Received: 27 August 2021 | Revised: 28 April 2022 | Accepted: 2 June 2022
DOI: 10.1111/raq.12705

REVIEW

REVIEWS IN Aquaculture

Embracing nanotechnology for selenium application in aquafeeds

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Funding information
This work was carried out as the basis of the CGIAR Research Program (Trust Fund) on Fish Agri-Food Systems (FISH), which was directed by the WorldFish Center. Additional funding was provided by Wageningen University through a Post-Doctoral fellowship.

Abstract

Selenium (Se) is an important micronutrient that has been used in aquafeeds for the normal growth, welfare and health of aquatic animals. Through nanotechnology, Se can be converted into nanoparticles that are more bioavailable, utilized and absorbed by aquatic animals. However, this is still a new and emerging area of research in aquafeeds. This paper aims to review the effect of Se and Se nanoparticles (Se-NPs) application in aquafeeds on aquatic animals. Specifically, different compounds of Se, requirement levels by different species, effects on animal growth, physiology, antioxidant capacity and immune response have been highlighted. The review shows that the application of Se in aquafeeds could improve the growth performance, physiology, antioxidant enzymes, immunity and disease resistance in aquatic animals. However, the effectiveness could be highly influenced by the source of Se, aquaculture species and administration quantity. Through nanotechnology, the utilization and absorption of Se could be improved while reducing its toxicity. Therefore, Se-NPs present an efficient way to utilize nutrients in aquafeeds. Important gaps, however, exist in the current knowledge, particularly with regard to the response of shrimps and crustaceans to dietary supplementation of Se and Se-NPs as most of the existing studies have focused on fish species. Also, some species of economic importance and life stages have not been investigated, which hinders the embracement of nanotechnology in aquafeeds production.

KEYWORDS
aquaculture, dietary supplementation, growth performance, immune response, micronutrient, selenium nanoparticles

1 | INTRODUCTION

The global population is projected to continue expanding and will reach approximately nine billion people by the year 2050.[1,2] This is expected to put extra pressure on the food production sector as it responds to the growing demand. Aquaculture, being the fastest-growing food production sector, has continued to make significant contributions to food and nutrition security globally.[3] However, the sustainability of the sector is threatened by rising feed costs as conventional feed ingredients become less available and more expensive. Therefore, efforts have been made toward improving the digestibility and utilization of existing ingredients to achieve the blue economy goals.[4]

The application of nanotechnology is an emerging but very promising technological advancement in the aquaculture industry. In particular, the application of nanoparticles and emulsion-based systems have been reported in the production of aquafeeds,[5–7] disease control and prevention,[8,9] and water purification.[10,11] In aquaculture, nanoparticle technology can considerably help to raise the utilization efficiency of aquaculture inputs, including medicines, vaccines, pelleted feed and even gene delivery.[12,13] Nevertheless, nanomaterial's particle sizes can increase the mobility, bioavailability and effectiveness of other compounds when compared to bulk materials.[14–16] Many researchers studied the valuable effects of these nano-sized feed additives as they have been shown to improve Nile tilapia, *Oreochromis niloticus*, growth performance, feed utilization, immunology and carcass characteristics.[5,14,15,17] Similar effects were reported for Asian sea bass, *Lates calcarifer*,[18] rainbow trout, *Oncorhynchus mykiss*,[19] African catfish, *Clarias gariepinus*,[20] silver carp, *Hypophthalmichthys molitrix*[16] and thinlip grey mullet, *Liza ramada*.[21]

The application of micronutrient nanoparticles in aquaculture occurs through one of two modes: dietary supplementation or introduction into the culture environment.[22] The chemical structure and size of nutritional supplements determine their effectiveness within the aquatic animal.[23] Very small nanoparticles (NPs) have new and special characteristics[24] and stay in the bloodstream for a long time, increasing their bioavailability.[25] Dietary supplementation of the nano-forms of some elements such as Se, copper and iron and feed supplements such as chitosan, cinnamon and sodium butyrate has shown a huge potential for improving the aquaculture production efficiency.[15,17,26–28]

In aquatic animals, selenium (Se) is a vital microelement with both nutritional and toxicological properties.[29–32] It is commonly dispersed in freshwater (0.2–10 μg L^{-1}) and seawater (approximately 0.09 μg L^{-1}).[33] Se can also be found in organic complexes in food ingredients, mainly selenomethionine, selenocystine and selenocysteine.[34,35] Among the traditional fish feed ingredients, fish meal and marine by-products are the greatest sources of Se.[30,36] However, the inorganic form of Se passes fast in the fish guts and is reported to have low bioavailability and digestibility compared with the organic compounds such as selenomethionine.[37] Therefore, the organic form of Se has previously been recommended to be the major form for Se supplementation in animal diets.[30]

Recently, the application of Se nanoparticles (Se-NPs), also referred to as 'nano-selenium', in aquafeeds has received considerable interest owing to their ready bioavailability and properties of defence against oxidation in aquatic animals.[38] The use of Se-NPs in aquafeeds has been extensively researched, with recorded benefits including increasing growth performance, nutrient absorption, antioxidant efficiency, immune response and disease resistance.[39–41] However, their application in fish diets is believed to have a narrow range of intake as their higher concentrations could be toxic,[42,43] while their deficiency could have adverse effects on fish health by causing tissues damage and weakening the physiological functions.[44] Furthermore, their safety in food fish is still debatable as a very limited number of studies have investigated their safe levels for administration to fish. In a recent study by Abdolahpur-Monikh, Arenas-Lago, Porcal, Grillo, Zhang, Guo, Vijver and JGM Peijnenburg,[45] some nanomaterials of Se were detected in the brain of Zebrafish (*Danio rerio*) fed 120 nm of Se/kg diet. The authors further observed that no residues were detected in the fish body when 60 nm of Se/kg diet was used. They suggested that an appropriate dietary supplementation dose of Se-NPs level is necessary to produce safe products for consumption.

Despite the numerous and potential benefits of Se-NPs in aquaculture, their application could be hindered by the insufficient insight into dose–response effects on fish quality and consumer safety. The latter are linked to differences in species and life stages of fish, rearing conditions and feed manufacturing, among others. The present review paper aims to explore the application of Se-NPs in aquafeeds with a special focus on their effect on growth performance, welfare and immune response of fish.

2 | COMPOUNDS OF Se USED IN AQUAFEEDS

The primary sources of Se are sedimentary rocks and the soils where it is immobilized.[46] Se broadly occurs as either inorganic or organic chemical compounds. Inorganic compounds of Se include selenite (Se^{4+}), selenide (Se^{2-}) and selenate (Se^{6+}). Organic compounds include selenomethionine (SeMet), selenoyeast, selenocysteine (SeCys) and methylselenocysteine.[47] However, SeCys derived from animal tissues and SeMet derived from plants, algae, yeast and bacteria are the most suitable sources of Se required for the synthesis of selenoproteins (SePs). Furthermore, SeCys and SeMet occur naturally in selenium-conjugated amino acids that are extremely bioavailable and regarded as the best Se sources to supplement in the diet. Organic compounds of Se have been shown to offer better results in terms of growth and antioxidant protection, compared with inorganic forms.[48] In the muscle tissues of juvenile grouper (*Epinephelus malabaricus*), organic Se supplemented diets showed greater growth efficiency and Se retention than inorganic Se supplemented diets.[49] In Atlantic salmon (*Salmo salar*) fed diets containing either fish meal, sodium selenite, DL-selenomethionine or selenocystine, the glutathione peroxidase (GSH-PX) ratio was almost two times higher in the fish fed selenite or selenocyctine than in those given either fish meal or SeMet,[37] showing that SeMet is absorbed more rapidly than other Se products.

Se is identified in the functional groups of a variety of proteins as selenomethionine. In zebrafish (*D. rerio*), a total of 18 selenoproteins have been identified, including three that do not have known orthologs in mammals.[50] One primary feature of Se is as an element of the selenoproteins glutathione peroxidase (GPx) isoenzymes, which shield lipid components and molecules at both extracellular and intracellular rates against oxidative stress.[51] The increase in hepatic or serum GPx activity is consequent to the rise in the dose of organic Se in feeds because Se is a part of the GPx enzyme composition.[52] This enzyme uses reduced glutathione to catalyse the response indispensable to convert hydrogen peroxide and fatty acid hydroperoxide into

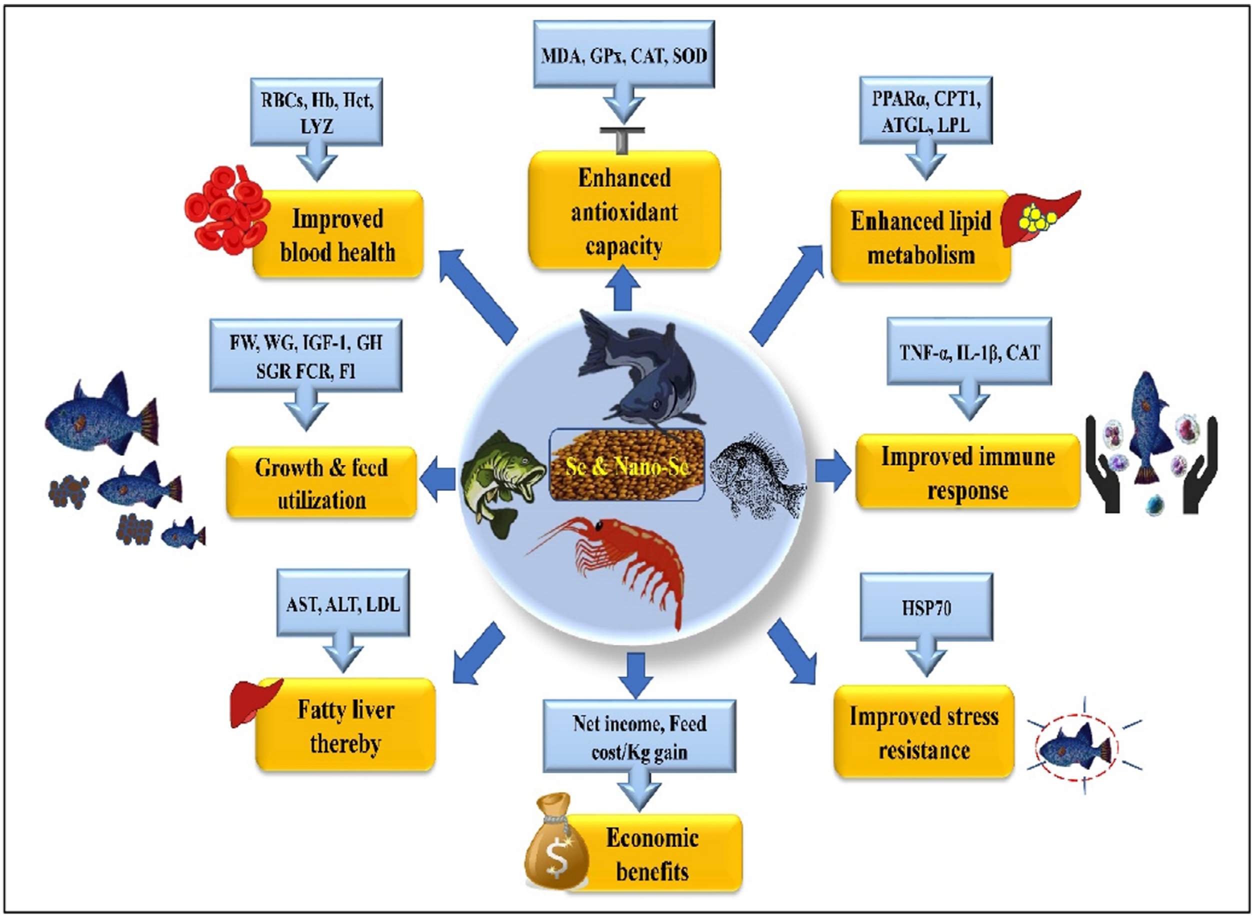

FIGURE 1 Modes through which selenium and nano-selenium impact on aquatic animal growth performance and health status. IGF-1, insulin-like growth factor 1; GH, growth hormone; FW, final weight; WG, weight gain; SGR, specific growth rate; FCR, feed conversion ratio; RBCs, red blood cells; Hb, haemoglobin; Hct, haematocrit; LZY, lysozyme; AMPK, adenosine monophosphate activated protein kinase; PPARα, peroxisome proliferator-activated receptor α; CPT1, carnitine palmitoyltransferase I; ATGL, adipose triglyceride lipase; LPL, lipoprotein lipase; GSH, glutathione; MDA, malondialdehyde; CAT, catalase; SOD, superoxide dismutase; TNF-α, tumour necrosis factor alpha; IL-1β, interleukin 1 beta; HSP70, heat shock protein 70.

water and fatty acid alcohols, that way for protecting cells from oxidative stress. The GPx efficiency correlates with the supplementary selenium level in the diet or the selenium concentration of the fish flesh.[53–55]

2.1 | Se application in aquafeeds

Compared to fishmeal, plant-based diets usually have a poor composition of micronutrients required for the normal growth of aquatic animals.[56] Therefore, replacing fishmeal with plant-based diets should pay attention to minerals composition. In a study by Domínguez, Sarmiento, Sehnine, Castro, Robaina, Fontanillas, Prabhu and Izquierdo,[56] supplementation of minerals including Zinc, Manganese and Se in plant-based diets significantly improved the growth performance in gilthead sea bream (*Sparus aurata*). Like other minerals, Se is required by aquatic animals for normal physiological functions. Figure 1 provides a graphical summary of the positive effects of supplementing Se and Se nanoparticles in aquafeeds. The role of Se in the physiological functions and health status of aquatic animals, particularly fish, has been extensively studied.

2.1.1 | Effects on the growth and physiology of aquatic animals

Like other minerals, Se is required by aquatic animals for normal physiological functions. For example, Jaramillo, Peng and Gatlin Iii[57] reported that Se plays a significant role in cells growth, bone structure and mineralization. Numerous studies have studied the effect of Se on growth and physiological functions, and the findings have been summarized in Table 1. Aquatic animal growth and physiology are important indicators considered when judging the suitability of feed ingredients in aquaculture. As an important micronutrient in aquafeeds, Se plays an important role in promoting the normal growth and physiology of aquatic animals.[82,83] According to Jaramillo, Peng and Gatlin Iii,[57] Se promotes cells growth, bone structure and mineralization. Regardless of the aquaculture species, numerous studies have

TABLE 1 Application of selenium in aquafeeds

Aquaculture species	Fish weight (g)	Administration period	Inclusion level	Effects	References
Nile tilapia (*Oreochromis niloticus*)	17.5 ± 7.5 g	90 days	2 mg/kg	Enhanced growth and activities of the digestive enzymes	39,58
	36.51 ± 10.88 g	42 days	0.86–1.22 mg/kg	Improved antioxidant capacity with negatively affecting the growth, biochemical and haematological parameters	59
	17.5 ± 7.5 g	90 days	2 mg/kg	Improved growth and promote better physiological performance without altering haematological parameters	60
	3.00 ± 0.01 g	56 days	0.75 mg/kg	Improved growth performance and antioxidant capability of the fish	61
Meagre (*Argyrosomus regius*)	3.20 ± 0.17 g	63 days	3.98 mg/kg	Improved growth performance, antioxidant balance and innate immune status	34
	3.20 ± 0.17 g	63 days	4 mg/kg	Enhanced growth rates, nutrients utilization, kidney and liver histology and the economic efficiency	30
Pacific white shrimp (*Penaeus vannamei*)	1.5 ± 0.5 g	30 days	0.3 mg/kg	Improved growth and survival after challenge with the Taura syndrome virus	62
Barramundi (*Lates calcarifer)*	5.20 ± 0.18 g	60 days	2–3 mg/kg	The fish fed high plant protein components had considerably higher glutathione peroxidase (GPx) activity, haematocrit, Se accumulation and muscle tissue integrity	63
White shrimp (*Litopenaeus vannamei*)	Unclear	56 days	0.15 mg/kg each	Could improve growth and immunity of the shrimp	64
Gilthead sea bream (*Sparus aurata*)	6.2 ± 0.04 g	63 days	0.2 mg/kg	Growth, hepatic morphology maintenance and better protection against acute and chronic stress are all benefits	65
	12.6 ± 1.4 g	42 days	0.94 mg Se/kg	Improved growth performance	66
Common carp (*Cyprinus carpio* L.)	7.5 ± 0.23 g	120 days	0.12–0.15 mg/kg	Promote growth and survival of the fish	67
Grass carp (*Ctenopharyngodon idella*)	226.48 ± 0.68 g	80 days	0.56–0.59 mg/kg	Improved activities of glutathione peroxidase (GPx) and reactive oxygen species (ROS) content in the head kidney, spleen and skin.	68
Japanese abalone (*Haliotis discus hannai*)	1.57 ± 0.01 g	100 days	0.15–0.30 mg/kg	Improved growth, antioxidation, immunity and gene expressions related to selenoproteins	69
Coho Salmon (*Oncorhynchus kisutch*)	0.38 ± 0.01 g	84 days	0.39–0.43 mg/kg	Enhanced specific growth rate (SGR), hepatic superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx) while decreasing the hepatic malondialdehyde (MDA) content	70
Rainbow trout (*Oncorhynchus mykiss*)	~75 g	70 days	4 mg/kg	Improved the fish response to viral pathogen-associated molecular pattern (PAMP) stimulation.	71
	144.87 ± 1.71 g	70 days	2–4 mg/kg	Improved flesh quality associated with the inhibited protein degradation in fish muscle.	72
	144.87 ± 1.71 g	70 days	2–6 mg/kg	Increased growth performance and up-regulation of selenoproteins genes in the muscle tissues	73

TABLE 1 (Continued)

Aquaculture species	Fish weight (g)	Administration period	Inclusion level	Effects	References
	12.68 ± 2.06 g	42 days	4 mg/kg	Improved growth rate and protein deposition in the fish muscle by accelerating postprandial protein synthesis.	74
	91 mg	84 days	0.50 mg/kg	Sustained the antioxidant status of the fish without significantly affecting the growth performance of the fish.	75
Blunt snout bream (*Megalobrama amblycephala*)	68.61 ± 0.98 g	56 days	0.20 mg/kg	Increased growth performance, antioxidant activities and enhanced meat quality of the fish	76
Grouper (*Epinephelus malabaricus*)	24.45 ± 0.73 g	56 days	0.90–0.98 mg/kg	Enhanced growth, meat quality and muscle Se retention of the fish	77
Crucian carp (*Carassius auratus gibelio*)	14.5 ± 0.49 g	30 days	0.50 mg/kg	Not significant effect on growth performance but glutathione peroxidase (GSH-Px) activities increased.	78
Cobia, (*Rachycentron canadum*)	6.27 ± 0.03 g	70 days	0.81 mg/kg	Improved survival, specific growth rate (SGR), feed efficiency and Se concentrations in the whole body of the fish	79
Chu's croaker (*Nibea coibor*)	Unclear	56 days	0.74 mg/kg	Improved weight gain, antioxidative enzyme activities/expression and tissue Se accumulation	80
Wuchang bream (*Megalobrama amblycephala*)	55.90 ± 2.60 g	60 days	0.50 mg/kg	Could effectively improve the growth performance and resistance against nitrite in the fish	81

shown that an appropriate amount of Se is important for the promotion of cell growth and cell functioning. The mechanism through which dietary Se promotes cell growth in aquatic animals was recently revealed by Wang, Zhang, Wu, Liu, Zhang and Yin.[73] In this study, the authors observed a positive correlation between growth performance and the expression of selenoproteins genes in fish. It is believed that during metabolism, selenomethionine, which is the main component of organic Se, is stored as selenoprotein which plays a role in protein synthesis and cellular growth.[55,84,85] Besides, Iqbal, Atique, Mahboob, Haider, Iqbal, Al-Ghanim, Al-Misned, Ahmed and Mughal[39] found that an appropriate supplementation level of Se in the diet of Nile tilapia could enhance the fish's digestive enzymes. Therefore, the enhancement of digestive enzymes promotes the digestion, absorption and metabolism of nutrients in the feed. Se is also thought to elevate thyroid hormone, which regulates growth and survival by controlling metabolism.[86] Furthermore, a study by Penglase, Nordgreen, Van der Meeren, Olsvik, Sæle, Sweetman, Baeverfjord, Helland and Hamre[87] revealed that dietary Se supplementation in cod (*Gadus morhua*) larvae enhanced the mRNA expression and activity of GPx isoenzymes that protect lipid components, indicating that higher supplementation of Se levels could protect aquatic animals against lipid oxidation and oxidation stress products. The conversion of Se to selenoprotein during metabolism is important for regulating the redox balance since numerous selenoproteins have oxidoreductase activity.[88] The protection of polyunsaturated fatty acids (PUFAs) against oxidation by Se may also be responsible for promoting the growth and development of aquatic animals.[89] However, a study by Penglase, Nordgreen, Van der Meeren, Olsvik, Sæle, Sweetman, Baeverfjord, Helland and Hamre[87] revealed that feeding cod larvae with Se-supplemented rotifers led to a higher incidence of vertebral deformities. This may have been caused by a change in the ionic form of skeletal mineralization, or by the antioxidant selenoenzymes.[90]

The effects of Se on the haematology of aquatic animals are somewhat still conflicting, but, in general, no adverse effects have been reported in aquatic species. For example, no adverse effects were reported in Nile tilapia,[59,60] while beneficial effects were reported in barramundi.[63] Accumulation of Se in tissues, such as the liver, swim bladder and muscles of aquatic animals, has been reported after dietary administration.[77,80,91] However, the level of Se accumulation in a given tissue depends largely on the level of administration in the diet. Besides, an appropriate level of Se administration could improve the flesh quality by inhibiting protein degradation in muscle tissues.[72,76,92] Many studies have also reported the beneficial effects of Se on the antioxidant capacity of aquatic animals.[34,59,63,69] Furthermore, Penglase,[87] reported that dietary Se supplementation could prevent the cell against lipopolysaccharide and oxidative stress. In some studies, Se could inhibit protein degradation in the fish muscles, and this has been associated with improved flesh quality.[72,76] Wang, Wang, Zhang, Li, Yin, Xu and Zhang,[74] reported that dietary Se could accelerate postprandial protein synthesis, which then improves

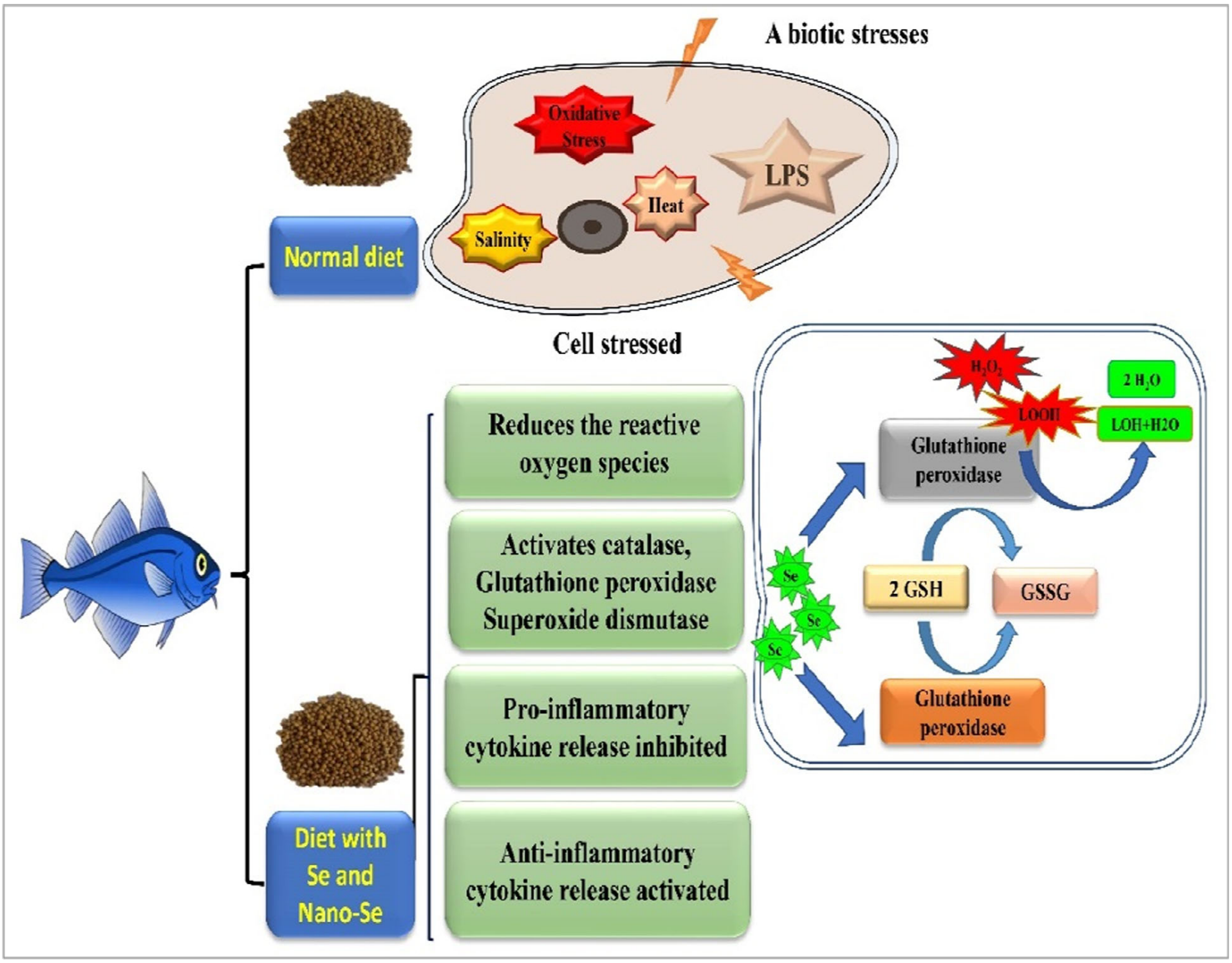

FIGURE 2 Schematic figure for the role of selenium and Se nanoparticles in immune responses of aquatic animals

protein deposition in fish muscles. This is achieved by up-regulating the expression of selenoproteins-related genes in the muscles.[73] Therefore, Se could enhance protein synthesis in fish muscles.

2.1.2 | Effect on immunity and disease resistance of aquatic animals

The effect and pathways of dietary Se on the immune response of aquatic animals are summarized in Figure 2. Furthermore, Table 1 also, highlights some studies that have investigated the effect of dietary supplementation of Se on immunity and disease resistance of aquatic animals. The effect of Se on immunity and disease resistance has been investigated in several aquaculture species. In Meagre (*Argyrosomus regius*), supplementation of Se in the diets improved the innate immune response parameters, including immunoglobulin, lysozyme (LZM), myeloperoxidase, air change per hour at 50 Pa (ACH50), and respiratory burst activity.[34] In rainbow trout, dietary supplementation of Se could increase the expression of principal mediators of the antiviral defences, such as Interferon-gamma (IFN-γ) and downstream molecules involved in cell-mediated haematopoiesis and immune response.[71] In the abalone (*Haliotis discus hannai*), activities of non-specific immune-related enzymes, such as alkaline phosphatase (AKP), acid phosphatase (ACP) and LZM, were significantly improved by Se inclusion in the diets.[69] Although the mechanism through which Se enhances non-specific immune parameters in fish is not very clear, Biller-Takahashi[93] believes that Se promotes the production of antioxidant compounds that boost the production of cellular and humoral compounds in the immune system. Le and Fotedar[94] however, suggested that Se enhances the immune response of fish by promoting lymphocyte protein synthesis, which in turn increases the activity of immune cells. In Pacific white shrimp (*Penaeus vannamei*), supplementation of Se in diets enhanced the shrimp's immunity,[64] and supplementing Se in the diets could promote survival after a challenge by Taura Syndrome Virus (TSV),[62] hence affecting the innate immune response.[34]

2.1.3 | Selenium requirement in aquaculture

The dietary Se requirement by different aquaculture species has been investigated with limited studies determining optimum levels. In fish, the minimum Se requirement varies with the source/form ingested, its availability in diets, polyunsaturated fatty acids (PUFAs), and vitamin E contents in the feed, as well as Se concentrations.[95] According to Watanabe, Kiron and Satoh,[96] fish generally require a 0.05–1.0 mg Se/kg diet. For example, the optimum dietary Se requirement was determined at 0.94 mg/kg for gilthead sea bream (*S. aurata*) fingerlings,[66] 0.7 mg/kg for grouper (*E. malabaricus*),[55] 0.96 mg/kg for the juvenile blunt snout bream (*Megalobrama amblycephala*),[97] 0.25 mg/kg diet for channel catfish (*Ictalurus punctatus*),[54] 0.1–0.15 mg/kg for the Atlantic salmon (*S. salar*)[98] and at 0.15–0.38 mg/kg for juvenile rainbow trout.[53] In hybrid tilapia, the optimum dietary supplementation of Se could improve the fish's red blood cells (RBCs) count and haematocrit percentage (Hct %).[99] In rainbow trout, dietary supplementation of Se at 0.15–0.38 mg/kg improved the growth and maximal plasma glutathione peroxidase,[53] while, in channel catfish, these parameters were improved by a 0.25 mg Se/kg diet.[54] Furthermore, rainbow trout juveniles fed a 0.06 mg Se/kg diet did not show deficiency and toxic symptoms.[100] At this level, the antioxidant capacity and anti-inflammatory ability of the fish were significantly enhanced. In juvenile grass carp (*Ctenopharyngodon idella*), the dietary Se requirement was found at 0.558–0.588 mg/kg diet.[68] However, requirement levels higher than 1.0 mg/kg have been reported in several species. The Se requirement for juvenile abalone *Haliotis discus hannai* was determined at 1.408 mg/kg,[101] 5–8 mg/kg for coho salmon (*Oncorhynchus kisutch*),[102] 2.06 mg/kg for Nile tilapia juveniles,[103] 3.67 mg/kg for the African catfish[104] and 5.56 mg/kg for yellowtail kingfish (*Seriola lalandi*).[105] Furthermore, although Se levels in the marine environment are lower than in freshwater, there are no clear dietary Se requirements between marine and freshwater species. For example, the dietary Se requirement was determined at 0.8 mg/kg for cobia (*Rachycentron canadum*),[79] and juvenile largemouth bass (*Micropterus salmoide*).[106] Therefore, the differences in requirement levels between aquaculture species may be influenced by the source of Se, administration period, and experimental conditions.[103] Se from organic sources is usually more available to the aquatic organism compared with inorganic sources.[57,107]

For fish exposed to rotifers in the culture facilities, it is important to note that Se content is considerably low (0.08–0.09 mg/kg dry weight (d.w.)) compared with that required by fish (0.5–0.3 mg/kg d.w.; NRC[33]) and copepod (3–5 mg/kg d.w.), and may contain insufficient Se to meet larvae requirements.[108] Therefore, Se could be one of the trace elements with a higher potential of being deficient in rotifers. Enrichment of rotifers with sodium selenite proved to increase survival in Atlantic cod larvae, but no differences were observed in their growth compared with the control group.[109]

2.1.4 | Se and the aquatic pollutants

The dietary Se could mitigate the toxicity of heavy metals via forming Se–metal protein and selenide–metal complexes with subsequent redistribution.[110–112] In this regard, Abdel-Tawwab, Mousa and Abbass[104] fed African catfish, *C. gariepinus*, with an initial weight (68.7 ± 2.3 g) with diets (30% crude protein) containing 0.0, 0.1, 0.3 or 0.5 g organic Se/kg diet. After 12 weeks, the fish of each treatment were further exposed to waterborne copper (Cu) at a dose of 2.27 mg Cu/L for 7 days. They found that the physiological measurements of fish subjected to a 0.3 g organic Se/kg feed. They found that after absorption in the liver, insoluble Cu–Se may be formed in the liver and excreted with the bile.[112] In another study, Abdel-Tawwab and Wafeek[113] evaluated the resistance of Nile tilapia fed with diets supplemented with organic Se and exposed to waterborne cadmium (Cd) toxicity. However, fish were fed with 0.0 (control) and 0.5 g organic Se/kg diet and exposed to either (0.0, 1.116 or 2.232 mg Cd/L) for 6 weeks. They concluded that supplementation of organic selenium reduces the deleterious impacts of cadmium in water on fish, thus improving growth performance, survival and nutrient use efficiency. Lin and Shiau,[114] evaluated the impacts of dietary supplementation of 0, 0.8 or 1.6 mg Se/kg of grouper, *E. malabaricus*, fed 20 mg Cu/kg for 8 weeks on the oxidative stress. They showed that 1.6 mg Se/kg decreased Cu stress and enhanced the immune system of the fish.

2.1.5 | Se deficiency

Deficiency of dietary Se has been reported to cause oxidative stress in organs,[100,107] reduced growth,[115] and survival[107] in several fish species. Growth depression has been reported in rainbow trout[53] and the channel catfish[54] fed Se-deficient diets. However, it is important to note that Se impoverishment did not make a pathological effect on the aquatic animal. Both vitamin E and Se were needed to avoid muscular dystrophy in Atlantic salmon[98] and exudative diathesis in rainbow trout.[116] Through Se deficiency, the activity of glutathione peroxidase in fish serum and liver decreased.[54] In tilapia, Se deficiency in the diets reduced the RBCs count and Ht value.[117] Recent findings, however, show that Se deficiency could also cause inflammation in the head kidney[118] and impair the immune response.[68] In rainbow trout, deficiency in Se (0.017 mg/kg diet) enhances hepatica glutathione transferase activity, plasma pyruvate kinase activity, erythrocyte fragility and glutathione reduction in the kidney.[107] In juvenile grass carp, dietary Se deficiency caused oxidative damage, down-regulating the mRNA expression of antioxidant capacity related genes via the Kelch-like-ECH-associated protein 1a (Keap1a)/NF-E2-related factor 2 (Nrf2) signalling pathway while partially aggravating apoptosis by up-regulating the p38MAPK/FasL/caspase-8 signalling and JNK/(BAX, Bcl-2, Mcl-1b, IAP)/(Apaf1, caspase-9) signalling.[68]

2.1.6 | Se toxicity

Despite the beneficial effects of Se supplementation in aquafeeds, excessive inclusion levels could have toxic effects. Excessive use of Se can have negative consequences for vertebrates' skeletal muscles growth.[33] The variation in selenium demand and its toxicity is probably due to the rule of selenium absorption in the intestinal tract.[119] The major toxicity effects of Se include poor growth, reduced feed efficiency and low fish survival. Other adverse effects are observed when the selenium content in aquatic animal feed is slightly above the requirement, including oxidative stress, cytotoxicity and genotoxicity.[120,121] Rainbow trout reared on high Se diets (10 mg/kg diet), and also showed renal calcinosis.[122] Yellowtail kingfish juveniles fed diets containing at least 20.9 mg/kg diet exhibited reduced feed intake, histopathological changes in the liver and spleen as well as a reduction in Ht value and hepatosomatic index.[94] Toxicity due to high Se levels was observed at dietary inclusion rates of 13 and 15 mg/kg for rainbow trout[53] and channel catfish,[54] respectively. In razorback sucker (*Xyrauchen texanus*) larvae, dietary Se concentrations above 4.6 mg/kg diet reduced survival.[123] In Atlantic salmon, higher Se levels (at least 15 mg/kg diet) resulted in oxidative stress and altered lipid metabolism for both organic and inorganic Se.[124] Also, excessive levels of Se in the diets have been associated with other morphological alterations including kidney hydropic degeneration in green sturgeon (*Acipenser medirostris*)[125] and hepatic hydropic degeneration in the gilthead sea bream[66] and common carp.[126] Furthermore, in the white sturgeon (*Acipenser transmontanus*), excessive Se in the diet resulted in cellular vacuolar degeneration and necrosis of the liver.[127] The mechanism through which selenium at higher levels negatively impacts on fish is not clear. However, a recent study by Bao, Li, He and Ren[128] reported the emergence of selenium nanovirus (SeNVs) in the abdomen and tail of the freshwater *Oryzias melastigma*, and the marine rosy bitterling (*Rhodeus ocellatus*), after exposure to selenite, leading to their death. The authors observed similar results in plants, particularly in the roots and leaves of corn (*Zea mays*), while chronic toxicity was observed in the Coast tea tree (*Leptospermum laevigatum*).[128] Therefore, the toxicity of selenium to fish at higher exposure levels could be due to the development of SeNVs, although this requires further investigation in aquatic animals.

Different fish species have different susceptibility to Se toxicity. Se toxicity even varies between closely related species. The ability to accumulate Se varies between species and life stages. For example, when rainbow trout were subjected to elevated Se levels in the environment, they experienced a higher percentage of larval deformity than brook trout (*Salvelinus fontinalis*) or cutthroat trout (*Oncorhynchus clarkia*).[129] Gatlin III and Wilson[54] found that rainbow trout exposed to 130 μg Se/l or more had an increased incidence of deformities, reduced growth, skin lesions and bulbous anus. The vulnerability of species to Se stress is strongly linked with their feed environment or other evolutionary, metabolic responses that, in particular, make even related species react differently.[130] Differences in oxidative enzymes, intestinal supply and differential aggregation rates are all biochemical processes that may be responsible for the susceptibility discrepancy. Se elimination, for instance, improved in fathead minnows (*Pimephales promelas*) fed higher levels of Se, implying that Se might induce enzyme-based Se elimination.[131]

3 | SELENIUM NANOPARTICLES (Se-NPs) APPLICATION IN AQUAFEEDS

In aquaculture, the application of nanotechnology has shown a great potential for improving the efficiency and sustainability of the aquaculture industry.[28] Whereas Se has a narrow range of intake in aquatic animals due to toxicity, Se-NPs allow a better control of toxicity,[88] and might considerably improve the culture of aquatic animals. There is a growing consensus that the application of nanotechnology in aquaculture could enable the development of more sustainable aquafeeds.[132] However, there are also important areas that require further investigation to realize the full potential and gain a better understanding of the limitations of its application. Particularly, the application of Se-NPs in aquafeeds has attracted significant research interest in recent years, mainly because of their positive effects on fish growth and welfare. Table 2 presents a summary of some key findings on the use of Se-NPs in aquafeeds.

Nanotechnology has enabled the transformation of nutrients to their nano-form (size range: 1–100 nm) making Se better digestible and easier absorbed and assimilated.[156–158] This could be an important step toward the efficient utilization of raw materials that are becoming more limited as the global population continues to expand. Besides, the use of nanoparticles in aquaculture feeds could minimize the sector's impact on the environment, which promotes sustainable development. Also, the nanoform of Se is reported to be less toxic compared with selenomethionine, which easily accumulates in fish tissues.[40,159]

In general, however, Se and its nanoparticles have common characteristics and properties. El-Ramady, Faizy, Abdalla, Taha, Domokos-Szabolcsy, Fari, Elsakhawy, Omara, Shalaby and Bayoumi[160] have provided a more detailed review of Se and its nanoparticles, focusing on their differences and similarities, as well as their role in animal nutrition. Their important differences lie mainly in their physical, chemical and biological properties, which might be the major reason accounting for the differences in their effectiveness when supplemented in aquatic animal diets. For example, selenium nanoparticles are reported to be more soluble in water than 'natural' or 'organic' Se.[160]

3.1 | The role of Se-NPs in aquaculture

Numerous research studies have provided the impact of dietary supplementation of Se and Se-NPs in aquaculture. A general summary of the findings on the immune response from existing studies is presented in Figure 2. Compared to the bulk Se, the nano form of Se has shown superior benefits in aquaculture. For example, Saffari, Keyvanshokooh, Zakeri, Johari and Pasha-Zanoosi[146] reported significantly enhanced growth performance and antioxidant status in common carp (*Cyprinus carpio*) fed with diets containing Se-NPs compared with those fed with diets containing organic (selenomethionine, SeMet) and inorganic (sodium selenite, Na_2SeO_3) forms of Se. The authors also found that the fish fed with Se-NPs and organic selenium supplemented diets had a higher accumulation of Se in fish muscles indicating that the smaller Se particles are absorbed by the fish. In crucian carp (*Carassius carassius*), Zhou, Wang, Gu and Li[159] observed that the fish fed with diets supplemented with Se-NPs and those fed diets supplemented with selenomethionine did not have a significant difference in terms of growth performance and antioxidant status although the difference with the control group was significant in both dietary Se supplements. Emerging studies suggest that supplementing

TABLE 2 Application of selenium nanoparticles (Se-NPs) in aquafeeds

Aquaculture Species	Se-NPs characteristics	Fish weight (g)	Administration period	Inclusion level	Effects	References
European seabass (*Dicentrarchus labrax*)	60 ± 20 nm	20.27 ± 0.12 g	90 days	1 mg/kg	Growth, haematological parameters, antioxidant capacity and immunity where significantly improved	133
Yellowfin (*Acanthopagrus latus*)	Unclear	25 ± 3 g	42 days	1–1.5 mg/kg	Improved growth performance, the activity of antioxidant enzymes GPX and CAT and reduced the content of MDA, AST and ALT. Further,	134
Grass carp (*Ctenopharyngodon idella*)	Unclear	11.85 ± 0.10 g	70 days	0.6 mg/kg	Alleviate intestinal injury of juvenile grass carp by improving intestinal barrier function and reducing intestinal inflammation and oxidative stress in high fat diets (HFD)	135
Rohu (*Labeo rohita*)	Unclear	3.43 ± 0.41 g	60 days	0.5 mg/kg	Enhanced growth performance, haematology, protein profile and survival rates of the fish	136
Chinese tongue sole (*Cynoglossus semilaevis*)	Unclear	120.45 ± 0.45 g	60 days	1.6–2.4 mg/kg	Improved growth performance and enhanced microbial community structure of fish gut.	137
Nile Tilapia (*Oreochromis niloticus*)	38.7 nm	24.55 ± 0.51 g	60 days	1 mg/kg	Growth, blood albumin, total protein, immunoglobulin M and immune related genes expression were significantly improved while heat shock protein 70 (HSP70) gene transcription was significantly downregulated	58
	30–45 nm	33 ± 0.29 g	70 days	0.7 mg/kg	Growth, immune response and antioxidant status were significantly enhanced as well as improved disease resistance against *Streptococcus iniae*	138
	70 nm	15.73 ± 0.05 g	90 days	1 mg/kg	Growth, physiological status, antioxidant capacity, immune response and resistance against *Aeromonas hydrophila* were significantly enhanced	139
	Unclear	40.0 ± 0.4 g	28 days	2 mg/kg	Enhanced antioxidant enzymes	140
	80 nm	15.73 ± 0.0 g	90 days	1 mg/kg	There was a significant improvement in growth, selenium regulation and the expression of immune-regulated selenoproteins	141
	Lactomicrosel® 100–500 nm	14.1 ± 0.03 g	56 days	1 mg/kg	Growth parameters, nutrients absorption capacity, antioxidant capacity and immune-related genes expression were significantly improved	142
	Unclear	unclear	38 days	1 mg/kg	Growth, immunity and antioxidant capacity were improved as well as alleviating the pathological disorders induced by cadmium (Cd) toxicity	143
	Unclear	40.0 ± 0.4 g	28 days	2 mg/kg	Enhanced immune response and disease resistance against *Aeromonas sobria*	140
	Unclear	–	65 days	1 mg/kg	Improved growth performance and overall health of the fish	144
	63.33 nm	2.45 ± 0.25 g	45 days	0.5–4.5 mg/kg	Increased significantly growth performance parameters	145

(Continues)

TABLE 2 (Continued)

Aquaculture Species	Se-NPs characteristics	Fish weight (g)	Administration period	Inclusion level	Effects	References
Common carp (*Cyprinus carpio* L.)	30–45 nm	10 g	58 days	1 mg/kg	Growth and antioxidant status were significantly improved	126
	30–45 nm	9.69 ± 0.12 g	56 days	0.7 mg/kg	Significantly improved growth performance and antioxidant defence system of the fish	146
	Unclear	8.07 ± 0.04 g	70 days	2 mg/kg	Growth performance parameters and nutrients digestibility were significantly improved compared with the control	147
Red sea bream (*Pagrus major*)	38.7 nm	4.04 ± 0.02 g	45 days	1 mg/kg	Significantly improved growth, feed efficiency, blood health and antioxidant defence system	148
	38.7 nm	4.04 ± 0.02 g	45 days	1–2 mg/kg	The serum and mucosal immune responses were significantly enhanced as well as resistance against low salinity stress	148
Rohu (*Labeo rohita*)	43.8–91.1 nm	360 ± 10 g	120 days	0.3 mg/kg	Enhanced immunity and resistance against bacterial infection in the fish	149
Mahseer (*Tor putitora*) fish	Unclear	2.27 ± 0.01 g	70 days	0.68 mg/kg	Haematological and biochemical parameters were significantly improved	150
Rainbow trout (*Oncorhynchus mykiss*)	30–45 nm	42.6 ± 2.3 g	60 days	1 mg/kg	No significant difference in growth and health status compared with control	151
Asian seabass (*Lates calcarifer*)	30–45 nm	32.78 ± 2.23 g	42 days	4 mg/kg	Enhanced humoral immunity and antioxidant capacity of the fish	152
Goldfish (*Carassius auratus*)	Unclear	4.54 g	63 days	0.6 mg/kg	Stimulation of growth, biochemical and mucosal immunity	153
Stripped catfish (*Pangasianodon hypophthalmus*)	38.7 nm	2.12 ± 0.12 g	60 days	1.02–1.11 mg/kg	Enhanced growth performance, antioxidative capacity and liver wellbeing	154
Iridescent shark (*Pangasianodon hypophthalmus*)	205 nm	4.68 ± 0.95 g	72 days	1 mg/kg	Enhanced protection against lead (Pb) and thermal stress	155

Se-NPs in plant-based diets could enhance feed utilization that would, otherwise not be achieved. In common carp, supplementation of Se-NPs in sunflower meal-based diets significantly enhanced the feed conversion ratio and nutrients digestibility.[147] Therefore, nanotechnology could promote the utilization of plant ingredients in aquafeeds, which is an important step toward reducing the environmental impact of aquaculture.

The inclusion of Se-NPs in aquafeeds has been shown to improve feed efficiency and growth performance, antioxidant capacity, immunity and resistance against pathogens in several species.[44,91,126,138] Specifically, dietary supplementation of Se-NPs significantly improved the final weight and relative final weight in gibel carp (*Carassius auratus gibelio*). In common carp, the optimum level for Se-NPs supplementation in a sunflower-based diet was established at a 2 mg/kg diet as it yielded the best growth performance.[147] In juvenile mahseer (*Tor putitora*), the best physiological and biochemical results were obtained in the fish fed diets containing 0.68 mg Se/kg diet.[150] In common carp juveniles, dietary supplementation of Se-NPs could significantly enhance the growth and feed utilization, the intestine morphology, serum biochemical parameters and immune status of the fish.[161] Grass carp fed with high-fat Se-NPs supplemented diets could regulate lipid metabolism via the adenosine monophosphate-activated protein kinase (AMPK) signalling.[162] However, the contribution of dietary Se-NPs in fish subjected to high stocking density conditions is still unclear. For example, no significant effect was observed in rainbow trout fed with Se-NPs supplemented diets under high fish density.[151] Recently, Dawood et al.[163] reviewed the role of Se-NPs as a natural antioxidant and regulator of metabolism in aquaculture. The authors showed that Se-NPs could play a key role in enhancing antioxidation in fish. Numerous other studies have also positively reported the effect of Se-NPs in various species, including Asian Seabass,[152] red sea bream,[164] Nile tilapia,[165–167] European Seabass,[133,168] rainbow trout,[169] Goldfish (*Carassius auratus*),[170] Crucian carp,[159] Rohu fish (*Labeo rohita*)[171] and Common carp.[126,146]

Unlike Se, limited information is available on the dietary requirement of Se-NPs of many fish species. In Table 3, a summary of the requirement levels of Se-NPs by different aquaculture species is presented. The optimal levels appear to be different between fishmeal-based and plant-based diets. This is because fishmeal usually contains higher amounts of Se compared with plant ingredients.[66] The requirement by most fish species of economic importance is still unknown which requires further investigations. Besides, like Se, dietary Se-NPs requirement by different species is likely to vary across species and life stages although the trend is not yet clear. For example, the dietary Se-NPs requirement of Nile tilapia with an average weight of 33 ± 0.29 g was estimated at 0.7 mg Se/kg diet,[138] while that of the fish weighing 15.73 ± 0.05 g was estimated at 1 mg Se/kg diet,[141] suggesting that the older fish required higher levels compared with the younger ones within species. There is a need to critically investigate how the Se-NPs requirement of the same fish species could vary at different life stages. However, like Se, dietary Se-NPs at too high or too low levels could reduce growth, and feed use efficiency,[147,153] and affect antioxidant capacity,[148,157] blood health status,[126] and immune response in fish.[139] These results, therefore, indicate the importance of utilizing correct levels of Se-NPs in fish diets to obtain optimal results. In Nile tilapia, dietary supplementation of Se-NPs at 2 mg/kg significantly improved immune system response of disease resistance to *Aeromonas sobria*.[140]

3.2 | Synergistic effects of Se-NPs

The synergistic effect of Se-NPs has been reported when supplemented in fish diets together with other feed supplements. The synergy between Se and other micronutrients has been reported in aquaculture. For example, Se and Vitamin E might work synergistically in fish organs to produce a powerful antioxidant protective mechanism.[172] Se is linked to vitamin E's functioning through GPx activation.[52] Besides, the presence of vitamin E in diets could have a compensatory effect against Se deficiency,[173] which enables fish to protect themselves against reactive oxygen species (ROS) by accumulating antioxidants.[30,87] In Nile tilapia, the combined supplementation of Se-NPs and zinc oxide improved growth performance, blood biochemical parameters and the fish's intestine histomorphology.[174] Combined dietary supplementation of Se-NPs and Vitamin E significantly enhanced the growth performance, intestinal integrity, blood health, antioxidant capacity and immune-related genes expression in Nile tilapia.[40] However, the blood biochemical composition was not significantly affected in common carp.[175] The combined supplementation of Se-NPs and vitamin C improved the growth rates, intestinal morphology, and health status in Nile tilapia,[142] and in mahseer fish (*T. putitora*).[150] In striped catfish (*Pangasianodon hypophthalmus*), Kumar, Gupta, Chandan, Bhushan, Singh, Kumar, Kumar, Wakchaure and Singh[176] reported significantly enhanced growth performance, antioxidant capacity, resistance against temperature stress and arsenic pollution when the fish were fed diets supplemented with Se-NPs and riboflavin. In addition, when combining Se-NPs and Zinc (Zn) in fish diets, growth performance, blood health and intestinal histomorphology in Nile tilapia improved.[167] Ayoub, Tohamy, Salama and Mohamed[140] reported the synergistic effect of Se-NPs and *Citrullus colocynthis* extract, which included significantly enhanced immunity, antioxidant status and disease resistance against *A. sobria* in cultured Nile tilapia. These results suggest that Se-NPs may enhance the effectiveness and application of other feed ingredients in aquaculture.

3.3 | Selenium nanoparticles on the immune response of fish

Immune parameters are affected by diet, environmental conditions and pathogens. Numerous studies with Se-NPs supplemented diets showed improvements in haematological parameters,[144,163,177,178] reported improvements to include elimination of anaemia, increased oxygen levels in the blood, protection of red blood cells against free oxygen radicals, reduction of cell hemolysis and degeneration due to its antioxidant properties.[82,126] In addition, changes in serum properties can signal liver damage and necrosis in fish.[34,179]

TABLE 3 Dietary requirement of selenium nanoparticles (Se-NPs) of different fish species

Fish species	Se-NP characteristics	Fish weight (g)	Optimal requirement	Determinant used	References
European seabass (*Dicentrarchus labrax*)	60 ± 20 nm	20.53 ± 0.10 g	0.5–1 mg/kg	Growth, hematobiochemical parameters, antioxidant capacity state and immune-related genes are all factors to consider	133
Nile tilapia (*Oreochromis niloticus*)	30–45 nm	33 ± 0.29 g	0.7 mg/kg	Antioxidant status, immune response and disease resistance against *Streptococcus iniae*	138
	70 nm	15.73 ± 0.05 g	1 mg/kg	Nutrition physiology, immunity, antioxidant activity and disease resistance against *Aeromonas hydrophila*	139
	80 nm	15.73 ± 0.0 g	1 mg/kg	growth, selenium regulation and expression of immune-regulated selenoproteins	141
	Lactic acid bacteria-produced Se-NPs spheres (LAB-Se: 100–500 nm)	14.03 ± 0.04 g	1–2 mg/kg	Growth, oxidative status and immune-related gene expression	142
Common carp (*Cyprinus carpio* L.)	30–45 nm	10 g	1 mg/kg	Growth and antioxidant defence system	126
Grass carp (*Ctenopharyngodon idella*)	Unclear	8.07 ± 0.04 g	0.3–0.6 mg/kg	Survival and hepatopancreas health status	147
Red sea bream (*Pagrus major*)	38.7 nm	4.04 ± 0.02 g	1 mg/kg	Growth, nutrient digestibility, blood health and the innate immune system are all factors to consider	148
	38.7 nm	4.04 ± 0.02 g	1–2 mg/kg	Overall health status	148
Mahseer (*Tor putitora*) fish	Unclear	2.27 ± 0.01 g	0.68 mg/kg	Physio-biochemical health aspects	150

Se-NPs protect the liver and other organs by increasing aspartate aminotransferase, alanine transaminase, and alkaline phosphatase activity, improving stress resistance in fish.[168,180] Lysozyme activity is a non-specific immune activity with bacteriolytic effects via neutrophils and macrophages in response to any pathogenic contamination and is affected by Se-NPs dietary levels.[138,169,181,182]

The Se-NPs remove ROS, prevent peroxidation in cell membranes, and catalyse the conversion of superoxide free radicals to hydrogen peroxide and molecular oxygen.[183,184] It has been reported that Se-NPs increase the glutathione peroxidase (GPx), Superoxide dismutase, and catalase activity and decrease malondialdehyde activity in fish species.[163–165,185]

The effects of Se-NPs' concentration were an important factor in immune response status for fish species are given in Table 2.

3.4 | Effect on gut health

Studies investigating the effect of Se-NPs on gut health in fish are still limited. The fish gut plays a critical role in feeding, digestive/absorptive processes, metabolism and immune responses.[186–188] In Nile tilapia, Ghaniem, Nassef, Zaineldin, Bakr and Hegazi[144] showed that Se-NPs could be more effective at enhancing growth performance and gut health in fish compared with inorganic and organic selenium. A recent study by reference 137 presented a new perspective on the effect of Se-NPs on gut health in fish. In this study, the authors investigated the effect Se-NPs on the intestinal microbiota of the Chinese tongue sole (*Cynoglossus semilaevis*). Despite a low overall diversity, Jia, Chen, Zhao, He and Zhang[137] observed that dietary inclusion of Se-NPs at 2.4 mg/kg could enhance the intestinal microbial community structure, besides the improved growth performance in the fish. Liu et al. Liu, Yu, Li, Wang, Liu, Zhang, Zhang, Qi and Ji[135] showed that Se-NPs inclusion in the diets of grass carp (*C. idella*) at 0.6 mg/kg could alleviate intestinal damage caused by high-fat diets (HFD), thereby maintaining the intestinal integrity. Furthermore, the expression of tight junction-related genes (such as ZO-1, claudin-3 and occluding), anti-oxidization (such as GPx4a and GPx4b), as well as the protein of ZO-1 depressed by HFD, was significantly up-regulated. However, the expressions of genes related to the inflammation, including inflammatory cytokines (IL-8, IL-1β, IFN-γ, TNF-α and IL-6), signalling molecules (TLR4, p38 MAPK and NF-κB p65), and protein expression of NF-κB p65 and TNF-α that had been induced by HFD were significantly suppressed in the fish. Liu et al.[135] further observed that the intestinal microbial community imbalance in the fish caused by HFD was normalized by Se-NPs. Therefore, existing studies so far show that Se-NPs could be an important regulator of gut health in fish. However, there is a need for further investigation.

4 | CONCLUSION

Selenium is an important micronutrient required by aquatic animals for normal growth and physiological functions. It has shown important beneficial effects, including improved growth and feed utilization, nutrients absorption, blood health, intestinal morphology, antioxidant capacity, immunity, and resistance against pathogens and environmental pollutants. However, the required levels in the diets depend on the aquaculture species in question, and any deviation from the required range yields adverse effects. Through nanotechnology, the beneficial effects of Se can be enhanced by converting it to its nanoform (Se-NPs), which are better utilized by the animals and have a wider intake range. Besides, Se-NPs are well absorbed by aquatic animals, allowing them to meet dietary requirements in aquafeeds using low inclusion levels. Therefore, further research on supplementation of Se-NPs in aquaculture diets might quickly result in major improvements in fish performance, environmental sustainability and disease control throughout the aquaculture industry.

Unfortunately, studies that have investigated the impacts of Se supplementation and its nanoparticles in aquaculture are biased toward fish species, with little attention being given to other species groups, for example, crustaceans. Even for existing studies on fish, only a few species of economic importance have been studied with a bias toward juveniles. For Se-NPs supplemented feed, this is quite expected as this is novel research. Going forward, researchers should look at all life stages of both fish and crustaceans for the most important aquaculture species, in local and international markets alike. This should also involve the application of molecular tools to gain in-depth knowledge of the regulatory pathways through which Se-NPs improve the antioxidant capacity and immunity of aquatic animals. This would provide important information for the commercialization of nanotechnology applications in the aquaculture industry.

AUTHOR CONTRIBUTIONS

Hala Saber Khalil: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Sahya Maulu:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; writing – original draft. **Marc Verdegem:** Conceptualization; data curation; investigation; methodology; software; validation. **Mohsen Abdel-Tawwab:** Conceptualization; data curation; investigation; methodology; software; validation.

ACKNOWLEDGEMENTS

The authors are grateful for the help rendered by the staff at Fish Nutrition, WorldFish Center, Egypt, as well as at the Centre for Innovative Approach Zambia (CIAZ), Zambia.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data were generated at Wageningen University and WorldFish Center and available from the corresponding author upon request.

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How to cite this article: Khalil HS, Maulu S, Verdegem M, Abdel-Tawwab M. Embracing nanotechnology for selenium application in aquafeeds. *Rev Aquac*. 2022;1-18. doi:10.1111/raq.12705