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Nano-enhanced diets: advancing sustainability in aquaculture - a review

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ABSTRACT

Aquaculture is the fastest-growing food sector and is essential for global food production and nutrition security. Continuous advancement with future innovations is therefore necessary for sustainability. In aquafeed, traditional feed additives have been used to enhance the nutritional value of formulated diets. Recently, nanotechnology has shown the potential to improve feed formulation and reduce the environmental impacts of aquafeeds. This research examines the use of nanotechnology to improve fish feed formulation for enhanced sustainability in aquaculture, focusing on how nanoparticles as dietary additives can boost nutrient availability, feeding efficiency, growth performance, and health in aquatic species. Results show that nano-enhanced diets improve fish growth performance, health, and environmental sustainability by enhancing nutrient efficiency and minimizing waste. Nanoparticles such as selenium, zinc, and iron have demonstrated notable benefits in enhancing fish growth, antioxidant defense, and disease resistance. However, challenges include nanoparticle toxicity, high costs, and regulatory concerns. While nanotechnology shows great promise in transforming aquaculture feed, its long-term environmental and health impacts require careful and thorough evaluation. This study advances sustainable aquaculture by providing new insights into integrating nanotechnology into fish diets, aiming to optimize aquafeed for improved productivity and sustainability.

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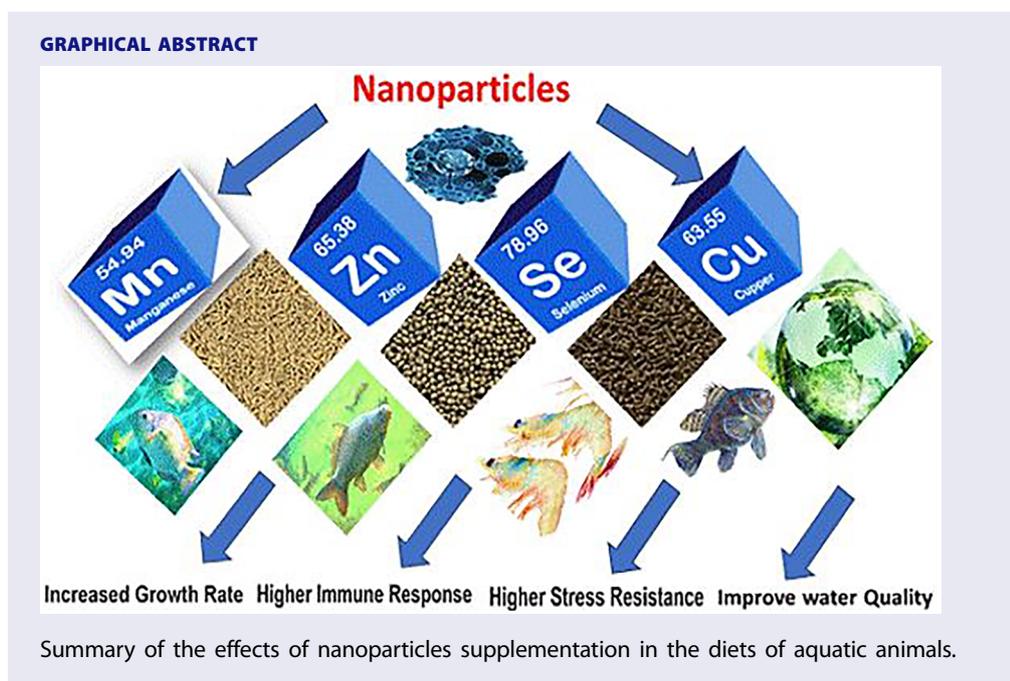
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1. Introduction

Aquaculture, as the fastest-growing sector in the food industry, currently accounts for over 50% of the world's seafood production for consumption (FAO, 2024; Hussain et al., 2019; Souza et al., 2017). The sector is recognized as one of the most important food production systems, significantly impacting both food security and economic development (Adam et al., 2023; FAO, 2024; Maulu et al., 2021a). Given the significant expansion of the aquaculture sector and its critical role in providing nutritious food for a rapidly growing population, it's imperative to ensure the industry adopts sustainable practices. The aquafeed industry, in particular, plays a pivotal role in meeting the escalating demand for aquatic animal feed (Khalil et al., 2023; Mansour et al., 2017). However, aquaculture's rapid growth creates increasing demand for production inputs such as feed which accounts for the largest variable costs in aquaculture production. Thus, there are sustainability concerns considering aquaculture's continued dependence on conventional feedstuffs like fishmeal and soy products as major ingredients in the diets of major fed species (Chen et al., 2024; El-Ouny et al., 2023; FAO, 2022). It can be argued that achieving sustainability in aquaculture requires not only the identification of alternative feedstuffs but also the improvement of the efficient utilization of existing ingredients.

Currently, the utilization of nanotechnology in aquaculture has garnered increasing attention due to its potential to promote sustainability through

innovative aquafeed formulations that address environmental concerns associated with conventional feed (Fajardo et al., 2022). Feed additives have long been used in aquaculture to supplement and optimize the nutritional value of feed, improve growth performance, enhance disease resistance, and promote the overall health and well-being of farmed animals (Kord et al., 2021). Nanotechnology and nanomaterials applied to the food field are relatively new concepts but growing steadily due to increasing demand. For instance, the global nanotechnology market in the food sector is forecasted to grow at a yearly rate exceeding 24% from 2019 to 2023, reaching a valuation of \$112.48 billion (Technavio, 2019). This growth is largely driven by expanding applications in nutraceuticals.

The exploration of nanoparticles as feed additives opens new possibilities and opportunities to further enhance the benefits of aquaculture feed (Mitra et al., 2023). The capability of nanoelements to improve protein stability may promote several biological functions such as digestion, metabolism, and nutrient uptake (Eissa et al., 2022; Sharma et al., 2007). These properties and capabilities of nanomaterials offer transformative potential, not only in streamlining food production processes and enhancing efficiency but also in the creation of novel functional foods endowed with superior attributes. This advancement holds promise for elevating the nutritional profile, safety, and overall quality of food products, marking a significant stride towards meeting evolving consumer demands and ensuring enhanced

dietary quality thereby reducing the environmental impacts of aquaculture (Ahmed et al., 2024; Khalil et al., 2023; McClements & Öztürk, 2021).

In recent years, multiple reviews have examined the effects of employing nanotechnology in aquafeed (Dawood et al., 2022; Fajardo et al., 2022; Gabriel et al., 2022; Khalil et al., 2023; Shah & Mraz, 2020; Vibhute et al., 2023). However, most of these studies have either focused on individual nanoparticles or broader aspects of aquaculture. The most recent review by Dube (2024) aimed to detail various nanoparticles used in fish feed and their effects but focused solely on finfish, without addressing how nanotechnology is applied across different stages of feeding including feed preparation, storage, and delivery. There is a notable gap in understanding the application of nanotechnology at various stages of feed formulation, particularly in enhancing raw materials, improving their utilization, and how different types of nanomaterials are applied to promote aquaculture sustainability. This paper seeks to address these gaps through a comprehensive review of nano-enhanced diets in aquaculture, focusing on the roles of various nanoparticles, their effects on aquatic animal performance, and eco-friendly methods for developing nanomaterials. Additionally, the study examines the benefits and challenges of integrating nano-enhanced diets in aquaculture, offering insights and future research directions for sustainable development in the sector.

2. Methodology

This study was undertaken through a comprehensive review of relevant literature, focusing on peer-reviewed articles obtained from reputable academic databases, including the Web of Science and Scopus. These databases were chosen based on their reliability considering that they are widely recognized for indexing reputable journals. To access the relevant literature, we employed a search strategy that involved the use of a combination of keywords related to the main objective of the study: “Aquaculture” or “aquafeed” or “feed” and “nanotechnology” or “nanomaterial” or “nano particle” or “nano”, ensuring that articles from diverse application of nanotechnology in aquaculture and perspectives were included.

To maintain the quality and relevance of the sources, the selection criteria were applied to include studies conducted on aquaculture species and published within the last ten years, except for seminal works that remain highly cited and foundational in

the field. Additionally, we prioritized studies that included all the relevant methodological data such as the experimental design, feed formulation table, nano particle supplementation levels, aquaculture species, and size and were published in the English language. This approach was used to ensure that the data collected from the literature were critically analyzed, compared, and synthesized, allowing for a comprehensive understanding of the current state of research on the topic.

3. Dietary enhancement through nanotechnology

3.1. Feed formulations

Feed formulation is a crucial stage in aquafeed production as it determines the overall quality of the diets and the impacts, they might have on the environment. The application of nanotechnology in aquaculture feed formulations is seen as an important step toward sustaining aquaculture production. Nanotechnology can be used to improve the quality of formulated feed and improve the availability of micronutrients such as minerals, vitamins, amino acids, and fatty acids (George et al., 2023). Enhanced quality of diets ensures easy nutrient absorption, consequently minimizing resource wastages by ensuring that a major proportion of administered and are utilized by aquatic animals for various physiological and biochemical processes for body growth, metabolism, health, and welfare. Poor waste management in the aquaculture system remains one of the major challenges threatening aquaculture production (Dauda et al., 2019). Improving dietary quality through nanotechnology can contribute to addressing this challenge by ensuring feed components are translated into animal processes leading to higher productivity and profits (Lall & Dumas, 2022). Nanotechnology can be applied to improve the quality of diets in many ways including the development of raw materials, diet formulation, and feeding practices.

3.1.1. Improving raw materials quality and feed utilization

Aquafeed production involves a variety of raw materials and processing methods designed to deliver balanced nutrition to aquatic species. Nanotechnology offers a range of benefits for aquaculture diet manipulation, particularly in improving the absorption of nutrients, encapsulating substances, and overseeing the gradual release of antimicrobials enclosed in microcapsules within packaging (He et al., 2016;

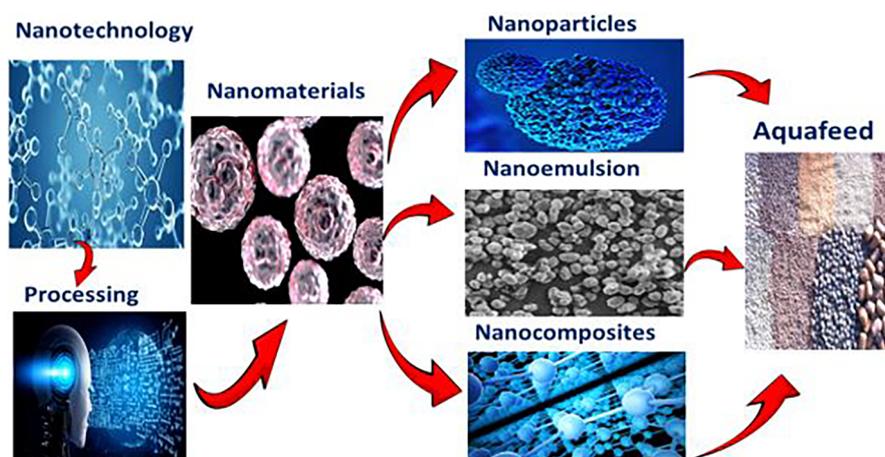


Figure 1. A graphical illustration of the development of nano-enhanced diets in aquaculture.

Fajardo et al., 2022). Three major nanomaterials: nanoparticles, nanoemulsions, and nanocomposites developed through nanotechnology have shown potential for enhancing formulated diets in aquaculture (Figure 1). Each of these nanomaterials can be applied to serve a specific purpose.

3.1.2. Nanoparticle

A fundamental principle behind the notion that nanoparticles can enhance the sustainability of aquaculture production is based on their ability to increase the quantity and nutritional quality absorbed throughout the digestive tract (Fajardo et al., 2022). Nanoparticles can encapsulate essential nutrients such as vitamins, minerals, and fatty acids, protecting them from degradation and ensuring their targeted delivery to aquatic organisms (Cui et al., 2009). This approach enables precise feeding, optimized metabolism, and efficient output, minimizing losses and maximizing profits while reducing environmental impact. For instance, nanoparticles loaded with vitamins have been shown to improve growth performance and nutrient utilization in fish (Khosravi-Katuli et al., 2014). Bioactive compounds such as probiotics, prebiotics, and immunostimulants can also be encapsulated within nanoparticles, enabling targeted delivery to specific gastrointestinal sites in aquatic organisms, ensuring efficient nutrient uptake and promoting health and growth performance (Khosravi-Katuli et al., 2014). Nanoparticle-encapsulated micronutrients and bioactive compounds in aquafeed have been proven to penetrate cells more efficiently compared to traditional feed formulation approaches (Ashouri et al., 2015; Eissa et al., 2023; Ogunkalu, 2019; Zhou et al., 2009). Moreover, nanoparticles with antimicrobial properties

can be incorporated into aquafeed to improve aquatic animal health, thus reducing the need for antibiotics, and promoting sustainable aquaculture practices. He et al. (2016) found that zinc oxide nanoparticles in nano-enhanced diets can help prevent diseases in aquatic animals by exhibiting antimicrobial properties against harmful bacteria in aquaculture systems. Nanotechnology presents opportunities to manipulate raw materials at the nanoscale and refine feed processing techniques, thereby enhancing the quality and efficacy of aquafeed. It offers several avenues for improving feed processing, including nanoemulsion techniques (Fajardo et al., 2022).

Beyond enhancing the durability and availability of feed components, nanoparticles have shown the potential to alter the physical characteristics of aquafeed. Even small amounts of nanomaterials can significantly improve the structural properties of aquafeed pellets. For instance, incorporating single-walled carbon nanotubes into trout feed resulted in the production of sturdy pellets that retain their shape in water (Fajardo et al., 2022). This not only minimizes feed loss but also reduces pollution in the aquaculture production system (Jafari et al., 2018). By leveraging nanomaterials, the decomposition process can be slowed, ensuring improved stability, and extending the shelf-life of delicate ingredients. In juvenile rainbow trout, supplementing the fish diets with Nanostructured Zeolite (NZ) on Aflatoxin B1 (AFB1) toxicity showed minimal impact on growth but improved physiological functions. Furthermore, the authors observed no significant histopathological damage to the fish (Alinezhad et al., 2017). In silver catfish (*Rhamdia quelen*), citral-loaded nanoemulsions (NE) and alginate nanoparticles (NP) modulated immune responses, reduced intestinal

bacterial populations, and altered gastrointestinal pH. However, the citral's impact on gut microbiota and immune function varied based on its delivery method, showing mode-dependent benefits (Sutili et al., 2019).

3.1.3. Nanoemulsions

Nanoemulsions, created via nanotechnology, form stable suspensions of oil droplets in water, which enhance the bioavailability of lipophilic compounds. These can be used to coat feed pellets, serving as carriers for bioactive components, protecting them from degradation, and improving the bioavailability of essential oils by boosting their antimicrobial activity (Yalçınöz & Erçelebi, 2018). Thus, the shelf life and palatability of the feed are improved, resulting in a consistent nutrient supply to aquatic organisms (Aswathanarayan & Vittal, 2019). Furthermore, the use of nanoemulsion thyme essential oil instead of just thyme essential oil in Nile tilapia (*Oreochromis niloticus*) diets showed effective antibacterial activity against *Aeromonas septicemia* (MAS). The authors further observed improved immune responses (IgM, IL-1 β , lysozyme) compared to control-fed fish (Salam et al., 2021). Korní et al. (2023) assessed the impact of thyme and *Nigella sativa* essential oils, along with their nanoemulsions, on reducing ammonia levels, boosting immune responses, and preventing *Streptococcosis* in *O. niloticus*. The study found that nanoemulsions, especially those of thyme, were more effective than bulk oils in lowering total ammonia nitrogen, reducing stress indicators, and enhancing fish immunity. However, the mechanism through which nanoparticles affect ammonia warrants further investigation. Moreover, in shrimp (*Litopenaeus vannamei*), curcumin-loaded olive oil nanoemulsion (CUR-OLNE) enhanced growth performance, digestive enzyme activity, and immune response, leading to improved economic efficiency (Fath El-Bab et al., 2024). These studies demonstrate that nanoparticles play a critical role in aquafeed by enhancing the delivery and bioavailability of nutrients, boosting immune responses, and improving the overall health and growth performance of aquatic animals. Recent developments show that the properties of nanoparticles can be improved further through novel hybrid nanocomposites. These are usually decorated with nanoparticles on graphene oxide nanosheets, developed to improve fish production. Their application has shown several benefits in aquatic animals (Ahmed et al., 2021; El-Shafai et al., 2021; Ibrahim et al., 2021; Karthick Raja Namasivayam et al., 2022;

Omar et al., 2024; Rahman et al., 2022; Srinivasan et al., 2024). This innovative feed formulation shows potential for enhancing fish growth and is recommended for further testing and development.

3.1.4. Nanocomposites

Nanocomposites are becoming a new class of materials with the potential to address water pollution issues. Nanocomposite films are derived from natural biopolymers, including lipids, proteins, and polysaccharides, making them eco-friendly, carcinogenic, and edible (Fajardo et al., 2022). Thus, they are being increasingly used as replacements for plastics derived from petrochemical sources (Dursun et al., 2010; Ogunkalu, 2019). In aquaculture, nanocomposites can play a critical role in aquafeed by enhancing the delivery and bioavailability of nutrients which increases the amount of the feed consumed by aquatic animals thus reducing wastes and pollution. For instance, Karthick Raja Namasivayam et al. (2022) found that chitosan-silver nanocomposite (CS-AgNC) could effectively be used as dye removal for methyl orange adsorption in tilapia aquaculture system without affecting fish growth, nutritional parameters, or tissue histology. Nanocomposites thus show biocompatibility, suggesting safe ecological application in aquaculture. Ghobish et al. (2025) assessed the aflatoxin adsorption efficiency of eight chitosan-based products, with nano-chitosan+mannan oligosaccharide+bentonite showing the highest adsorption (74.77%). However, the authors observed that adsorption was influenced by environmental factors such as pH and temperature, emphasizing the need for optimized conditions to maximize aflatoxin removal in food and feed using nanocomposites.

Various novel hybrid nanocomposites, decorated with nanoparticles on graphene oxide nanosheets have been developed to improve fish production (El-Shafai et al., 2021; Hamouda et al., 2023; Singh et al., 2024). In Nile tilapia, graphene oxide-Selenium (GO@Se) and graphene oxide-Selenium-Zinc oxide (GO@Se.ZnO) nanocomposites showed positive antioxidant activity and physiological effects despite degeneration of the liver post-challenge with *Streptococcus iniae* (El-Shafai et al., 2021). Similarly, Ibrahim et al. (2021) found that dietary chitosan-vitamin C nanocomposite (CVCN) enhanced growth, antioxidant activity, immune response, and resistance to *Aeromonas sobria* in Nile tilapia. Ahmed et al. (2021) compared the effects of conventional vitamin E and chitosan vitamin E nanocomposite (CVEN) and found that growth performance, immune response,

serum vitamin E, and resistance against *A. sobria* were better in CVEN. A dietary nanocomposite of vitamins C and E (VCE-NPs) significantly improved growth, feed utilization, immunity, and antioxidant activity in Nile tilapia (Sherif et al., 2024). Omar et al. (2024) investigated a ZnO-*Ulva lactuca* nanocomposite (ZnO-UI NC) in *Procambarus clarkii*, finding it effectively inhibited bacterial growth, enhanced immune response, and boosted antioxidant levels in crayfish, presenting a cost-effective immunostimulant for aquaculture. However, it must be noted that the beneficial effects obtained in these studies could be dose-dependent. For example, Rahman et al. (2022) revealed that dietary supplementation of chitosan-*Ocimum basilicum* nanocomposite (COBN) in Nile tilapia at 2g/Kg yielded the best growth, intestinal morphometrics, immunity, antioxidant status, and resistance against *A. sobria* and *Candida albicans* infection. Further research is required to explore optimal requirement levels in aquafeed for various aquatic species. Overall, the innovative utilization of nanocomposites in feed formulation shows potential for improving water quality and enhancing growth and health performance in aquatic animals.

3.2. Feed delivery strategies

Nanotechnology not only enhances the nutritional quality of aquafeed but also facilitates precise delivery mechanisms, thereby promoting optimal nutrition for aquatic animals (Soundhariya et al., 2023). Due to their smaller sizes and larger surface areas, nanoparticles offer significant potential across a wide range of biological, physical, and chemical applications (Khan et al., 2019). Their application in feed delivery to aquatic animals can promote precision nutrition due to their enhanced dispersion and solubility which improves the stability of diets against environmental degradation during feeding (Ogunkalu, 2019; Pateiro et al., 2017). Degraded water quality can reduce feed intake, further deteriorate water conditions, and negatively impact animal performance, leading to increased susceptibility to disease, feed losses, and poor economic returns (Barua et al., 2011; Barua & Sarker, 2010; Maulu et al., 2021b). Besides, delivering bioactive compounds to improve animal health while mitigating the adverse effects of antimicrobial agents presents a significant challenge. Nano-micelle-based carriers for nutraceuticals and dietary supplements have shown promising potential in addressing this issue in aquaculture (Muthukrishnan, 2022).

Delivery systems for feed supplements and nutraceuticals utilize a variety of processes, including

nanoemulsions, surfactant micelles, emulsion micelles, emulsion bilayers, and reverse micelles (Muthukrishnan, 2022; Tarhan & Spotti, 2021). Advanced nano-enabled delivery system offers numerous advantages, including reduced risk of leaching into water, decreased dosage requirements, protection against oxidation and interactions with feed ingredients, enhanced efficacy of antioxidants and preservatives, improved bioavailability of active components, preservation of chemical integrity, stability under mechanical, thermal, and pH conditions, prolonged storage protection, and extended shelf life (Aklakur et al., 2016). Consequently, nanotechnology presents a promising approach for encapsulating essential nutrients in animal feed, optimizing their delivery and effectiveness.

3.3. Nanoparticles as a growth promoter and immunomodulator in aquatic animals

Over the past few years, there has been an increasing interest in studying dietary feed additives that contain nanoparticles of selenium, manganese, zinc, iron, copper, and magnesium, demonstrating the multiple advantages in aquatic animals compared to conventional feed formulations (Ashouri et al., 2015; Ogunkalu, 2019; Vijayaram et al., 2024; Zhou et al., 2009). These advantages have been found in terms of improved animal growth performance and health, as compared to conventional chemicals (Table 1).

3.3.1. Selenium nanoparticles (SeNPs)

Over the past few years, dietary feed additives containing selenium nanoparticles (SeNPs) have gained attention for their multiple benefits in aquatic animals, including improved growth performance and health. A recent review conducted by Khalil et al. (2023), emphasized the beneficial effects on growth performance and immune response that were detected in fish-fed SeNPs, as compared to those given with control diets. Nevertheless, the authors advise against excessive supplementation of SeNPs due to the possibility of unfavorable consequences (Khalil et al., 2023). In Nile tilapia (*O. niloticus*), Eissa et al. (2024) found that dietary supplementation with SeNPs up to 1 mg/kg significantly enhanced growth, immune response, antioxidant capacity, digestive enzyme activity, and histopathological parameters, while reducing mortality when challenged with *Aspergillus flavus*. Additionally, supplementing SeNPs in the diets of crucian carp (*Carassius auratus gibelio*) increased muscle selenium levels, and antioxidant status, and promoted growth performance (Zhou

Table 1. Summary of the reported effects of some nanoparticles applied in aquafeed.

Fish species	Fish size (mean ± SE, g)	Nanoparticles used	Inclusion level	Reported results compared with the control diet	References
<i>Acipenser stellatus</i>	182.09 ± 9.05	Fe-NPs	50 mg/kg	Optimum of red and white blood cells, neutrophils, and total protein, in respiratory burst activity, and total immunoglobulin level	Ebrahimi et al., 2020
<i>Acanthopagrus arabicus</i>	237.5 ± 8.1	N-Se	2–4 mg/kg	Improved the larval quality by reducing the percentage of embryo abnormality, and increasing the length and survival of hatchlings	Saffari et al., 2021
<i>Acanthopagrus arabicus</i>	Males: 195.3 ± 10.8, Females: 237.5 ± 8.1	N-Se	0.2 mg/kg	Enhanced physiological health and performance of brooders and larvae	Izadpanah et al., 2022
<i>Catla catla</i>	6.41 ± 0.02	nano-selenium	1.64 mg/kg	Improved growth performance, health status and response to stressor	Sultan et al., 2024
<i>Cyprinus carpio</i>	5.51 ± 0.04	Fe ₂ O ₃ -NPs	40 mg/kg	Improved growth, nutrient absorption, body composition and haematological indices	Hussain et al., 2023
<i>Carassius auratus</i>	4.3	Fe-NPs	0.5 g mg/kg	Higher specific growth rates (SGR) and lower feed conversion ratios (FCR)	Akbary & Jahanbakhshi, 2018
<i>Carassius auratus gibelio</i>	–	Se-NPs	1 mg/kg	Growth performance, muscle composition and glutathione peroxidase enzyme activity	Zhou et al., 2019
<i>Clarias gariepinus</i>	6.89 ± 0.05	Ascorbic acid: Fe NPs	6:4g/kg	Better response to hyperthermia induced stress and improved biochemical and histological indices	Oluyemi, 2021
<i>Clarias gariepinus</i>	90 ± 10	MnO NPs	1.2 mg/kg	Promoted blood lipid levels (triglycerides and cholesterol), kidney function markers (creatinine and urea), liver function indicators (ALT, AST, ALP, LDH), antioxidant levels (CAT, SOD, GPx), and growth performance	Thabet et al., 2021
<i>Ctenopharyngodon idella</i>	5.49 ± 0.03	ZnO-NPs	30 mg/kg	Better growth performance and RBCs count improved absorption, bioavailability of nutrient	Faiz et al., 2015
<i>Cyprinus carpio</i>	–	Se NPs	1 mg/kg	Better fish growth and antioxidant defense system	Ashouri et al., 2015
<i>Cyprinus carpio</i>	50	Fe NPs + Probiotic <i>Lactobacillus</i>	0.50 mg/kg	Optimum biochemical parameters such as total plasma protein, albumin, globulin, creatinine, triglycerides, cholesterol, as well as ALP, ALT, AST, and LDH enzymes.	Ziaei-Nejad et al., 2021
<i>Cyprinus carpio var. communis</i>	–	MnO NPs	6 mg/kg	Better growth parameters and haematological parameters	Soundhariya et al., 2023
<i>Cyprinus carpio</i>	30.63 ± 0.61	NNSe3	3 mg/Kg	Improved stress resistance and post-stress recovery	Rezaei et al., 2024
<i>Dicentrarchus labrax</i>	20.27 ± 0.12	Se NPs	1 mg/kg	Improved growth rate, feed efficiency, hematobiochemical indices, immune function, antioxidant activity, and anti-inflammatory properties.	Abd El-Kader et al., 2020
<i>Dicentrarchus labrax</i>	12.80 ± 0.64	nano-Se and nano-clay	5 mg/kg	Enhanced the growth rate, biochemical indices, and immunity	Khaled et al., 2024
<i>Etroplus suratensis</i>	–	Fe ₂ O ₃ -NPs	20 mg/kg	Better growth and serum biochemical profile	Nirmalkar et al. 2023
<i>Hypophthalmichthys molitrix</i>	–	nano-scale chitosan (CNP)	5 g kg ⁻¹	Enhance fish productivity and fish immune response towards the invading pathogens	Younus et al., 2020
<i>Labeo rohita</i>	–	Fe-NPs + Zn-NPs	5 mg/kg	Improved growth performance and nutrient metabolism, improved antioxidant enzymatic activities (SOD and GSH level), survival, growth and biochemical compositions	Thangapandiyan and Monika 2020
<i>Labeo rohita</i>	–	ZnO NPs	5–7.5 mg/kg	Improved growth and metabolic functions	Thangapandiyan & Monika, 2020
<i>Labeo rohita</i>	–	nano-Fe	0.54 ± 0.002/ kg	Improved antioxidant enzymatic activities (SOD and GSH level)	Behera et al., 2014
<i>Labeo rohita</i>	0.37 ± 0.02	ZnO NPs Se NPs	10 mg/kg 0.3 mg/kg	Enhanced growth and non-specific immune parameters such as respiratory burst, lysozyme, and myeloperoxidase activities.	Swain et al., 2016
<i>Liza ramad</i>	23.67 ± 0.05	ZnO NPs	24.61–35.5 mg/kg	Better growth performance, antioxidative capacity, and intestinal histomorphology	Shukry et al., 2021

(Continued)

Table 1. Continued.

Fish species	Fish size (mean ± SE, g)	Nanoparticles used	Inclusion level	Reported results compared with the control diet	References
<i>Macrobrachium rosenbergii</i>	0.11 ± 0.04	Fe ₂ O ₃ NPs	20 mg/kg	Increased survival rates, growth, protease, amylase, and lipase activities, total protein, amino acid, carbohydrate, and lipid concentrations, improved profiles of protein, amino acids, and fatty acids, as well as enhanced haemocytes.	Srinivasan et al., 2016
<i>Macrobrachium rosenbergii</i>	–	Zn-NPs	60 mg/kg	Improved in survival, growth, feed intake, specific growth rate, essential amino acids, unsaturated fatty acids, nonspecific immune responses (total haemocytes and differential haemocytes count)	Thirunavukkarasu et al., 2019
<i>Macrobrachium rosenbergii</i>	0.11 ± 0.04	MgO NPs	500 mg/kg	Better growth indices [survival rate (SR), weight gain (WG), SGR, FCR and protein efficiency ratio (PER)], activities of digestive enzymes (protease, amylase and lipase), concentrations of basic biochemical constituents (total protein, amino acid, carbohydrate, lipid, profiles of amino acids and fatty acids) and population of haemocytes [total and differential (hyalinocytes, semigranulocytes and granulocytes)]	Srinivasan et al., 2016
<i>Macrobrachium rosenbergii</i>	0.18 ± 0.02	ZnNPs	80 mg/kg	Improved performance in survival, growth and activities of digestive enzymes (protease, amylase and lipase). The concentrations of biochemical constituents (total protein, total amino acid, total carbohydrate and total lipid), total haemocyte count and differential haemocyte count	Muralisankar et al., 2014
<i>Macrobrachium rosenbergii</i>	0.15 – 0.22	Cu-NPs	40–80 mg/kg	Improved survival, growth, digestive enzyme activities, concentrations of biochemical constituents and total and differential haemocytes count	Muralisankar et al., 2016
<i>Micropterus salmoides</i>	7.00 ± 0.02	Nano-curcumin	20 mg/kg	Promoted mucosal immunity, antioxidant properties, and glucose metabolism and alleviated ERS induced by long-term carbohydrate intake	Bao et al., 2022
<i>Macrobrachium rosenbergii</i>	0.23 ± 0.06	MnO NPs	3.0–18 mg/kg	Enhanced survival, growth, and production	Asaikkutti et al., 2023
<i>Oncorhynchus mykiss</i>	4.74 ± 0.14	LEO/CNPs	1 mg/kg	Significantly improved FCR, better growth performance and immuno-physiological responses	Gheytsi et al., 2021
<i>Oncorhynchus mykiss</i>	82.3 ± 11.6	ZnO-NPs	50 mg/kg	Enhanced growth performance and feed utilization.	Shahpar & Johari, 2019
<i>Oncorhynchus mykiss</i>	9.1 ± 0.3	MnO NPs	12 mg/kg	Higher level of erythrocytes, hemoglobin, and hematocrit	Rajabi et al., 2016
<i>Oreochromis niloticus</i>	1.00	Se-NPs	1 mg/kg	Enhanced the growth performance and meat quality	Moges et al., 2022
<i>Oreochromis niloticus</i>	12.50 ± 1.03	Se-NPs Zn-NPs	1 mg/kg 10 mg/kg	Improved growth, hemato-biochemical profile, immune and antioxidation capacity, and intestinal morphology	Ghazi et al., 2021
<i>Oreochromis niloticus</i>	16.2 ± 0.45	Fe, Zn, Cu, Se NPs	–	Improved growth performance and biochemical indicators.	Khan et al., 2020
<i>Oreochromis niloticus</i>	12.0 ± 0.53	NCur	0.013 mg/kg	Promoted growth, digestion, immune status, liver function, antioxidant status, and related gene expression	Elabd et al., 2023
<i>Oreochromis niloticus</i>	15.73 ± 0.05	Se NPs	1.0 mg/kg	Improved growth, better selenium regulation and expression of immune-regulated selenoproteins.	Rathore et al., 2021
<i>Oreochromis niloticus</i>	9.09 ± 0.014	Nano-Fe ₂ O ₃	0.4 mg/kg	Enhanced fish growth, immune response, antioxidant capacity, and intestinal integrity.	Mohammady et al., 2021
<i>Pagrus major</i>	–	Se-NPs	1 mg/kg	Enhanced growth, feed efficiency, blood parameters, and antioxidant defense mechanisms	Dawood et al., 2019

(Continued)

Table 1. Continued.

Fish species	Fish size (mean ± SE, g)	Nanoparticles used	Inclusion level	Reported results compared with the control diet	References
<i>Pangasianodon hypophthalmus</i>	2.13 ± 0.01	Se NPs	1.02–1.11 mg/kg	Better growth performance, antioxidative capacity, and liver wellbeing	El-Sharawy et al., 2022
<i>Pelteobagrus fulvidraco</i>	–	MnO NPs	8.33–12.57 mg/kg	Improved growth performance and feed utilization of the fish.	Xu et al., 2023
<i>Schizothorax zarudnyi</i>	23.97 ± 0.45	Fe NPs + Cu NPs	3 mg/kg	Fish growth, antioxidant capacity, and hemato-immunological parameters were enhanced.	Afshari et al., 2021
<i>Sparus aurata</i>	0.12 ± 0.03	Zn, Mn, Se	–	Enhanced ability to withstand stress without affecting bone mineralization.	Izquierdo et al., 2017
<i>S. aurata</i>	8.2 ± 0.4	Zn and Mn	8.2 g	Increased growth, elevated protein deposition, and reduced lipid levels.	Domínguez et al., 2019
<i>Tor putitora</i>	2.27 ± 0.01	Se-NPs	0.68 mg/kg	Improved growth performance, higher red blood cell count, hemoglobin level, hematocrit values, and lysozyme activity	Khan et al., 2019

Note: Se, selenium; Zn, zinc; Fe, iron; Mn, manganese; Cu, copper; ZnO, zinc oxide; Fe₂O₃, iron (III) oxide; NPs, nanoparticles; ALT, alanine aminotransferase; AST, aspartate aminotransferase; ALP, alkaline phosphatase; LDH, lactate dehydrogenase; CAT, catalase; SOD, superoxide dismutase; GPx, glutathione peroxidase; RBCs, red blood cells; LEO, lemon essential oil; CNPs, chitosan nanoparticles.

et al., 2009). Kumar et al. (2018) observed improved growth, increased antioxidant defense, and better immunological response in fish that were fed diets containing selenium nanoparticles (Se-NPs) while being exposed to lead (Pb) and high temperature (34 °C) conditions. Ziaei-Nejad et al. (2021) found that feeding *Acanthopragrus latus* with SeNPs resulted in enhanced growth performance and increased antioxidant capacity. Moreover, the inclusion of selenium and magnesium nanoparticles in the diet of Asian sea bass (*Lates calcarifer*) had a beneficial impact on growth and the non-specific immune system, without causing any negative effects on serum biochemical and hepatic enzyme parameters (Pour et al., 2020).

3.3.2. Manganese nanoparticles (MnO-NPs)

Manganese (Mn) is crucial for enhancing the growth and biological functions of fish (Viegas et al., 2021). Supplementing fish diets with different amounts of MnO-NPs has been demonstrated to enhance growth and hematological traits in common carp (*Cyprinus carpio*) (Soundhariya et al., 2023). Similarly, freshwater prawns (*Macrobrachium rosenbergii*) showed an enhanced antioxidant defense system and growth when fed a diet containing MnO-NPs at a concentration of 16 mg/kg (Asaikkutti et al., 2023). Manganese nanoparticles enhance feed conversion ratios and protein efficiency, leading to better weight gain in fish (Nalage et al., 2023).

3.3.3. Iron nanoparticles (Fe-NPs)

Rainbow trout exhibited improved growth parameters when their diet was supplemented with iron nanoparticles (Fe-NPs) (Mohammadi et al., 2015).

Studies show that dietary Fe-NPs at optimal concentrations (30 mg/kg) significantly improve weight gain, biomass, and specific growth rates in *Labeo rohita* (Jewel et al., 2023). Iron oxide nanoparticles have also been linked to increased hemoglobin levels, which contribute to better growth performance (Kumar et al., 2024). Fe-NPs exhibit immunomodulatory effects, enhancing the fish's resistance to pathogens and improving overall health (Rashk-E-Eram et al., 2022). The combination of Fe-NPs with other natural extracts has been shown to boost antioxidant enzyme activities, further supporting fish health during disease challenges (Ibrahim et al., 2024).

3.3.4. Magnesium nanoparticles (Mg-NPs)

Magnesium nanoparticles have demonstrated positive effects on growth performance and immune system functionality, particularly in species like Asian sea bass (*Lates calcarifer*). They offer a safe means to enhance dietary intake without negatively affecting serum biochemical and hepatic enzyme levels (Pour et al., 2021). Studies show that dietary MgO NPs at optimal levels (e.g., 120 mg/kg) significantly improve growth metrics such as weight gain and feed conversion ratios in fish like *Megalobrama amblycephala*. Mg-NPs enhance glucose metabolism and reduce oxidative stress, as evidenced by increased transcription of glucose transporters and decreased oxidative markers (Zhang et al., 2023). Supplementation also leads to improved digestive enzyme activity, which is crucial for nutrient absorption in *Macrobrachium rosenbergii* (Srinivasan et al., 2017). The inclusion of Mg-NPs in aquafeed has been linked to improved non-specific immune responses, with significant

changes in serum biochemical parameters indicating better health status (Pour et al., 2021).

3.3.5. Chitosan nanoparticles (CSNPs)

Chitosan nanoparticles are widely studied for their immunomodulatory properties. The incorporation of N-acetyl-D-glucosamine (NAG) loaded CSNPs has been shown to boost immune responses, growth performance, and disease resistance in fish like Nile tilapia (*O. niloticus*). These nanoparticles also improve the efficiency of feed utilization and enzyme activities such as lipase and amylase. According to Abd El-Naby et al. (2019), the addition of chitosan nanoparticles to the diet of *O. niloticus* can enhance both the efficiency of feed utilization and the rate of growth and the presence of chitosan particles enhance the activity of enzymes like lipase and amylase. Furthermore, it has been discovered that the utilization of these nanoparticles controls the proliferation of both aerobic and anaerobic bacteria, but also enhances the functionality of the innate immune system. Subramanian et al. (2021) examined the effects of incorporating N-acetyl-D-glucosamine (NAG) loaded chitosan nanoparticles (CSNPs) into the diet of *O. niloticus* and demonstrated that the dietary inclusion of NAG-loaded CSNPs increased the immune-modulatory characteristics, growth performance, and disease resistance, suggesting their potential as helpful supplements for aquaculture. Marwa et al. (2022) found that the use of CS and CSNP supplements can effectively regulate the innate immune response and improve growth performance.

3.3.6. Gold nanoparticles (Au NPs)

Au NPs are known to increase the permeability of cell membranes, facilitating the uptake of essential nutrients and minerals. This improved nutrient bioavailability can lead to enhanced growth rates and better feed efficiency. Phytochemically synthesized gold nanoparticles have been found to mitigate hepatic damage in Asian carp exposed to environmental pollutants. These nanoparticles show promise in reducing oxidative stress markers, improving liver function, and enhancing survival rates (Kunjiappan et al., 2015). The detoxification capabilities of Au NPs were further highlighted by Muralisankar et al. (2016), who observed that gold nanoparticle supplementation in the diet of red sea bream enhanced hepatic detoxification processes. Sharif et al. (2017) demonstrated that dietary supplementation with Au NPs improved the carcass composition, growth rate, and survival of Siberian sturgeon (*Acipenser baerii*) by

boosting their immune response. According to Vijayaram et al. (2024), the inclusion of Au NPs in aquafeed led to a significant increase in antioxidant enzyme activities, such as superoxide dismutase (SOD) and catalase (CAT), in common carp. Gold nanoparticles are very likely to significantly enhance the levels of oxidative stress markers, decrease hepatic ions, metabolic enzymes, hepatotoxic markers, aberrant liver histology, and alter tissue enzymes (Zugravu et al., 2024).

3.3.7. Nanoencapsulated ascorbic acid

Fish depend on dietary ascorbic acid (AA) for their reproductive, developmental, and immune systems. Nanoencapsulation helps in preserving the stability of AA, thereby improving its effectiveness. Studies show that polymeric nanoparticles of AA significantly enhance immune responses and growth in species like rainbow trout and Nile tilapia (Naiel et al., 2020; Angélica et al., 2021). Fish depend on ascorbic acid (AA) for their reproductive, developmental, and immune systems, yet they must obtain it through their diet as they cannot synthesize it internally (Luis et al., 2021). Nanoencapsulation can minimize losses caused by external factors by providing protection and preserving the physicochemical properties of AA for extended durations (Pateiro et al., 2021). Angélica et al. (2021) evaluated the efficacy of polymeric nanoparticles (polycaprolactone and chitosan) in safeguarding AA from degradation through nanoencapsulation. Naiel et al. (2020) found that combining vitamin C with chitosan nanoparticles improved immune function, growth, food utilization, antioxidative status, hepatocyte structure, and overall health in *O. niloticus* exposed to sub-lethal levels of imidacloprid, offering benefits beyond immune modulation. A study conducted by Alishahi et al. (2011) found that adding chitosan-based nanoparticles containing vitamin C to the diet of rainbow trout (*O. mykiss*) considerably increases the concentration of vitamin C in the blood serum. This supplementation also improved the natural immune response by elevating levels of lysozyme and hemolytic serum complement activity. Ismael et al. (2021) discovered that the addition of zeolites to the diet, either on their own or in combination with chitosan nanoparticles, successfully reduces the harmful effects of imidacloprid on fish. In contrast, the combination of chitosan nanoparticles with thymol improves the development and food utilization in *O. niloticus*. According to Abd El-Naby et al. (2020), this combination enhances both enzymatic activity and the length of intestinal villi. Several researchers support the use of chitosan

(CS) and chitosan nanoparticles (CSNP) as substances that enhance the immune system and stimulate growth (Abd El-Naby et al., 2019; Abdel-Ghany & Salem, 2020; Abdel-Tawwab et al., 2019; Alishahi et al., 2014; Gopalakannan & Arul, 2006).

3.3.8. Zinc nanoparticles (ZnO-NPs)

Insufficient zinc levels in aquatic animals negatively affect their biological processes and impair their physiological functions (Lall & Kaushik, 2021). Therefore, the addition of ZnO-NPs can serve as a viable approach to address zinc deficiency. El-Saadony et al. (2021) investigated the use of zinc nanoparticles (Zn-NPs), particularly biological zinc nanoparticles (BIO-ZnO-NPs), to reduce stress and combat harmful bacteria in fish. The study assessed the effects of BIO-ZnO-NPs on growth, behavior, and immunity in *O. niloticus*, comparing them with chemical zinc nanoparticles (CH-ZnO-NPs). Results indicated that Zn-NPs improved growth performance and reduced oxidative stress in treated fish. Kumar et al. (2018) found that dietary zinc nanoparticles (Zn-NPs) supplementation significantly improved immunological parameters, including total protein, albumin, globulin, and the A/G ratio. Additionally, stress biomarkers such as blood glucose, cortisol, and HSP 70 were reduced in the groups receiving Zn-NPs. Thangapandiyam and Monika (2020) assessed the impact of zinc oxide nanoparticles (ZnO-NPs) in feed on the growth of *Labeo rohita* fingerlings, revealing significant improvements in growth and metabolic activities. Additionally, a combination of silver and zinc oxide nanoparticles demonstrated strong inhibitory effects against pathogens such as *A. salmonicida*, *A. invadans*, and *Y. ruckeri*. Hence, these nanoparticles provide alternative antibacterial substances against infections (Shaalaa et al., 2017; Tamanna et al., 2015).

3.3.9. Iron nanoparticles (Fe-NPs)

Dietary supplementation with iron (Fe) in *Macrobrachium rosenbergii* showed various benefits, including enhanced growth, survival rates, food consumption, digestion, and metabolic processes (Starsich et al., 2019). Iron nanoparticles (Fe-NPs) have attracted considerable attention because of their distinct physicochemical characteristics and potential as growth enhancers in fish feed supplements. The addition of Fe-NPs at a concentration of 40 mg/kg to fish meal improved growth indices, feed consumption, and metabolism, as reported by Akter et al. (2018). The application of magnetic iron oxide

nanoparticles (Mag iron NPs) to the coating of *Chlorella vulgaris* extract (ChVE) in Nile tilapia allows for the generation of an external magnetic field, which aids in the specific release of substances in the tissue. Fish-fed Fe-NPs exhibited enhanced immunological barrier and antioxidant capacities in their skin and gills, leading to higher survival rates during infections, accompanied by alterations in gene expression (Ibrahim et al., 2024).

3.3.10. Combined nanoparticle supplements

Combining various nanoparticles, such as chitosan, zinc, and selenium, has been shown to improve growth performance, feed efficiency, and immunity in several aquatic species. These combinations can further enhance stress resistance and reduce oxidative damage, making them effective dietary supplements (Alishahi et al., 2011; Ismael et al., 2021; Kumar et al., 2018).

In addition, the inclusion of copper nanoparticles enhanced the non-specific immune response, levels of antioxidant metabolic enzymes, activities of digestive enzymes, biochemical components, and growth in red sea bream (*Pagrus major*) (El Basuini et al., 2017) and freshwater prawn (Muralisankar et al., 2016). The study conducted by Izquierdo et al. (2017) showed that the presence of manganese, zinc, and selenium nanoparticles in gilthead seabream (*Sparus aurata*) resulted in enhanced bone mineralization and increased resilience to stress.

4. Eco-friendly production of nanoparticles for aquaculture

4.1. Green synthesis

The production of nanoparticles for feed formulations may be accomplished through the utilization of ecologically acceptable approaches such as green synthesis (Figure 2). "Green synthesis" refers to an eco-friendly and sustainable approach that utilizes microorganisms such as bacteria, fungi, and yeast, as well as plants, to safely produce various compounds (Gowramma et al., 2015; Makarov et al., 2014; Mohammed & Hawar, 2022). Microorganisms and plants have long been utilized for their metabolic processes to convert inorganic metallic ions into metal nanoparticles (Baker et al., 2013; Vicas et al., 2019). Consequently, various studies have explored the use of various microorganisms including bacteria (Saravanan et al., 2018), fungi (Joshi & Devi, 2015), yeast (Jiang et al., 2022), actinomycetes (Kumari et al., 2021), algae (Sathishkumar et al., 2019), and

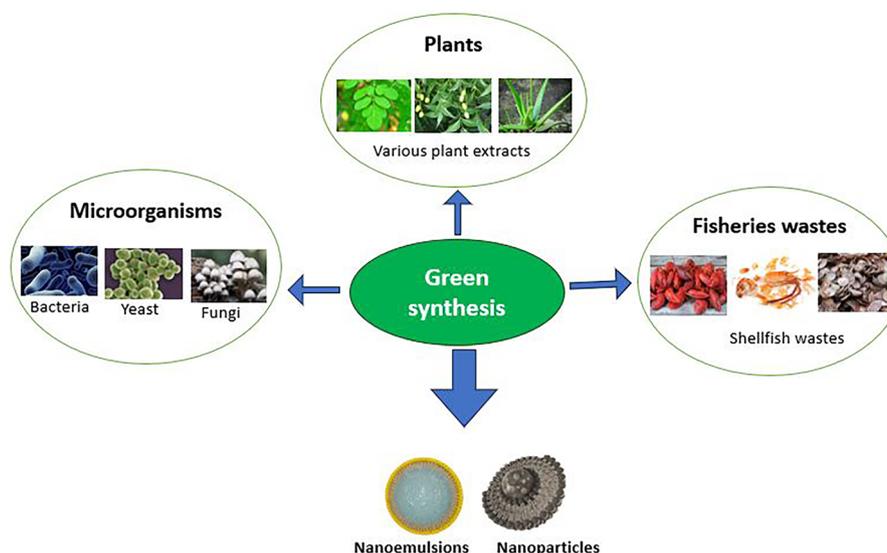


Figure 2. Eco-friendly approaches to nanoparticle production.

other microorganisms as greener methods of producing a variety of NPs. Plants, algae, fungi, bacteria, and viruses have been used to produce low-cost, energy-efficient, and non-toxic nano mineral particles in the past years (Kaushik et al., 2010). These microorganisms possess lipid-based amphipathic membranes, enabling them to interact with their environment. These interactions trigger coupled oxidation-reduction processes, which accelerate the production of nanoparticles (Lengke et al., 2006). Therefore, green synthesis enables the generation of compounds that are both efficient and sustainable for aquafeed.

Various metal nanoparticles such as silver, gold, cadmium, selenium, palladium, barium titanate, and titanium have successfully been synthesized by biological methods using different plant materials (Narayanan & Sakthivel, 2010; Philip & Unni, 2011). These nanoparticles are not toxic to cells and offer a substitute antibacterial therapy against pathogens. Notably, the biosynthesis of ZnO nanoparticles is in its infancy, thus further research is required to promote its utilization. Nevertheless, nano Zn was successfully prepared using leaves of *Parthenium hysterophorous* (El-Houseiny et al., 2021), highlighting the potential of plants for biosynthesis.

The use of plants for nanoparticle synthesis offers several advantages, making it a preferable method. This green synthesis approach is straightforward, often involving a single-step or one-pot process, which simplifies both the procedure and the recovery of nanoparticles from the final solution (Rajendran et al., 2013). It is eco-friendly, eliminating the need for harmful chemicals, and compatible with

pharmaceutical and biomedical applications due to its nontoxic nature. Additionally, it is cost-effective, economically viable, and less time-consuming, with no requirement to maintain specific cultures, making it a highly efficient and sustainable option for nanoparticle production (Rajendran et al., 2013). Metal nano mineral particles have been successfully synthesized from *Avena sativa*, *Azadirachta indica*, *Aloe vera*, *Moringa oleifera* extract, alfalfa, lemongrass, *Sesbania drummondii*, papaya fruit extract, and latex of *Jatropha cutcas* (El-Houseiny et al., 2021; Mohammed & Hawar, 2022; Swain et al., 2021; Younas et al., 2023). Despite its many advantages, the biological synthesis of nano mineral particles using plants has some significant drawbacks. These include the need to maintain specific cultures and their conditions, as well as the culture media, which can be resource intensive. The time required for nanoparticle formation can be prolonged, and product recovery from the solution is often challenging. These limitations could reduce the efficiency and scalability of this biological method.

4.2. Other emerging synthesis methods

Besides the green synthesis methods discussed above, there are other emerging promising approaches such as nanoemulsions and the utilization of fisheries wastes. Nanoemulsions play a key role in the development of edible films. Researchers have developed alginate films infused with nanoemulsions loaded with essential oils (Acevedo-Fani et al., 2015). This approach prevents the essential oils from deteriorating and improves the dispersion of water.

Research by Otoni et al. (2014) and Hussain et al. (2019) revealed that incorporating nanoemulsions containing essential oils into antibacterial films improves the antimicrobial properties of thyme essential oil. Other studies have focused on the utilization of a variety of biopolymers in aquaculture (Alboofetileh et al., 2016; Dursun et al., 2010; Joukar et al., 2017), likely due to their biodegradability and improved functionality. Additionally, nano-liposomes that contain essential oils demonstrate regulated release, which increases the antibacterial capability of these nano-liposomes against pathogens in aquaculture (Fajardo et al., 2022; Hussain et al., 2019).

Managing waste from shellfisheries is a significant global challenge, particularly affecting coastal regions. Chitosan, derived from shellfish, is used as a feed additive for various fish species, enhancing both their immune system and overall production. The successful synthesis of extremely stable selenium nanoparticles (SeNPs) using abalone viscera as the starting material and a polysaccharide-protein complex (PSP) as the capping agent has been reported (Ren et al., 2021). Thus, marine viscera polysaccharides present an opportunity to produce SeNPs in an ecofriendly manner. A study by Saad et al. (2022) evaluated the effectiveness of dual-functioning Bio-SeNPs in mitigating heavy metal toxicity and bacterial load in Nile tilapia (*O. niloticus*). The results showed that, in a concentration-dependent manner, Bio-SeNPs reduced heavy metal accumulation in fish organs and decreased bacterial load in the rearing medium.

5. Challenges and prospects

Nano-enriched aquafeeds represent a transformative innovation in aquaculture, enhancing nutrient delivery, promoting fish growth, bolstering immunity, and reducing environmental impacts. Advances in green synthesis methods provide a sustainable alternative for producing nanoparticles (NPs), leveraging eco-friendly materials such as plants, algae, fungi, and bacteria to minimize harmful chemical usage. For instance, selenium nanoparticles (SeNPs) have successfully been synthesized using abalone viscera and polysaccharide-protein complexes. Nanoparticles improve feed formulations by enhancing nutrient bioavailability and reducing waste (Ni et al., 2023). Nano-encapsulation of essential nutrients protects them from degradation, allowing controlled release and improved feed efficiency. These advancements reduce nutrient runoff and water pollution, lowering the

environmental footprint of aquaculture systems. Additionally, nanoparticles like chitosan and zinc oxide have shown potential in boosting immune responses and disease resistance in aquaculture species, reducing reliance on antibiotics. Biodegradable NPs, such as those derived from chitosan and alginate, align with circular economy principles by enhancing feed efficiency while mitigating environmental impacts (Okeke et al., 2022).

Despite their potential, significant challenges remain in adopting nano-enhanced aquafeeds (Figure 3). One concern is nanoparticle toxicity, as their small size allows them to penetrate cell membranes, potentially causing genotoxicity, oxidative stress, and DNA damage (Ahmed et al., 2024). Zinc oxide nanoparticles (ZnONPs) can induce oxidative stress and inflammation more readily than bulk zinc additives, and SeNPs, while nutritionally beneficial, may negatively impact sperm quality and increase oxidative stress at non-optimal doses. The long-term effects of NP accumulation in fish tissues and their release into aquatic environments remain unclear, raising concerns about ecosystem disruption and biodiversity loss (Dube, 2024; Martínez et al., 2020).

Overuse of nanoparticles at high concentrations can lead to oxidative stress, cellular damage, and bioaccumulation in aquatic organisms (El-Saadony et al., 2021). Liver and kidney health, as well as overall fish well-being, can be compromised by prolonged NP exposure (Ogunkalu, 2019). Limited research on long-term impacts on fish health and human consumers complicates regulatory approval processes (Dube, 2024). Environmental risks are another concern, as NP runoff from aquaculture systems may contaminate nearby water bodies, affecting non-target organisms and disrupting ecological balance (Shalan et al., 2017; Tamanna et al., 2015). Additionally, the synthesis of certain nanoparticles using chemical methods may produce harmful by-products that contribute to environmental pollution.

The high cost of NP synthesis, particularly for precious metals like gold and silver, limits accessibility. Green synthesis methods, while sustainable, are not yet scalable for commercial applications, and the need for specialized equipment further increases costs, posing barriers to small-scale operations (Vibhute et al., 2023). Regulatory hurdles arise from the lack of standardized guidelines for NP safety assessment and limited data on long-term environmental and health impacts (Kord et al., 2021). Public skepticism towards nano-enhanced products may further hinder market acceptance.

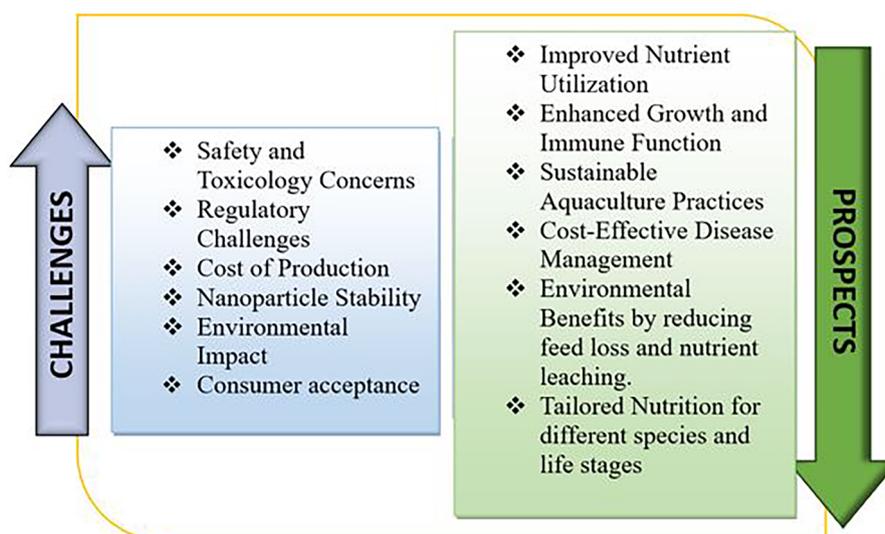


Figure 3. Challenges and prospects of nano-enhanced diet in aquaculture.

Overcoming these challenges requires robust regulatory frameworks and best management practices. These should include comprehensive testing of environmental impacts and effects on human and aquatic health. International collaborations between developed and developing countries could help promote sustainable aquaculture practices (Gruère et al., 2011). Toxicological studies suggest that nanomaterials pose lower occupational hazards compared to other chemicals used in aquaculture, but more specific guidelines for their use, including concentration limits, are needed (World Health Organization, 2017). Research must shift from lab-scale studies to field applications to evaluate practical viability and environmental impacts. Technological advancements and specialized knowledge will be crucial for integrating nanotechnology into the aquafeed production chain, enabling sustainable development while supporting global food security (Abbas, 2021).

6. Conclusion

This review highlights the transformative potential of nanotechnology in aquafeed, offering enhanced growth, health, and sustainability in aquaculture. Nanotechnology allows the manipulation of feed ingredients at the nanoscale, improving nutrient bioavailability and functional properties. Green synthesis of nanoparticles using microorganisms and plants provides an eco-friendly alternative, promoting environmental safety and sustainability. However, significant limitations exist. Key challenges include the long-term safety and sustainability of nanoparticle-

based diets across a fish's life cycle, inconsistent particle size, limited scalability, and quality control in green synthesis methods. The economic feasibility of integrating nanotechnology into commercial aquafeeds remains uncertain, necessitating detailed cost-benefit analyses. Additionally, regulatory frameworks and consumer acceptance require consideration for successful market adoption. The review focused primarily on the direct impacts of nanoparticles on growth and health, leaving unexplored the interactions between nanoparticles and other feed additives, such as probiotics and antibiotics. Future research must address these gaps to optimize nanotechnology's application in aquaculture.

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Author contribution

AM: formulated the study objectives and wrote the original manuscript draft, FDA: wrote the original draft manuscript, PB: drafted original manuscript, SO: wrote the original draft manuscript, PM: wrote the original manuscript, HSK: revised critically, edited the drafted manuscript, and created graphical illustrations, SM: conceptualized the study and wrote the original draft. All authors reviewed and approved the final draft for publication consideration.

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Data availability statement

The authors declare all the data used in this study are included in this document.

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