatic animals and must be obtained from their diet. These essential amino acids include methionine, lysine, arginine, and others, and their levels must be carefully balanced in aquafeed formulations to support optimal growth and health (Tacon 1992).

Antioxidants and immune enhancers such as vitamins C and E, selenium, and beta-glucans play important roles in reducing oxidative stress, enhancing immune function, and improving disease resistance in aquatic species (Li and Gatlin 2006).

In addition to dietary nutrients, water quality parameters such as dissolved oxygen, pH, temperature, and ammonia levels can also impact the nutritional status and overall health of aquatic organisms. Proper management of water quality is essential for optimizing nutrient utilization and minimizing stress in aquaculture systems (Li and Gatlin 2006).

Meeting the nutritional requirements of aquatic species through well-formulated aquafeeds is essential for promoting growth, health, and sustainability in aquaculture operations.

3. CHALLENGES IN TRADITIONAL AQUAFEED FORMULATIONS

Traditional aquafeed formulations have faced several challenges, stemming from their narrow focus on maximizing growth rates without sufficient consideration for broader health and sustainability concerns. Many traditional aquafeed formulations have been primarily focused on delivering macronutrients such as proteins, lipids, and carbohydrates to support rapid growth. However, achieving the right balance of these nutrients can be challenging, leading to imbalances that may compromise the overall health and performance of cultured species. Traditional aquafeed formulations have often relied on a limited range of ingredients, typically sourced from fishmeal and fish oil, which may not only be unsustainable but also prone to fluctuations in availability and price. This overreliance on marine-derived ingredients has raised concerns about the long-term sustainability of aquafeed production and its impact on marine ecosystems (Naylor et al. 2009). By prioritizing growth over health, traditional aquafeeds may inadvertently weaken the immune systems of cultured species, making them more susceptible to diseases and pathogens. This can result in increased mortality rates, reduced productivity, and negative environmental impacts due to the use of antibiotics and other pharmaceutical interventions. The production of traditional aquafeeds often involves resource-intensive processes, such as the extraction of fishmeal and fish oil from wild-caught fish stocks. This not only contributes to overfishing and habitat degradation but also exacerbates environmental pollution and greenhouse gas emissions associated with feed production and transportation. Perhaps the most significant challenge facing traditional aquafeed formulations is their overall lack of sustainability. From the depletion of wild fish stocks to the environmental degradation caused by intensive feed production, traditional aquafeeds have been associated with a range of unsustainable practices that undermine the long-term viability of aquaculture systems (Tacon and Metian 2008). Addressing these challenges requires a fundamental shift in the way aquafeeds are formulated and produced. Moving towards more holistic, environmentally friendly feed formulations that prioritize health, sustainability, and resilience will be essential for ensuring the continued growth and success of the aquaculture industry in the face of mounting environmental and socio-economic pressures.

4. NUTRACEUTICALS IN AQUAFEED

Nutraceuticals represent a fascinating intersection between nutrition and pharmaceuticals; encompassing a broad spectrum of bioactive compounds that not only provide essential nutrients but also offer an array of health-promoting benefits beyond basic sustenance. These compounds, derived from food or formulated to mimic natural sources, serve as potent allies in enhancing human health and well-being. At the heart of nutraceuticals lies their multifaceted nature, which allows them to be categorized into various types based on their diverse physiological functions and properties. These classifications provide a nuanced understanding of how different nutraceuticals interact with the body to promote optimal health. Let's investigate into some of these types:

4.1 The Vital Role of Vitamins in Human Health

Vitamins are indispensable for the proper functioning of numerous biochemical pathways in the body. From bolstering immune defenses to supporting vision, vitamins play indispensable roles in nearly every aspect of human health (Biesalski 2009). For example, vitamin C acts as a powerful antioxidant, while vitamin D regulates calcium absorption and bone health.

4.2 The Essential Functions of Minerals in Human Physiology

Minerals play indispensable roles in maintaining the structural integrity of tissues, facilitating enzymatic reactions, and transmitting nerve impulses, making them indispensable components of a well-rounded diet (Goswami et al. 2005). Calcium exemplifies this importance by fortifying bones and teeth, while iron ensures efficient oxygen transport through the bloodstream. Together, minerals collaborate synergistically to uphold physiological balance and promote holistic well-being.

4.3 Probiotics: Guardians of Gut Health and Beyond

Probiotics are often hailed as the "good bacteria," which colonize the gut microbiota, promoting digestive health and bolstering immunity. By restoring microbial balance, probiotics aid in digestion, alleviate gastrointestinal discomfort, and may even exert systemic effects on mood and cognition **(**Hill et al. 2014).

4.4 Prebiotics: Fuel for a Healthy Gut Microbiome

Prebiotics, acting as nourishment for probiotics, are indigestible fibers that selectively stimulate the growth and activity of beneficial gut bacteria (Gibson et al. 2017). By fostering a robust microbial ecosystem, prebiotics contribute to digestive regularity, enhance nutrient absorption, and fortify immune defenses.

4.5 Essential Fatty Acids: Building Blocks of Health and Vitality

Essential Fatty Acids like omega-3 and omega-6 fatty acids are critical components of cell membranes and serve as precursors for signaling molecules involved in inflammation and immunity (Calder 2015). Found abundantly in fatty fish, flaxseeds, and nuts, these essential fatty acids play pivotal roles in cardiovascular health, brain function, and inflammatory regulation.

4.6 Antioxidants: Protectors against Oxidative Stress and Aging

In a world fraught with oxidative stress, antioxidants emerge as formidable defenders against cellular damage and chronic disease. These compounds scavenge harmful free radicals, mitigate inflammation, and protect against age-related degeneration. Examples include vitamin E, selenium, and polyphenols found in colorful fruits and vegetables (Valko et al. 2007).

4.7 Phytochemicals: Nature's Powerhouse for Health and Healing

Phytochemicals are plentiful in plant-based foods. They are bioactive compounds with diverse health benefits. From quelling inflammation to inhibiting cancer cell growth, these natural wonders exhibit a remarkable array of therapeutic properties (Liu 2004). Examples include resveratrol in grapes, curcumin in turmeric, and sulforaphane in broccoli.

In essence, nutraceuticals represent a goldmine of bioactive compounds that hold immense promise for optimizing health and combating disease. By harnessing the power of nature's pharmacy, we can unlock new frontiers in preventive medicine and pave the way towards a healthier, more vibrant future.

5. ROLE OF NUTRACEUTICALS FOR AQUATIC SPECIES

Nutraceuticals offer a multitude of benefits for aquatic species, ranging from enhanced growth and immunity to increased stress resistance. Here are several significant benefits:

5.1 Enhanced Growth

Nutraceuticals can provide essential nutrients and bioactive compounds that promote optimal growth and development in aquatic species. By ensuring that fish and other aquatic organisms receive a balanced diet rich in vitamins, minerals, and amino acids, nutraceuticals can support healthy growth rates, leading to improved size, weight, and overall productivity (Samanta et al.2022, Sarker and Satoh 2007).

5.2 Improved Immunity

Many nutraceuticals contain immunomodulatory properties that bolster the immune system of aquatic species. Ingredients such as probiotics, prebiotics, and certain vitamins and minerals can stimulate immune responses, enhance disease resistance, and reduce susceptibility to pathogens and infections (Nayak 2010, Balcazar et al. 2006). This helps to maintain the health and well-being of cultured species and minimize the need for antibiotics or other pharmaceutical interventions.

5.3 Stress Resistance

Aquaculture environments can subject aquatic species to various stressors, including environmental fluctuations, handling, and transportation. Nutraceuticals with adaptogenic properties can help aquatic organisms cope with stress more effectively by regulating physiological processes and minimizing the negative impacts of stressors (Balcazar et al. 2006). This can reduce mortality rates, improve survival during challenging conditions, and enhance overall resilience in aquaculture systems.

5.4 Enhanced Nutrient Utilization

Nutraceuticals can optimize nutrient utilization and absorption in aquatic species, ensuring that they derive maximum benefit from their diet. Ingredients such as enzymes, probiotics, and specific amino acids can enhance digestive efficiency, increase nutrient uptake, and reduce waste production (Francis et al. 2001). This not only improves growth performance but also promotes environmental sustainability by minimizing nutrient excretion and pollution.

5.5 Antioxidant Protection

Oxidative stress caused by reactive oxygen species (ROS) can damage cells and tissues in aquatic organisms, leading to reduced growth, increased susceptibility to diseases, and impaired reproductive performance. Nutraceuticals rich in antioxidants, such as vitamins C and E, selenium, and carotenoids, can neutralize ROS and protect against oxidative damage, promoting overall health and vitality in aquatic species (Mourente et al. 2002).

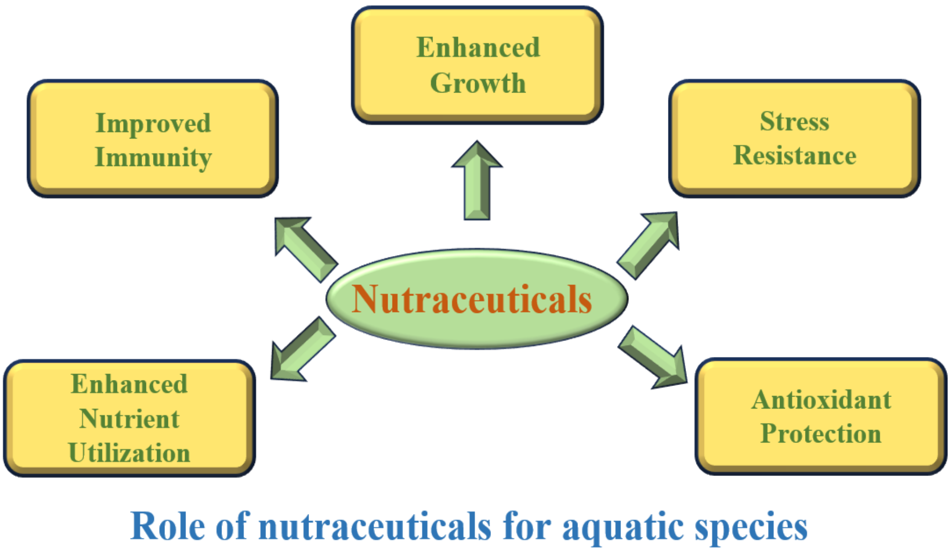

Fig. 1. Role of nutraceuticals for aquatic species

Overall, nutraceuticals play a crucial role in promoting the health, growth, and sustainability of aquaculture systems. By harnessing the benefits of these bioactive compounds, aquaculture practitioners can optimize production efficiency, minimize disease risks, and ensure the welfare of cultured species, ultimately contributing to the long-term viability and success of the aquaculture industry.

6. NANOTECHNOLOGY ENHANCING NUTRACEUTICAL DELIVERY

Nanotechnology offers innovative solutions for enhancing the delivery and efficacy of nutraceuticals through various modes of action. The main strategies include nanoencapsulation, nanocarriers, and other related techniques. Nanoencapsulation involves enclosing active nutraceutical compounds within a nanoscale protective coating or capsule. Encapsulating nutraceuticals in nanomaterials protects them from degradation caused by environmental factors such as light, oxygen, and moisture. Nano-encapsulation allows for controlled and sustained release of the nutraceuticals, ensuring a steady supply over time and improving bioavailability. Nano-capsules can be designed to release their payload in specific parts of the gastrointestinal tract or within specific cells, enhancing the efficiency of the nutraceuticals. Common materials for nanoencapsulation include lipids (forming liposomes), polymers (forming nanospheres or nano capsules), and proteins (Couvreur and Vauthier 2006). Nano-carriers are nanoscale vehicles that transport nutraceuticals to specific sites within the body. Spherical vesicles composed of lipid bilayers, which can encapsulate both hydrophilic and hydrophobic nutraceuticals. Made from biocompatible and biodegradable polymers, these nanoparticles can be engineered to have specific release profiles and target tissues. These carriers combine the advantages of liposomes and polymeric nanoparticles, offering high stability and controlled release properties. Nanocarriers improve the solubility and absorption of poorly water-soluble nutraceuticals. They protect the encapsulated nutraceuticals from chemical and enzymatic degradation in the gastrointestinal tract. Functionalizing nanocarriers with ligands allows for targeted delivery to specific cells or tissues, enhancing therapeutic efficacy and reducing side effects (Mohanraj and Chen 2006).

Other nanotechnology approaches which improve nutraceutical delivery include: nano-crystals, nano-emulsions, dendrimers, nano-tubes, nano-fibers etc. Nano-crystals reduce the size of nutraceuticals to the nanoscale increases their surface area, improving dissolution rates and bioavailability (Shegokar and Müller 2010). Nano-emulsions are fine oil-in-water or water-in-oil emulsions with droplet sizes in the nanometer range, improving the solubility and absorption of lipophilic nutraceuticals (Shegokar and Müller 2010). Dendrimers are highly branched, tree-like macromolecules that can carry multiple nutraceutical molecules on their surface or within their structure, allowing for high loading capacity and targeted delivery (Kannan et al. 2014). Nano-tubes and nano-fibers provide a high surface area for loading nutraceuticals and can be used to create scaffolds for controlled release (Vashist and Ahmad 2013). Nanotechnology significantly advances nutraceutical delivery by addressing key challenges such as poor bioavailability, instability, and non-specific distribution. Through nano encapsulation, nanocarriers, and other nanoscale innovations, nutraceuticals can be delivered more effectively and safely, offering enhanced health benefits to consumers.

Improving the bioavailability and absorption of nutrients is essential for maximizing the nutritional benefits from the food we consume. Certain nutrients enhance the absorption of others. As for example, consuming vitamin C-rich foods (like citrus fruits) alongside iron-rich foods (like spinach) can enhance non-heme iron absorption and vitamins A, D, E, and K are better absorbed when eaten with dietary fats (Hurrell and Egli 2010). Say for example, adding a bit of olive oil to a salad can help with the absorption of these vitamins from the vegetables. Proper cooking methods can enhance nutrient bioavailability, some nutrients become more bioavailable after cooking, such as lycopene in tomatoes. Light steaming or sautéing can help in this process. Soaking beans, grains, and nuts can reduce antinutrients like phytates and improve mineral absorption. Sprouting can also enhance the bioavailability of vitamins and minerals. Fermented foods (like yogurt, kefir, sauerkraut, and kimchi) contain beneficial bacteria that can help with the digestion and absorption of nutrients. Fermentation can also break down antinutrients (Jeffery and Araya 2009).

Certain compounds can inhibit nutrient absorption, available in seeds, nuts, and some leafy greens; these can bind minerals and reduce their absorption. Soaking, fermenting, and cooking can reduce their levels. Tannins arepresent in tea, coffee, and some fruits, tannins can inhibit iron absorption. It's beneficial to consume these in moderation or separately from iron-rich meals. Maintaining a healthy gut microbiome is crucial for nutrient absorption. Consuming prebiotics (fibers that feed beneficial bacteria) and probiotics (live beneficial bacteria) can support gut health (Umu et al. 2017). Foods like garlic, onions, bananas (prebiotics), and fermented foods (probiotics) are good choices in some cases, supplements and fortified foods can help improve nutrient intake, especially for individuals with specific deficiencies or absorption issues. However, it's essential to consult with a healthcare professional before starting any supplementation (Marco and Tachon 2013).

A varied and balanced diet ensures a wide range of nutrients, which can support overall nutrient absorption. Including a mix of fruits, vegetables, whole grains, proteins, and fats is crucial. Eating smaller, more frequent meals can sometimes help with better absorption compared to large, infrequent meals (Samtiya et al. 2020). This is particularly relevant for individuals with digestive issues. Proper hydration supports digestion and nutrient transport in the body. Drinking enough water is essential for maintaining these processes. Age, health status, and specific medical conditions can affect nutrient absorption. Personalized dietary advice from a nutritionist or dietitian can address these individual needs. Optimizing nutrient bioavailability and absorption involves a combination of dietary strategies, food preparation techniques, and lifestyle choices (Mason 2012). By paying attention to how foods are combined, prepared, and consumed, one can significantly enhance the body's ability to absorb and utilize essential nutrients.

7. NANOMATERIALS USED IN AQUAFEED

Nanomaterials are increasingly being explored for use in aquafeeds due to their unique properties and potential benefits. Some types of nanomaterials used in aquafeeds, along with examples and their advantages are following:

7.1 Nano Minerals and Nano Trace Elements

Nano minerals and nano trace elements are nanometer-sized particles of essential minerals and trace elements that play crucial roles in the growth, development, and overall health of aquatic organisms. Nano-sized particles have a larger surface area to volume ratio, which enhances their dissolution and absorption in the gastrointestinal tract. This means that the nutrients are more readily available to the fish, leading to improved health and growth. Their better nutrient absorption translates to improved growth rates and feed efficiency. Fish can achieve optimal growth with smaller amounts of supplemented nano minerals compared to traditional forms. Nano minerals can boost the immune system, making fish more resistant to diseases. This is particularly important in aquaculture, where disease outbreaks can have significant economic impacts. Because of their higher bioavailability, lower doses of nano minerals are required to achieve the desired nutritional effects. This results in less excretion of unused minerals into the water, reducing the risk of environmental pollution and eutrophication. Nano minerals often exhibit greater stability in feed formulations and during storage. This ensures that the fish receive the intended nutritional benefits without degradation of the nutrients over time.

Zinc is an essential trace element involved in numerous biological functions, including enzyme activity, protein synthesis, and immune function. Nano ZnO is more readily absorbed by the fish's digestive system. Studies have shown that nano ZnO supplementation can enhance growth rates and feed efficiency. It can improve the immune response, making fish more resistant to diseases. Lower amounts are required to achieve the desired effect, reducing zinc excretion and environmental contamination (Xu et al. 2023, Yazdani et al. 2023).

Selenium is a vital trace element with important roles in antioxidant defense and thyroid hormone metabolism. Nano selenium exhibits better antioxidant activity, protecting cells from oxidative stress (Sumana et al. 2023). It promotes better growth performance and feed conversion ratios, increases the resilience of fish to various stressors, including handling and environmental changes. Enhances immune function and helps prevent selenium deficiency-related diseases (Weeks et al. 2012).

Copper is necessary for various enzymatic processes, iron metabolism, and nervous system function. Nano-copper is more efficiently absorbed than conventional copper sources. It supports optimal enzyme activity necessary for growth and metabolism (Hualiang et al. 2020). Nano-copper also maintains healthy blood and nerve cells, and supports overall health and growth.

The application of nano minerals and nano trace elements in aquafeeds presents a promising approach to enhancing the nutritional quality, growth performance, and health of aquaculture species. Their superior bioavailability and reduced environmental impact make them valuable tools for sustainable and efficient aquaculture practices (Nasr-Eldahan et al. 2021).

7.2 Nano Vitamins

Nano vitamins are vitamins engineered at the nanoscale, offering unique properties that enhance their effectiveness in aquafeeds. Due to their small size and increased surface area, nano vitamins provide improved stability, bioavailability, and targeted delivery compared to conventional vitamin forms. Vitamin C is essential for collagen synthesis, antioxidant defense, and immune function (Fajardo et al. 2022). Nano-encapsulation protects vitamin C from oxidation and degradation, extending its shelf life. Higher absorption rates of vitamin C leads to more effective utilization by fish. Better antioxidant properties of vitamin C improve the fish's resistance to diseases and stress (Xu et al. 2022).

Vitamin E is a fat-soluble antioxidant that protects cell membranes from oxidative damage. Nano-vitamin E is more efficient in neutralizing free radicals due to its enhanced bioavailability. It improves overall growth performance, reproductive health, and disease resistance. Nano-encapsulation helps maintain the stability of vitamin E during feed processing and storage (You et al. 2016).

Vitamin D3 is crucial for calcium and phosphorus metabolism, bone health, disease resistance and immune function. Nano-sized vitamin D3 particles are more readily absorbed in the intestines. It enhances calcium uptake, promoting stronger bones and better skeletal health (Sivagurunathan et al. 2022).

Nano vitamins have a higher absorption rate due to their small size, allowing for more efficient uptake and utilization by the fish. This leads to better health outcomes and improved growth rates. Nano-encapsulation techniques protect vitamins from environmental factors such as light, heat, and oxygen, which can degrade them. This ensures that the vitamins remain effective throughout the feed's shelf life and during digestion. The enhanced bioavailability of nano vitamins means that lower doses are required to achieve the desired nutritional effect (Sivagurunathan et al. 2022). This not only makes the feed more cost-effective but also reduces the risk of toxicity from over-supplementation. Nano vitamins can be engineered to release their payload in specific parts of the digestive system or under certain conditions, ensuring that the nutrients are delivered where they are needed most. By improving the nutritional status of the fish, nano vitamins boost the immune system, making the fish more resilient to diseases and reducing the need for antibiotics or other treatments. Lower doses of nano vitamins result in less nutrient waste being excreted into the water, reducing the risk of environmental pollution and promoting sustainable aquaculture practices. Nano vitamins represent a significant advancement in the field of aquafeeds, offering enhanced stability, bioavailability, and targeted delivery (Nasr-Eldahan et al. 2021). Their use can lead to improved health, growth, and disease resistance in aquaculture species, while also promoting more sustainable and cost-effective feeding practices.

7.3 Nano Lipids

Nano-lipids are tiny lipid-based particles that play a significant role in various fields, particularly in medicine and pharmaceuticals. Nano-lipids typically range in size from 10 to 1000 nanometers. They have a core-shell structure where the core can encapsulate hydrophobic (water-insoluble) substances, and the shell, usually made of phospholipids, can interact with the aqueous environment. Common types of nano-lipids include liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs) (Khan et al. 2015).

Nano-lipids are widely used to deliver drugs, particularly in targeting specific tissues or cells, improving drug solubility, stability, and bioavailability. They can encapsulate both hydrophobic and hydrophilic drugs. They serve as carriers for delivering genetic material (e.g., DNA, RNA) into cells (Carbone et al. 2013). For instance, mRNA vaccines, such as those developed for COVID-19 by Pfizer-BioNTech and Moderna, utilize lipid nanoparticles to protect and transport the mRNA into cells. Due to their ability to penetrate the skin effectively; they are used in various skincare products to deliver active ingredients more efficiently. Nano-lipids are generally biocompatible and biodegradable, making them safe for use in the human body. They can be engineered to release their payload in a controlled manner, enhancing the therapeutic effect and reducing the frequency of dosing (Filipczak et al. 2021). Nano-lipids protect encapsulated substances from degradation, thereby increasing the stability and shelf-life of the product.

Producing nano-lipids on a large scale with consistent quality can be challenging and costly. Regulatory approval for nano-lipid-based products can be complex due to stringent safety and efficacy requirements. Nano-lipids represent a versatile and powerful tool in modern medicine and other industries, offering enhanced delivery and effectiveness of therapeutic and cosmetic agents (Sercombe et al. 2015). Ongoing research and development are likely to expand their applications and overcome current challenges.

7.4 Nano Encapsulated Nutrients

Nano encapsulated nutrients refer to nutrients that are encapsulated within nanoparticles to enhance their stability, bioavailability, and targeted delivery within the body. This technology is used in various fields, including food science, pharmaceuticals, and cosmetics, to improve the effectiveness of nutrient delivery and to protect sensitive compounds from degradation (McClements 2015). Nano encapsulation can improve the absorption and utilization of nutrients in the body. Smaller particles have a larger surface area, facilitating better interaction with biological membranes. Encapsulation allows for the controlled release of nutrients, providing a sustained supply over time rather than a rapid, unregulated release. Nutrients sensitive to environmental factors such as light, heat, and oxygen can be protected within nanoparticles, extending their shelf life and efficacy. Nano encapsulation can be designed to target specific tissues or cells, reducing side effects and improving therapeutic outcomes; especially in drug delivery (Mozafari et al. 2008). Nano encapsulation is used to fortify foods with vitamins, minerals, and other nutrients without affecting taste or texture. For example, encapsulating omega-3 fatty acids can prevent oxidation and off-flavors. This technology is widely used for drug delivery systems, improving the solubility and stability of drugs, and targeting specific areas in the body to treat diseases like cancer more effectively (Pandey and Khuller 2006). This technology is widely used for drug delivery systems, improving the solubility and stability of drugs, and targeting specific areas in the body to treat diseases like cancer more effectively. Nano encapsulated nutrients represent a promising advancement in enhancing the delivery and effectiveness of essential nutrients. Ongoing research and technological improvements continue to address the challenges associated with this technology, paving the way for its broader application and acceptance in various industries (Pathak and Thassu 2009).

7.5 Nano Carriers for Probiotics and Enzymes

Nanocarriers are emerging as a versatile platform for delivering probiotics and enzymes, enhancing their stability, bioavailability, and targeted delivery. Spherical vesicles with a lipid bilayer, providing protection from the gastrointestinal (GI) tract's harsh conditions. These nano-carriers provide a solid lipid core matrix that can encapsulate probiotics, improving stability. Blend of solid and liquid lipids, offering better loading capacity and release properties. Nano-particles are made from biodegradable polymers like PLGA (poly(lactic-co-glycolic acid)), enhancing protection and controlled release (Modi et al. 2022). Future research is focused on optimizing nanocarrier formulations, exploring new materials, and understanding the interaction between nanocarriers and biological systems to fully realize the potential of nanotechnology in delivering probiotics and enzymes.

7.6 Nano Antimicrobials

Nano antimicrobials refer to the use of nanoparticles as antimicrobial agents. These tiny particles, often measuring less than 100 nanometers in size, exhibit unique properties that make them effective at killing or inhibiting the growth of microorganisms, including bacteria, viruses, and fungi. The effectiveness of nano antimicrobials stems from their high surface area to volume ratio, which enhances their interaction with microbial cells. Silver Nanoparticles (AgNPs) are known for their strong antimicrobial activity against a broad range of microorganisms **(**Modi et al. 2022). They release silver ions which disrupt microbial cell membranes and interfere with their metabolism. Gold Nanoparticles (AuNPs) are often used in combination with other antimicrobial agents for enhanced effect. They can also be functionalized with biomolecules for targeted delivery. Zinc Oxide Nanoparticles (ZnO-NPs) are effective against a variety of bacteria and fungi. They generate reactive oxygen species (ROS) that damage microbial cells. Copper-Nanoparticles (CuNPs) are known for their broad-spectrum antimicrobial properties, effective against bacteria, viruses, and fungi. Titanium Dioxide (TiO_2) nanoparticles are utilized primarily for their photocatalytic properties, generating ROS under UV light which destroys microbial cells. Magnesium Oxide (MgO) and Calcium Oxide (CaO) nanoparticles are known for their bactericidal properties and ability to disrupt microbial membranes (Sanguansri and Augustin 2006). Carbon Nanotubes (CNTs) exhibit antimicrobial properties due to their ability to physically damage microbial cells and generate reactive oxygen species (ROS). Graphene Oxide (GO) are effective against bacteria and fungi by disrupting cell membranes and oxidative stress. Chitosan Nanoparticles are biodegradable and biocompatible; these nanoparticles exhibit antimicrobial properties through electrostatic interaction with microbial cell walls. Nano antimicrobials represent a promising area in the fight against microbial infections, with applications spanning various industries. However, careful consideration of their safety and environmental impact is essential to fully harness their potential benefits (Lv and Xu 2022).

7.7 Nano Emulsions of Omega-3 Fatty Acids

Nano emulsions of Omega-3 fatty acids are advanced delivery systems designed to enhance the stability, bioavailability, and effectiveness of these essential fatty acids. Omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and decosahexaenoic acid (DHA), are known for their numerous health benefits, including anti-inflammatory properties, cardiovascular health, and cognitive function improvement (Skwarczynski et al. 2022). However, their poor water solubility and susceptibility to oxidation present challenges for their incorporation into food products and supplements. Nano emulsions of Omega-3 fatty acids represent a promising technology to overcome the limitations associated with these essential nutrients. By enhancing their stability, bioavailability, and incorporation into various products, nano emulsions can significantly improve the delivery and effectiveness of Omega-3 fatty acids, benefiting a wide range of consumers (Vandamme 2002). However, continued research and development, along with careful consideration of safety and regulatory aspects, are crucial for their successful implementation.

7.8 Chitosan Nanoparticles for Probiotics

Chitosan nanoparticles offer a promising avenue for the encapsulation and delivery of probiotics. Probiotics are live microorganisms that confer health benefits when administered in adequate amounts, typically by improving the gut microbiota composition and function (Janes et al. 2001). However, probiotics face challenges related to their stability during storage and transit through the harsh conditions of the gastrointestinal tract. Chitosan nanoparticles can address these challenges and enhance the efficacy of probiotic delivery. Chitosan is a biodegradable and biocompatible polysaccharide derived from chitin, found in the exoskeletons of crustaceans like shrimp and crab. Chitosan is generally regarded as safe (GRAS) and non-toxic, making it suitable for biomedical applications (Zhang et al. 2008). These nanoparticles can adhere to the mucus layer of the gastrointestinal tract, prolonging the residence time of encapsulated probiotics and enhancing their absorption. Chitosan is soluble in acidic environments, such as the stomach, but forms nanoparticles under neutral to alkaline conditions, providing protection to probiotics in the acidic stomach environment. Chitosan also exhibits inherent antimicrobial properties, which can further protect probiotics from degradation by harmful microorganisms in the gastrointestinal tract (Mikušová and Mikuš 2021).

8. BENEFITS OF NANOTECHNOLOGY IN AQUAFEED

Nanotechnology offers several potential benefits in the field of aquafeed production and aquaculture.

8.1 Enhanced Digestibility

Nanoparticles can be used to encapsulate nutrients and supplements, improving their digestibility and absorption by aquatic organisms (Marquez et al. 2018). This can lead to better feed conversion ratios and improved growth rates in farmed fish.

8.2 Nutrient Delivery

Nanoparticles can serve as carriers for essential nutrients, vitamins, and minerals (Khosravi-Katuli et al. 2017) ensuring their targeted delivery to specific tissues or organs within the fish, thereby maximizing their utilization and reducing waste.

8.3 Water Quality Management

Nanomaterials such as nanoparticles of silver or titanium dioxide can be incorporated into aquafeed (George et al. 2023) to control water quality by reducing pathogens, algae, and harmful bacteria. This can help maintain a healthier environment for the fish and reduce the need for chemical treatments.

8.4 Improved Feed Efficiency

Nanoparticles can be engineered to release nutrients slowly over time, providing a steady supply of essential nutrients to the fish (Gabriel et al. 2022). This can result in reduced feed waste and improved feed efficiency.

8.5 Disease Prevention

Nanoparticles with antimicrobial properties can be added to aquafeed to help prevent the spread of diseases among farmed fish (Ahmed et al. 2023). This can reduce the need for antibiotics and other pharmaceuticals, promoting sustainable aquaculture practices.

8.6 Enhanced Immunity

Nanoparticles can be used to deliver immunostimulants or vaccines to farmed fish, boosting their immune response and increasing their resistance to diseases and pathogens (Vibhute et al. 2023).

8.7 Environmental Sustainability

By improving feed efficiency and reducing the need for chemical treatments and antibiotics, nanotechnology can contribute to more sustainable aquaculture practices with lower environmental impacts (Gabriel et al. 2022, Vibhute et al. 2023).

8.8 Customized Formulations

Nanotechnology enables the development of customized feed formulations tailored to the specific nutritional requirements of different species of farmed fish at various stages of their life cycle (George et al. 2023), optimizing their growth and health.

8.9 Bioavailability Enhancement

Nanoparticles can increase the bioavailability of certain nutrients and supplements, ensuring that fish can efficiently utilize these compounds for growth and development (Vibhute et al. 2023).

8.10 Reduced Environmental Contamination

Nanoparticles can be engineered to degrade into harmless byproducts, reducing the risk of environmental contamination associated with conventional aquafeed additives (Nasr-Eldahan et al. 2021).

However, it's essential to consider potential risks and ethical implications associated with the use of nanotechnology in aquafeed, such as nanoparticle toxicity, environmental impact, and regulatory concerns (Khosravi-Katuli et al. 2017, Ray et al. 2009). Ongoing research and careful evaluation are necessary to ensure the safe and responsible application of nanotechnology in aquaculture.

9. CHALLENGES AND RISKS OF NANOTECHNOLOGY IN AQUAFEED PRODUCTION

While nanotechnology holds promise for improving various aspects of aquafeed production and aquaculture, there are several challenges and risks that need to be addressed.

9.1 Toxicity

Some nanoparticles may have toxic effects on aquatic organisms if they are not properly engineered or if they accumulate in the environment. It's crucial to thoroughly assess the toxicity of nanomaterials used in aquafeed and their potential impact on fish health and the ecosystem (Canesi and Corsi 2016).

9.2 Environmental Impact

Nanoparticles released into the aquatic environment through aquafeed or waste from aquaculture facilities could have unintended consequences on water quality, ecosystems, and non-target organisms (Kah et al. 2013). Long-term environmental monitoring is necessary to understand the fate and behavior of nanoparticles in aquatic systems.

9.3 Regulatory Uncertainty

The regulatory framework for nanotechnology in aquafeed and aquaculture is still evolving (Collins et al. 2012), with uncertainties regarding safety assessments, labeling requirements, and risk management strategies. Clear guidelines and standards are needed to ensure the responsible development and use of nanotechnology in this context.

9.4 Nano-Bio Interactions

Understanding the interactions between nanoparticles and biological systems is complex and requires interdisciplinary research efforts. Factors such as nanoparticle size, shape, surface chemistry, and aggregation behavior can influence their biological effects and fate in aquatic organisms (Hassellov et al. 2008).

9.5 Cost and Scalability

Developing nanotechnology-based solutions for aquafeed may entail higher production costs compared to conventional feed additives (Peters et al. 2016). Scaling up production methods and ensuring cost-effectiveness are essential for widespread adoption in the aquaculture industry.

9.6 Public Perception and Acceptance

Concerns about the safety and ethical implications of nanotechnology in food and agriculture may influence public perception and acceptance of nanotechnology-enhanced aquafeed products. Transparent communication and engagement with stakeholders are critical to building trust and addressing concerns (Oberdörster et al. 2005).

9.7 Risk of Nanoparticle Release

During the production, handling, and disposal of nanomaterials used in aquafeed, there is a risk of unintentional release into the environment (Handy et al. 2008). Effective containment measures and waste management strategies are necessary to minimize environmental exposure.

10. EMERGING NANOMATERIALS

The rapid advancement of nanotechnology introduces new nanomaterials and formulations with unknown properties and risks (Baun et al. 2008). Continuous research and risk assessment are essential to stay ahead of potential challenges associated with emerging nanomaterials in aquafeed.

Addressing these challenges and risks requires collaborative efforts among researchers, industry stakeholders, regulators, and policymakers to ensure the safe and sustainable integration of nanotechnology in aquafeed production and aquaculture practices (Martínez et al. 2020). Comprehensive risk assessments and responsible innovation practices are essential to harness the benefits of nanotechnology while minimizing potential adverse impacts on aquatic ecosystems and food safety.

11. FUTURE PERSPECTIVES

Looking ahead, the future of nanotechnology in aquafeed holds significant promise and potential for revolutionizing the aquaculture industry. Nanotechnology enables the precise delivery of nutrients, supplements, and bioactive compounds to meet the specific nutritional needs of different aquatic species at various life stages (Sabo-Attwood et al. 2021). This personalized approach to nutrition can optimize growth, health, and productivity while minimizing feed waste and environmental impact.

Future aquafeed formulations will likely incorporate nanoscale ingredients and additives designed to enhance digestibility, nutrient absorption, and feed efficiency. Nanoparticles can improve the stability, palatability, and shelf life of aquafeed while reducing the reliance on conventional feed additives and antibiotics (Khalil et al. 2023).

Nanotechnology-enabled sensors and monitoring devices will play a crucial role in developing smart feeding systems for aquaculture. These systems can continuously monitor fish behavior, feed consumption, and water quality parameters, allowing for real-time adjustments to feeding schedules and feed compositions to optimize performance and minimize environmental impact (Hassellov et al. 2008, Peters et al. 2016).

Nanotechnology holds promise for advancing disease diagnosis, prevention, and treatment in aquaculture. Nanoparticle-based biosensors, vaccines, and antimicrobial agents can help detect pathogens, boost immune responses, and mitigate disease outbreaks, leading to improved fish health and welfare.

Nanotechnology offers innovative solutions for enhancing the sustainability of aquaculture operations. Nanomaterials can improve water quality management, nutrient recycling, and waste treatment processes, reducing environmental pollution and resource consumption associated with fish farming.

Collaboration among researchers, industry stakeholders, and regulatory agencies is essential to ensure the safe and responsible use of nanotechnology in aquafeed production and aquaculture practices (Ray et al. 2009). Robust regulatory frameworks and international standards will help address safety concerns, promote transparency, and foster public trust in nanotechnology-enabled aquaculture solutions.

Overall, the future of nanotechnology in aquafeed is poised to drive innovation, efficiency, and sustainability in the aquaculture industry, contributing to food security, economic development, and environmental stewardship on a global scale (Fajardo et al. 2022). Continued research, investment, and collaboration will be key to unlocking the full potential of nanotechnology in meeting the growing demand for nutritious and sustainable seafood production.

12. CONCLUSION

In conclusion, nanotechnology represents a promising frontier in the realm of aquafeed production and aquaculture. Its potential to revolutionize the industry lies in its ability to offer tailored nutrition advanced feed formulations, smart feeding systems, improved health management, and enhanced environmental sustainability. By leveraging nanotechnology, stakeholders in aquaculture can optimize growth, health, and productivity while minimizing environmental impact and resource consumption. However, realizing the full benefits of nanotechnology in aquafeed requires concerted efforts in research, development, regulation, and global collaboration. Addressing challenges such as toxicity, environmental impact, regulatory uncertainty, and public perception is essential to ensure the safe and responsible integration of nanotechnology into aquaculture practices. As we look to the future, continued investment, innovation, and cooperation among researchers, industry stakeholders, policymakers, and regulators will be crucial for unlocking the transformative potential of nanotechnology in aquafeed production and aquaculture. By embracing sustainable and responsible practices, we can harness the power of nanotechnology to meet the growing demand for nutritious seafood while safeguarding the health of aquatic ecosystems and future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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