



EFFECT OF SELENIUM AND NANO-SELENIUM APPLICATIONS ON BIOLOGICAL FUNCTIONS IN AQUACULTURE – A REVIEW

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Abstract

Selenium plays a crucial role in vital physiological processes for fish, by being involved in many processes of cellular metabolism and increasing the growth performance and health status of fish. Nano-selenium (nano-Se) has been shown to promote fish growth more than other traditional inorganic Se forms. Additionally, it increases the capacity to absorb various nutrients and provides protection from pathogens. In general, the growth, hematological, biochemical and immune characteristics of fish improved with the incorporation of dietary selenium. When fish are fed small amounts, Se can also function as an antioxidant. There is a need for more research on the use of dietary Se as a supplement in the diets of various aquatic species since there are a few variables that could affect the levels of dietary Se and make it more difficult to estimate its required levels. The actual bioavailability of Se nanoparticles to fish also needs to be determined. This review has tried to evaluate and draw conclusions about the advantages of Se in various forms and its potential application as a mineral supplement to various aquatic animal species in different biological functions.

Key words: selenium, nano-selenium, growth performance, immune response, antioxidant capacity, aquatic animal

By 2050, there will be 9.7 billion people on the planet, an increase of 2 billion, necessitating the need to produce high-quality food and improve existing food production systems (Filipa-Silva et al., 2025; Ragab et al., 2025). Therefore, modulating feed is crucial for enhancing growth, health, immunity, controlling disease outbreaks (El-Dahhar et al., 2024; Zhou et al., 2024), and mitigating stress in fish during the culture period. Among different immunomodulation and stress-mitigating strategies, supplementing trace elements in aquafeeds is a promising strategy for stress management in aquafarms (Anwar et al., 2024; Abdollahi-Mousavi et al., 2024 a). Among these micronutrients, selenium (Se) plays a crucial role as an essential trace mineral involved in vital physiological processes. Selenium is particularly important in promoting the antioxidant defenses and maintenance of the body's redox equilibrium, which are critical for preventing cellular damage and supporting overall health (Huang et al., 2023; Saremi et al., 2024; Filipa-Silva et al., 2025). Historically, fish meal has served as the main selenium source in commercial feeds (Wang et al., 2022; Thangarani et al., 2024). However, efforts to reduce dependency on marine ingredients have led to the inclusion of alterna-

tive sources, mainly of plant origin, which, depending on their origin, are lower in their Se content (Mohammady et al., 2023).

To overcome potential deficiencies, Se has been supplemented in fish diets (Filipa-Silva et al., 2025). Recently, several studies have shown the effects of selenium (Keyvanshokoo et al., 2024; Vijayaram et al., 2024; Sharif-Kanani et al., 2024) for different fish species in improving their growth, feed utilization, and immune resistance to diseases, such as Asian seabass (*Lates calcarifer*) (Longbaf et al., 2019; Deilamy et al., 2021), red seabream (*Pagrus major*) (Abu-Elala et al., 2021), Nile tilapia (*Oreochromis niloticus*) (Dawood et al., 2019), rainbow trout (*Oncorhynchus mykiss*) (Aramli et al., 2023), gilthead sea bream (*Sparus aurata*) (Filipa-Silva et al., 2025), European seabass (*Dicentrarchus labrax*) (Abd El-Kader et al., 2021), rohu (*Labeo rohita*) (Swain et al., 2019), and Caspian roach (*Rutilus caspicus*) (Zahmatkesh et al., 2020). According to Wang et al. (2022) Se can guarantee better fish health and secure food production. Normally, Se can be included in aquafeeds in inorganic (e.g., selenate sodium) or organic (e.g., hydroxy selenomethionine) forms.

Due to higher bioavailability, an interest in the application of nano form of trace elements in aquafeeds has increased (Wang et al., 2022; Jafari et al., 2024). Recently, dietary supplements with various nano elements have become the most important strategy used to achieve optimal production of aquaculture, because the active surface of nano elements facilitates the absorption of the nutrients, thus improving the growth rate, and inducing the physiological parameters, the immune and antioxidative responses of aquatic animals (Abd El-Kader et al., 2020; Khan et al., 2020; Khaled et al., 2024). The rest of the paper is organized as follows: Section 1: Introduction; Section 2: Selenium dietary requirements; Section 3: Forms of selenium; Section 4: The role of bulk selenium in aquaculture feed; Section 5: The role of nano-selenium (nano-Se) in aquaculture feed; Section 6: Effects of nano-selenium (nano-Se) on the biological functions of fish; Section 7: Conclusions and future perspective.

Selenium dietary requirements

The effects of Se supplementation vary with dosage and the chemical form used (Keyvanshokoo, 2024; Sharif-Kanani et al., 2024; Vijayaram et al., 2024). Fish need an appropriate Se concentration because of the slight margin between the essentiality and toxicity (Thomas and Janz, 2011). To avoid toxicity, the European Union limits Se concentrations in fish diets to 0.1–2 mg/kg (Sumana et al., 2023) according to types of fish and age. Optimum dietary Se levels for fish varies with different species, development stages, Se source,

and environmental conditions, diet formulation, experimental conditions, and water quality and the form of Se used in diets (Anwar et al., 2024). Table 1 shows the selenium requirements for different types of fish and crustaceans.

Table 1. Selenium requirements for different aquatic animal species

Fish species	Se requirements (mg kg ⁻¹)	References
Rainbow trout (<i>Oncorhynchus mykiss</i>)	0.50–0.38 mg kg ⁻¹	Pacitti et al. (2015)
Grass carp (<i>Ctenopharyngodon idella</i>)	0.83 mg kg ⁻¹	Lin et al. (2021)
Common carp (<i>Cyprinus carpio</i>)	0.434–0.517 mg kg ⁻¹	Lin et al. (2021)
Black seabream (<i>Acanthopagrus schlegelii</i>)	0.86 mg kg ⁻¹	Wang et al. (2019)
Red seabream (<i>Pagrus major</i>)	0.94 mg kg ⁻¹	Domínguez et al. (2020)
Gilthead seabream (<i>Sparus aurata</i>)	0.79 mg kg ⁻¹	Tseng et al. (2023)
Chinese mitten crab (<i>Eriocheir sinensis</i>)	4–0.6 mg/kg	Qiang et al. (2020)
Pacific whiteleg shrimp (<i>Penaeus vannamei</i>)	0.2 and 0.4 mg/kg	Ghaffarizadeh et al. (2022)
Olive flounder (<i>Paralichthys olivaceus</i>)	1.07 mg kg ⁻¹	Mansour et al. (2017)

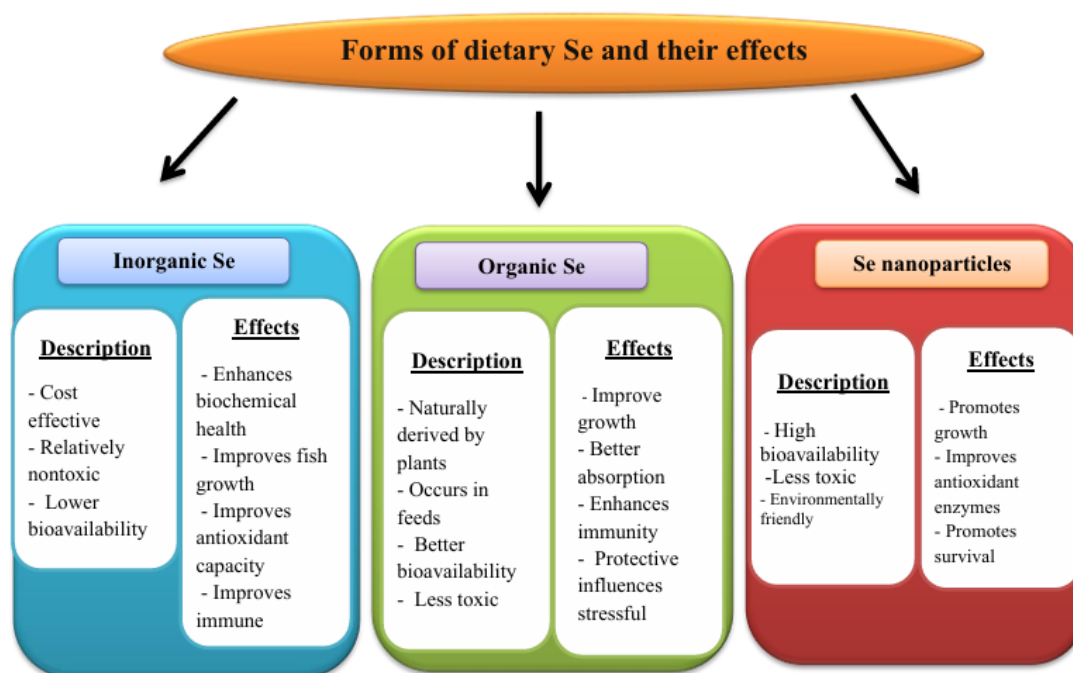


Figure 1. Forms of dietary Se and their effects

Forms of selenium

Depending on the molecular form of Se supplement in the diet, the absorption and metabolic pathways in fish change (Figure 1; Tseng et al., 2024). Commercially, there are three main forms of selenium additives: i) inorganic Se (e.g., sodium selenite (Na_2SeO_3), which enters fish through passive diffusion in the form of Se^{4+} , and is quickly reduced to selenides (H_2Se) in the intestine; ii) organic Se (e.g., selenomethionine, selenocysteine), which is actively absorbed by fish in the form of amino acids, combines with plasma protein to form SeMet; iii) Se nanoparticles (nano-Se) activate Nrf 2 signal transduction pathway to express genes related to antioxidant enzymes (Li et al., 2023). They differ in toxicity, with Na_2SeO_3 being slightly less toxic than Na_2SeO_4 (Sumana et al., 2023). Selenium is commonly added to fish diets in its inorganic form (Filipa-Silva et al., 2025).

Recently, due to higher bioavailability, an interest in applying nano trace elements in aquafeeds has increased (Abdollahi-Mousavi, 2024 b; Filipa-Silva et al., 2025). Compared to inorganic and organic forms, nano-Se has some advantages such as lower toxicity, higher bioavailability, more water solubility, superior permeability due to its wide surface and better functionality because of the gradual release of Se that leads to its better absorption (Rathore et al., 2021; Çiçek and Özoğul, 2021; Ghaffarizadeh et al., 2022). For example, Saffari et al. (2022) revealed that selenium nanoparticles had a more beneficial effect on the growth and antioxidant capacity of sea bream (*Acanthopagrus arabicus*) compared to organic and inorganic forms. Figure 1 shows forms of dietary Se and their effects.

The role of bulk selenium in aquaculture feed

Selenium (Se) is one trace element that has long obtained noticeable responsiveness in fish nutrition. The feed quality can be ameliorated by the supplementation of seleni-

um (Filipa-Silva et al., 2025). In natural condition, Se is usually absorbed from the environment by aquatic animals, but in fed aquaculture, the primary source of this element is diet and its optimum level ranges from 0.2 to 1.8 mg/kg in different farmed aquatic species (Ghaffarizadeh et al., 2022).

Selenium (inorganic and nano form) is a vital micro-nutrient for fish, which improves the antioxidant defense systems (thioredoxin reductases and glutathione peroxidases), thyroid metabolism (iodothyronine deiodinases) (Filipa-Silva et al., 2025), promoting growth, development, and enhancing flesh quality, and growth in fish and crustaceans (Abdollahi-Mousavi et al., 2024). Selenoproteins such as selenocysteine synthesized by selenium have an important role in proliferation, activation and differentiation of cells that drive adaptive and innate immune response (Karamzadeh et al., 2022). Beyond its antioxidant functions, selenium also modulates the transcription of genes regulating immune defense, phospholipid synthesis, and redox reactions (Jafari et al., 2024). It is also important for immunoregulation in the fish (Sumana et al., 2023). It has three essential biological roles in living organism viz. (a) essential for normal development and growth, (b) stored in the tissues with nutritional and supra-nutritional levels which helps homeostasis (c) toxicity is induced at higher level and results in deleterious effects (Filipa-Silva et al., 2025).

Dietary Se deficiency can suppress appetite, hinder growth, and ultimately lead to increased mortality, through cellular and membrane oxidative damage, and a compromised immune response (Abdollahi-Mousavi et al., 2024). On the other hand, excessive Se levels may generate toxic products that can disturb Se-dependent enzymes, compromising the defense mechanism against oxidative stress (Filipa-Silva et al., 2025). Figure 2 shows effects of Se and nano-Se in aquaculture.

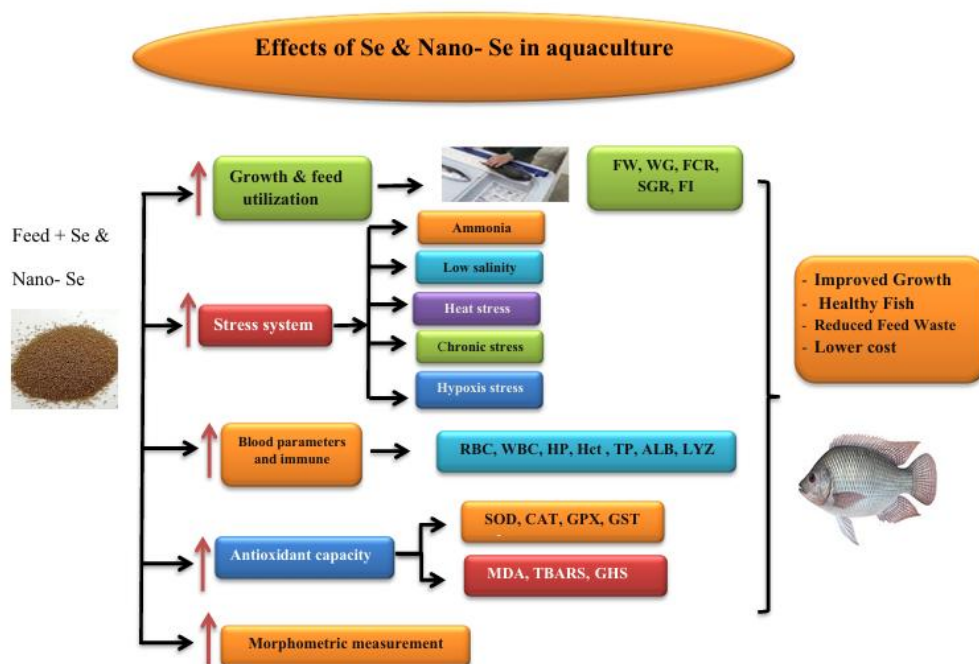


Figure 2. Effects of Se and nano-Se in aquaculture

The role of nano-selenium (nano-Se) in aquaculture feed

The focus on developing biogenic-mediated nanoparticles for use in aquatic feed is a forward-looking and innovative approach (Figure 2, Abdel-Wareth et al., 2024). Over the past decade, nanotechnology has emerged as a revolutionary force across various scientific disciplines, offering innovative solutions and advancements in numerous applications (Vijayaram et al., 2024). In aquaculture, the application of nanotechnology holds immense promise for advancing aquatic health, genetic improvement, biotechnology, and reproductive techniques (Ghafarifarsani et al., 2024 b; Hajirezaee et al., 2023). In addition, some authors have demonstrated the mitigating role of nano-Se under biotic and abiotic stressful environments (Abd El-Kader et al., 2023), promising significant contributions to enhancing production and addressing global challenges (Ghafarifarsani et al., 2024 a; Hajirezaee et al., 2020; Moges et al., 2020; Vijayaram et al., 2024).

The use of nanoparticle-based products in aquaculture will reduce the pollution load and make the farming system sustainable through avoiding the indiscriminate use of chemicals, and antibiotics (Filipa-Silva et al., 2025). Nano-selenium offers unique advantages over traditional forms of selenium supplementation, including enhanced bioavailability, reduced toxicity, and potent biological activity (Dar et al., 2020; Vijayaram et al., 2024), which can have positive impacts on the quality of aquaculture products and the overall health of aquatic organisms. Optimizing the dietary supplementation of Se nanoparticles has the potential to enhance growth performance, digestibility, and antioxidant activity in various aquatic species (Chen et al., 2020; Eissa et al., 2023). Selenium nanoparticles (nano-Se) have higher chemical stability, lower toxicity, a large surface which increases the efficacy of the element even when supplied at low levels, and high capacity to slowly release Se after ingestion that enhance selenoprotein synthesis efficiency in the body (Dawood et al., 2021). In this sense, nano minerals decrease the cost of mineral supplementation and the expected toxicological impacts (Karamzadeh et al., 2022). The recommended dosage of nano-Se dietary inclusion ranges from 0.15 to 4 mg/kg depending on the fish and crustacean species (Dawood et al., 2021; Karamzadeh et al., 2022).

Recently, several studies demonstrated the beneficial effects of supplementing aquafeeds with selenium nanoparticles on growth, feed efficiency and antioxidant capacity in various fish species (Saffari et al., 2022) such as Asian seabass (*Lates calcarifer*) (Mohtashemipour et al., 2024), Nile tilapia (*Oreochromis niloticus*) (Rathore et al., 2021), common carp (*Cyprinus carpio*) (Rezaei et al., 2024; Sharif-Kanani et al., 2024), European seabass (*Dicentrarchus labrax*) (El-Dahhar et al., 2024) and Pacific white leg shrimp (*Penaeus vannamei*) (Ghaffarizadeh et al., 2022).

Effects of nano-selenium (nano-Se) on the biological functions of fish

Many fish species' biological processes are positively impacted by dietary Se, such as thyroid regulation, growth promotion, immune system enhancement, and antioxidant activity (Pan et al., 2023; Sumana et al., 2023; Zhou et al., 2024; Saremi et al., 2024). Table 2 shows some studies of the effects selenium nanoparticles on growth and physiological functions in fish and crustaceans.

Using nano-Se as a growth enhancer

Modulating feed is crucial for enhancing growth in aquatic animals (El-Dahhar et al., 2024). The growth performance of aquatic animals is influenced by a range of factors, including water quality, temperature, vaccination, and effective management practices. These variables play a crucial role in ensuring the health and growth of aquatic species in aquaculture settings (Dawood et al., 2021 a, b; Vijayaram et al., 2024). Se, as a crucial constituent of deiodinases, participates in thyroid hormone metabolism by catalyzing the conversion of T_4 to T_3 , which is the active type of thyroid hormones (Khan et al., 2016) and subsequently raises the transcripts of growth-related genes, including growth hormone (GH) and IGF-I (Filipa-Silva et al., 2025).

Adequate Se supplementation in aquafeeds is essential for the growth and development of fish. Previous studies show that nano sources of Se have higher bioavailability than inorganic Se sources for aquatic species (Wang et al., 2022; Keyvanshokoo et al., 2024; Aramli et al., 2023; Deilamy et al., 2021; Ahmad et al., 2024). Nano-selenium can be an efficient growth enhancer by boosting gut surface area (Eissa et al., 2023; Ibrahim et al., 2021), thyroid hormone (triiodothyronine) production (Izadpanah et al., 2022), digestive enzymes synthesis (Eissa et al., 2023; Ibrahim et al., 2021), as well as activation of the growth hormone/insulin-like growth factor I (GH/IGF-I) axis (Khan et al., 2016; Rezaei et al., 2024).

The size of nanominerals ranges from 1 to 100 nm, making them more readily absorbable by the body's tissues and fluids (Moges et al., 2020; El-Dahhar et al., 2024). Their small size and high surface area facilitate the biological potential and physiological benefits of mineral nanoparticles. In several studies, adding nano-Se to the fish diet improved their final body weight, survival rate, weight gain and average daily gain in different species such as red seabream (*Pagrus major*) (Dawood et al., 2019), Nile tilapia (*Oreochromis niloticus*) (Sheikh et al., 2023; Eissa et al., 2023; Li et al., 2023), European seabass (*Dicentrarchus labrax*) (Abd El-Kader et al., 2021), striped catfish (*Pangasianodon hypophthalmus*) (El-Sharawy et al., 2021), grass carp (*Ctenopharyngodon idella*) (Yu et al., 2020; Zhu et al., 2024), gilthead seabream (*Sparus aurata*) (Izquierdo et al., 2017), yellowfin seabream (*Acanthopagrus arabicus*) (Kianersi et al., 2021), and striped catfish (*Pangasianodon hypophthalmus*) (El-Sharawy et al., 2021).

Table 2. Some studies of the effects of selenium nanoparticles on growth and physiological functions in fish and crustaceans

Aquaculture species	Optimum substitution levels	Effect	Reference
Asian seabass (<i>Lates calcarifer</i>)	Up to 4 mg kg ⁻¹	↑ growth performance; ↑ health status; ↑ feed utilization; ↑ Hb; ↑ Ht; ↑ TP; ↑ SGR; ↓ cholesterol; ↓ triglycerides; ↓ ALP; ↓ aspartate aminotransferase; ↓ alanine aminotransferase; ↓ lactate dehydrogenase	Mohtashempour et al. (2024)
European seabass (<i>Dicentrarchus labrax</i>)	1 mg kg ⁻¹	↑ growth; ↑ feed utilization; ↑ immune response; ↑ disease resistance; ↑ IL-2; ↑ IL-6; ↑ IL-12	Khaled et al. (2024)
	0.5–1 mg/kg	↑ growth; ↑ feed utilization; ↑ Hb; ↑ PCV; ↑ RBCs; ↑ WBCs; ↑ lysozyme; ↑ SOD; ↑ antioxidative; ↑ immune-related genes	Abd El-Kader et al. (2021)
	0.3 mg	↑ FBW; ↑ survival; ↑ SGR; ↑ WG; ↑ ADG; ↑ FCR; ↑ GPx; ↓ MDA; ↓ AST; ↓ ALT	El-Dahhar et al. (2024)
Yellowfin seabream (<i>Acanthopagrus arabicus</i>)	Up to 1 mg kg ⁻¹	↑ growth performance; ↑ stress resistance; ↑ survival; ↑ HIS; ↑ VSI; ↑ FCR; ↑ CAT; ↑ SOD; ↑ GPx; ↓ MDA; ↑ immune-related (IL-1β and Lys)	Abdollahi-Mousavi et al. (2024)
Nile tilapia (<i>Oreochromis niloticus</i>)	1 mg kg ⁻¹	↑ nutrition physiology; ↑ immunity; ↑ antioxidant activity; ↑ disease resistance; ↑ WG; ↑ SGR; ↑ ADG; ↑ PER; ↑ FCR	Rathore et al. (2021)
Common carp (<i>Cyprinus carpio</i>)	Up to 3 mg kg ⁻¹	↑ growth; ↑ feed utilization; ↑ stress resistance	Rezaei et al. (2024)
	3 mg kg ⁻¹	↑ lysozyme; ↑ total immunoglobulin; ↑ WG; ↑ SGR; ↑ FBW; ↓ cholesterol; ↓ triglycerides; ↑ TP; ↑ FCR	Sharif-Kanani et al. (2024)
Sobaity seabream (<i>Sparidentex hasta</i>)	Up to 2 mg kg ⁻¹	↑ interleukin-1β; ↑ lysozyme genes; ↑ WG; ↑ SGR; ↑ FI; ↑ triglyceride; ↑ thyroid hormone; ↑ TP; ↑ albumin; ↑ globulins	Abdollahi-Mousavi et al. (2024)
White leg shrimp (<i>Litopenaeus vannamei</i>)	0.15 mg kg ⁻¹	↑ antioxidant status; ↑ immune responses; ↑ lysozyme; ↑ TP; ↑ lysozyme; ↑ CAT; ↑ SOD; ↑ GPx; ↑ FBW; ↑ WG; ↑ SGR	Karamzadeh et al. (2022)
Grass carp (<i>Ctenopharyngodon idella</i>)	0.3 mg kg ⁻¹	↓ crude fat; ↓ heavy metal; ↑ EPA; ↑ DHA; ↑ PUFA; ↑ flesh quality; ↑ growth; ↑ feed utilization; ↑ stress resistance	Zhu et al. (2024)
	0.3 mg kg ⁻¹	↑ growth; ↑ feed utilization; ↑ CAT; ↑ GSH-Px; ↓ GOT; ↓ GPT; ↓ MDA; ↑ intestine health	Ye et al. (2023)
Arabian yellowfin sea bream (<i>Acanthopagrus arabicus</i>)	Up to 4 mg kg ⁻¹	↑ FBW; ↑ survival; ↑ HSI; ↑ VSI; ↑ K; ↑ FBW; ↑ SGR	Saffari et al. (2021)
Pacific whiteleg shrimp (<i>Penaeus vannamei</i>)	Up to 0.4 mg/kg	↑ growth performance; ↑ feed utilization; ↑ feed utilization; ↑ PO; ↑ CAT; ↑ GPx; CAT; ↑ SOD; ↑ GPx; ↓ MDA; ↑ lysozyme; ↑ penaeidin-3α genes mRNA transcript; ↑ immune-related genes	Ghaffarizadeh et al. (2022)
Sobaity seabream (<i>Sparidentex hasta</i>)	2 mg/kg	↑ growth performance; ↑ antioxidant; ↑ immune parameters	Abdollahi-Mousavi et al. (2024)

↑: increase; ↓: deficiency; EPA: eicosapentaenoic acid; DHA: docosahexaenoic acid; PUFA: polyunsaturated fatty acid. FBW: final body weight; HIS: hepatosomatic index; K: Fulton condition factor; VSI: viscerosomatic index. PO: plasma phenoloxidase CAT: catalase; SOD: superoxide dismutase; GPx: glutathione peroxidase; GSH-Px: glutathione peroxidase; MDA: malondialdehyde; GOT: glutamic oxaloacetic transaminase; GPT: glutamic pyruvic transaminase.

The increase in intracellular protein of intestinal epithelial cells may cause better metabolism of feed ingredients resulting in higher growth enhancement. Another possible reason is the role of Se, which acts as coenzyme for digestive enzymes synthesis and hence increases its activity (Abd El-Kader et al., 2021). The activation of digestive enzymes increases nutrient digestibility and releases more nutrients for absorption by the intestinal epithelial cells. In this context, the level of feed conversion ratio (FCR) is expected to enhance, and the growth performance increases. The growth promoter properties of nano-Se might be due to its role in biological function such as nucleic acid metabolism, enzymatic oxidation-reduction, and in promoting the activity of easily oxidized substances like vitamin A and carotenoids which is useful for increasing water and protein in the cell (Mohammady

et al., 2023). Zahmatkesh et al. (2020) found that the use of nano-Se at 1 mg kg⁻¹ diet improved immunity in fish. Kumar et al. (2018) demonstrated that nano-Se at 1 mg kg⁻¹ diet has a beneficial effect on growth performance attributes (SGR, FCR, weight gain %, and PER). Abd El-Kader et al. (2021) reported that dietary Se nanoparticles enhancement upregulated *GH* and *IGF-1* gene expressions in European seabass, which explains the enhanced growth performance. El-Dahhar et al. (2024) reported that feeding the larvae of *D. labrax* with diets containing extracted organic selenium from 1 mg/kg (nano-Se) resulted in a significant improvement in their final body weight (FBW), survival rate, specific growth rate (SGR), weight gain (WG), and average daily gain (ADG), compared to the control group without nano-Se. Likewise, Abd El-Kader et al. (2021) revealed that feeding

D. labrax with 0.5–1 mg/kg Se nanoparticles resulted in a rise in the FBW, SGR, WG, and FCR. Zhu et al. (2024) found that the use of 0.3 mg/kg of nano-Se in the diet of grass carp improved growth rate and feed utilization. Similarly, Ibrahim et al. (2021) reported that including 0.4 to 0.8 mg/kg of nano-Se in the diet enhanced the feed utilization and growth rate of Nile tilapia. Saffari et al. (2021) found that nano-Se enhanced growth rate, feed efficiency and the antioxidant protection capacity of sea bream. Ghaffarizadeh et al. (2022) found that the nano-Se supplementation in diet up to 0.4 mg/kg increased growth performance and feed utilization in *P. vannamei*. Dawood et al. (2020) found that the inclusion of nano-Se significantly improved feed conversion ratio and feed intake.

Dietary supplementation with nano-Se at concentrations ranging from 0.39 to 0.43 mg/kg has demonstrated significant enhancements in growth performance and antioxidant activity without negatively affecting the survival rate in coho salmon (*Oncorhynchus kisutch*) alevins (Du et al., 2021). Nano-Se at a concentration of 0.3% can improve various growth parameters in *O. niloticus* fingerlings. This includes significant improvements in weight gain, weight gain percentage, feed intake, growth ratio, and a reduction in the feed conversion ratio (Khalid et al., 2023). The dietary supplementation at a concentration of 2 mg/kg can also significantly improve the growth performance, antioxidant activity, and nutrient digestibility of *Cyprinus carpio*. Moreover, it has led to reduced fish feed costs and contributes to the ecofriendly nature of aquaculture practices (Khaled et al., 2024). El-Dahhar et al. (2024) found that fish fed with nano-Se and SP diets exhibited improved weight gain and decreased feed conversion ratio, which led to increased activity of antioxidant enzymes GPx and CAT and reduced contents of MDA, AST, and ALT. Also, Li et al. (2023) confirmed that dietary nano-Se supplementation in rainbow trout (*Oncorhynchus mykiss*) alleviated heat stress-induced intestinal damage by promoting antioxidant enzyme activity, enhancing protein repair, alleviating inflammatory responses, and restoring intestinal microbiota composition. Nano-Se improved intestinal villus height, muscularis thickness, goblet cell number, tight junction protein expression, and reduced the expression of pro-inflammatory cytokines and malondialdehyde content. At the same time, it was found that dietary supplementation with nano-Se at 30 g/kg enhances the growth performance and blood parameters of Nile tilapia when compared with a fish fed diet without any supplementation (Soliman et al., 2017). Khaled et al. (2024) reported that the use of nano-Se as fish feed additives caused a low mortality rate and an improvement in growth rate and biochemical parameters. Nano-Se has high permeability and availability in the fish body, so it enhances the growth rate, biochemical indices and immunity of fish (Abd El-Kader et al., 2020). Abdollahi-Mousavi et al. (2024 a) found that supplementing nano-Se efficiently improved

the growth of Arabian yellowfin seabream. The findings are in agreement with the current literature indicating the efficacy of adequate dosage of nano-Se as a growth enhancer in various fish species at the juvenile stage (Abd El-Kader et al., 2021; Eissa et al., 2023; Sheikh et al., 2023).

Izadpanah et al. (2022) reported that seabream fed plant-protein diets supplemented with nano-Se at 2–4 mg/kg exhibited improved growth and feed utilization. Keyvanshokoo (2024) and Abdollahi-Mousavi et al. (2024) reported that nutritional nano-Se enhanced growth performance in fish by stimulating the thyroid hormone-growth hormone axis. FCR improvement in response to dietary nano-Se could be attributed to the positive roles of nano-Se either in (i) heightening the number and length/width of the goblet cells in the intestinal epithelium (Eissa et al., 2023) or (ii) enhancing the activity of digestive enzymes (Ibrahim et al., 2021). This can be explained by Khaled et al. (2024) who revealed that the level of selenium needed to achieve optimum growth efficiency may vary based on the type of selenium, the time of administration and the experimental technique, as well as fish species.

Effects of nano-Se on fish whole body

Selenium serves as a crucial trace mineral intricately involved in maintaining the body's redox balance and bolstering antioxidant defenses, while it also plays a pivotal role in regulating lipid and protein oxidation processes, thereby enhancing meat quality and nutritional value (Filipa-Silva et al., 2025; Deilamy et al., 2021; Ahmad et al., 2024). Therefore, the supplementation of a proper amount of dietary selenium in the fish diets is needed for the balanced hormone production and metabolism, and the synthesis and regulation of selenoproteins, improvement of the antioxidant defense status, and more importantly the flesh quality of fish (Khan et al., 2017).

The body chemical composition reflects the chemical composition of the diet, nutrient digestibility and availability (Sherine et al., 2024). Ghaffarizadeh et al. (2022), Saffari et al. (2021) and Jafari et al. (2024) found that Se retention in the fish whole body augmented with increasing the nano-Se concentration in the diet. These results concern common carp (*Cyprinus carpio*) Rezaei et al., 2024), gilthead sea bream (*Sparus aurata*) (Dominguez et al., 2020), Nile tilapia (*Oreochromis niloticus*) (Mohammady et al., 2023), black seabream (*Acanthopagrus schlegelii*) (Wang et al., 2019), redfish (Juhász et al., 2017) and Asian bass (Siddik et al., 2022). Similarly, Zhu et al. (2024) found that the Se concentration in the muscle of grass carp significantly increased after feeding of 0.1 mg/kg nano-Se. Saffari et al. (2022) reported that nano-Se (2–4 mg/kg) supplementation in the diet of seabream resulted in higher concentration of Se in the whole body that was mainly associated with the increment of GPx activity and TAC and reduction of MDA level in the whole body of fish. Elia et al. (2011) confirmed that

fish fed Se-supplemented diets had higher growth rates and Se accumulation than the control group. Zhu et al. (2011) investigated the effect of dietary Se on growth, body composition, and hepatic GPxs activity of largemouth bass; the researchers discovered that dietary Se supplementation improved growth and body composition and increased hepatic GPxs activity in largemouth bass, which may have a positive effect on their health.

Using nano-selenium supplements for stress resistance

Selenium is also one of the most widely studied micronutrients regarding stress management. Numerous studies have documented higher utilization of Se in fish under stressful conditions, and thus supplementing Se in commercial diets may be necessary to meet the higher requirements of fish during stress (Abdollahi-Mousavi et al., 2024 b; Ahmad et al., 2024). During the process of fish growth, any pressure condition will directly or indirectly cause stress, leading to the level of intracellular ROS related to stress increasing, causing destructive effects on lipids, proteins, and DNA (Li et al., 2023). In addition, the oxidative stress occurs and pathogenic invasion liberates ROS due to the imbalance of ROS production and removal. The overproduced ROS impair the lipid contents in the cell membranes and damage RNA. Excessive ROS also induce lipid peroxidation, which can be measured by the level of malondialdehyde (MDA) (Abd El-Kader et al., 2021). Selenium is an antioxidant agent that induces the production of glutathione peroxidase (GPx) to counteract oxidative stress (Sherif and Zommara, 2024). Any such disturbance in selenium supply results in its impaired antioxidant activity, due to which the fish is not capable to fight well against stressful conditions and protect itself from the oxidative damage (Khan et al., 2017). Therefore, the dietary inclusion of nano-Se supplements can help to increase resistance to multiple stressor conditions (Vijayaram et al., 2024), in mitigation of multiple stressors, including pollution, climate change, water quality parameter and other factors. For example, at concentrations of 1–2 mg/kg, it has been found to significantly enhance the resistance of *Pangasianodon hypophthalmus* (*P. major*) against low salinity stress (Dawood et al., 2019; Vijayaram et al., 2024). Similarly, nano-Se (0.5 mg kg⁻¹ diet) has an important role in maintenance of antioxidant status in fish reared under abiotic and biotic stress (Kumar et al., 2020).

Previous studies on various fish species have demonstrated that nutritional nano-selenium (nano-Se) supports the alleviation of biotic and abiotic stressful conditions by neutralizing harmful free radicals, enhancing immune-related functions, maintaining the structural integrity of liver tissue, and influencing the expression of heat-shock protein (HSP) genes (Abdollahi-Mousavi et al., 2024; Li et al., 2022; Vijayaram et al., 2024). Rezaei et al. (2024) reported that nano-Se groups showed lower plasma cortisol levels cou-

pled with lower glucose levels; these data underline the intervention of nano-Se in the rapid metabolic recovery of the stressed fish. In support of this possibility, a study by Zhang et al. (2022) on yellow catfish (*Pelteobagrus fulvidraco*) demonstrated that adequate Se intake can decrease glucose by converting it to glycogen, which is the storage form of glucose in liver and muscle cells. In agreement with the results of our study, previous studies showed that nano-Se can reduce glucose production in stressed fish (Kumar et al., 2020; Rezaei et al., 2024). The Se nanoparticles supplemented at concentrations of up to 2 mg/kg has been shown to significantly improve the resistance of *O. mykiss* against sublethal ammonia stress (Nazer et al., 2020), and at concentrations of 0.3 mg and 0.6 mg in a 56-day trial, it has been shown to alleviate the negative impacts (mitigating the effects on fish growth, oxidative damage, immunosuppression, and apoptosis) of ammonium stress in yellow catfish (*Tachysurus fulvidraco*) (Zhang et al., 2020). Dietary incorporation of Se supplements at a concentration of 1.0 mg/kg has been shown to significantly enhance the immune response, antioxidant defenses, and metabolic processes in Chinese mitten crab (*Eriocheir sinensis*) under nitrite stress (Wang et al., 2019 a, b) and to enhance growth and antioxidant activity in juvenile rainbow trout exposed to chronic stress conditions (Fontagne-Dicharry et al., 2020). Harsij et al. (2020) reported that the use of nano-Se at 0.3 mg kg⁻¹ diet improved the antioxidant status of *Oncorhynchus mykiss* against ammonia stress. Dawood et al. (2019) demonstrated that nano-Se at 2 mg kg⁻¹ diet enhanced the antioxidative status in *Pagrus major* against salinity stress.

Even though antioxidant nutrients may promote the protection of membrane lipids against the oxidative stress, some nutrients can induce the oxidative stress in fish when fed in with excess or deficiency level. Therefore, it is important to supplement an adequate level of antioxidant nutrients in micro diets to avoid the negative effects of oxidative damage in fish (Tseng et al., 2024). Therefore, the type of aquatic species, dosage of Se, duration of diet, and other influencing factors should be considered to evaluate the Se diet in aquaculture (Wang et al., 2022; Vijayaram et al., 2024).

Using nano-selenium supplements as an antioxidant system

Selenium is an extra-effective antioxidant element extra-effective and plays an important role in the antioxidant defense mechanism of fish. It protects the cell membrane from oxidative damage through regulation of glutathione peroxidase (GPx) activity (Jafari et al., 2024; Li et al., 2023). Se can decompose and clear peroxides, thus preventing the accumulation of reactive oxygen species and free radicals such as hydrogen peroxide (H₂O₂) in the body tissues (Zuo et al., 2019), enhancing resistance to inflammation, maintaining immune function and stabilizing the internal environment (Wande et al., 2020).

However, dietary Se deficiency will reduce the expression of selenoproteins, increase the peroxidation reaction of lipids, proteins, DNA and then pose a threat to the health of the body (Rao et al., 2020). Excessive Se will also produce toxic side effects on the body, leading to liver damage, physiological function decline, immune capacity reduction, and even death (Chadio et al., 2015). Furthermore, selenium nanoparticles (nano-Se) have an important role in modulation of antioxidative status against multiple stressors in fish. It has several mechanisms to enhance the antioxidant status (SOD, catalase, GPx, GST, and MDA) against the different stress (Abdollahi-Mousavi et al., 2024).

The antioxidant defense system consists of two parts, encompassing the enzymatic and nonenzymatic antioxidant systems. The non-enzymatic antioxidant system includes a set of low-molecular-weight compounds such as vitamin C, vitamin E, and carotenoids. Superoxide dismutase (SOD), glutathione peroxidase (GPx), catalase (CAT), glutathione S-transferase (GST), and thioredoxin reductase (TR) constitute the enzymatic part of the cellular antioxidative defense system (Santana et al., 2022), among which Se is an integral part of the thioredoxin reductases and glutathione peroxidases (Prabhu et al., 2016; Keyvanshokoo et al., 2024). No matter inorganic Se, organic Se or nano-Se, it will be converted into selenoproteins to play a role after being absorbed by fish. Selenoproteins related to fish antioxidant mechanism include GPXs, TXNRDs, SELENOP, SELENOS, and

other selenoproteins, which regulate lipid metabolism, inflammatory damage, ROS and H_2O_2 formation oxidative stress through antioxidant enzymes (SOD, GPx, and CAT) in fish antioxidant system (Yu et al., 2020; Wischhusen et al., 2020) (Figure 3).

Additionally, dietary intake of Se nanoparticles has antioxidative, immunostimulant, and antibacterial influences on several aquatic species, such as Asian seabass (*Lates calcarifer*) (Longbaf et al., 2019), red seabream (*Pagrus major*) (Dawood et al., 2019), Nile tilapia (*Oreochromis niloticus*) (Dawood et al., 2020), rainbow trout (*Oncorhynchus mykiss*) (Naderi et al., 2017), rohu (*Labeo rohita*) (Swain et al., 2019), *Pangasinodon hypophthalmus* (Kumar et al., 2018), *Cyprinus carpio* (Ashouri et al., 2015), *Dicentrarchus labrax* (Abd El-Kader et al., 2021), *Ctenopharyngodon idella* (Yu et al., 2020), *Oreochromis niloticus* (Neamat-Allah et al., 2019, Rathore et al., 2021). A plethora of studies reported that supplementing diet with nano-Se enhanced antioxidant enzymes activities (e.g., CAT, SOD and GPx) in different crustacean species and fish (Ghaffarizadeh et al., 2022). Similarly, Yu et al. (2022) reported that GPx and SOD activities increased in *P. vannamei* with the inclusion of diet with 0.4 mg/kg nano-Se and organic selenium compared to control group. Kumar et al. (2018) revealed that nano-Se at 1 mg kg⁻¹ diet significantly improved the antioxidative status in fish reared under high temperature and lead toxicity stress, because of antioxidative properties of selenium.

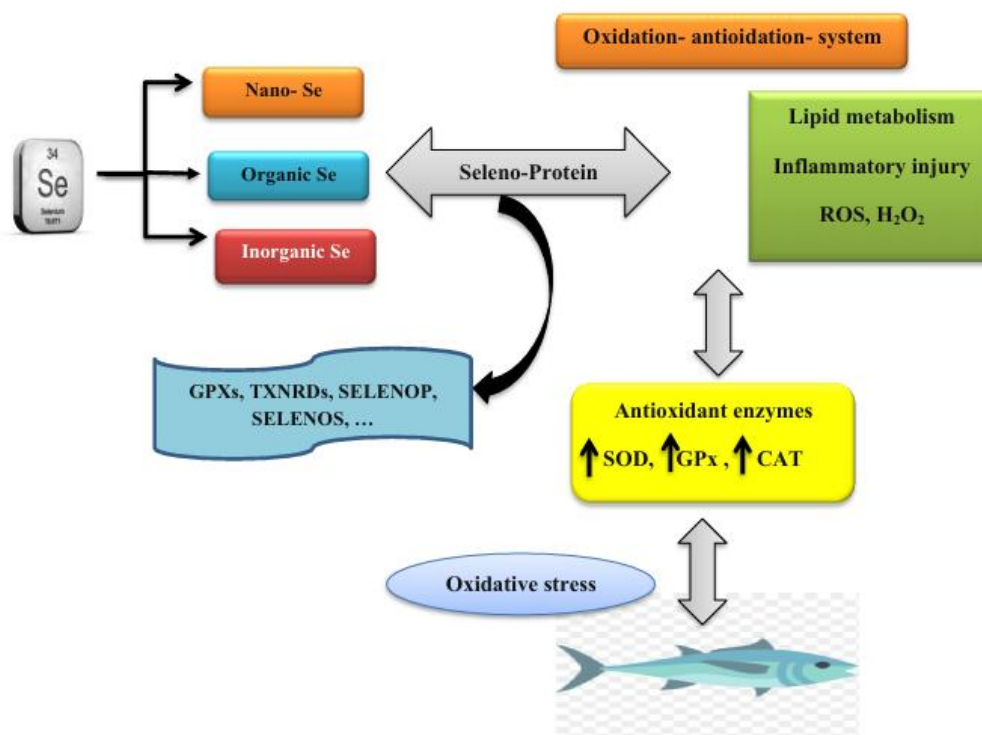


Figure 3. Antioxidant mechanism of different Se forms in fish (Li et al., 2023)

Nano-Se at 0.7 mg kg⁻¹ diet also protects against *Streptococcus iniae* infection in *Oreochromis niloticus* by improving antioxidative status viz. SOD, catalase, GPx and NO and reduced the MDA level. This diet also enhanced the gene regulation in the form of CAT and GPx (Neamat-Allah et al., 2019). Ghaffarizadeh et al. (2022) reported that the use of up to 0.4 mg/kg nano-Se in diet increased antioxidant status and indicated an improvement of antioxidant capacity as a remarkable decrease in malondialdehyde with increasing CAT, SOD and especially GPx activities in *P. vannamei*. Similarly, Kong et al. (2017) reported that supplementing nano-Se at 0.31–0.59/kg in diet enhanced antioxidant enzymes activities (e.g., SOD, GPx, total antioxidant capacity and glutathione reductase) in oriental river prawn *Macrobrachium nipponense*. Chen et al. (2013) and Ye et al. (2023) demonstrated that nano-Se improved the antioxidant capacity of the common carp (*Cyprinus carpio*) under fluoride stress and reduced the damage of stress to the liver. Dietary nano-Se also improved the resistance against salinity stress in red seabream (*Pagrus major*) (Dawood et al., 2021).

A study reported the use of 3.15±0.04 mg/kg nano-Se in a basal diet can enhance the antioxidant capacity of various fish species (Sharif-Kanani et al., 2024). Previous studies reported that the use of dietary Se can affect an antioxidant gene in *Nibeia coibor*. A similar study reported that Se supplement can increase the antioxidant SOD, CAT, and GPx activity in rainbow trout (*Oncorhynchus mykiss*) (Hunt et al., 2011) and in juvenile white sturgeon (*Acipenser transmontanus*) supplement with 0.04–19.1 mg Se/g diet (Le and Fotedar, 2014). Increased dietary Se concentration positively impacted the expression of SOD1, highlighting the importance of optimal Se levels for enhancing antioxidant activity and protecting cell membranes from oxidative damage (Chadio et al., 2015). Moreover, it was concluded the increase in the dietary Se concentration can increase the SOD1 expression. El-Dahhar et al. (2024) found that fish fed with diets containing nano-selenium have a higher GPx activity than the larvae fed the control diet. This emphasizes the potent antioxidant properties of selenium. Jafari et al. (2024) reported that increased CAT and SOD activity is associated with increased levels of nano-Se in the diet. Similarly, Jha et al. (2022) demonstrated high antioxidant capacity in common carp (*Cyprinus carpio*) fed 2 mg/kg nano-Se by the increment of CAT, SOD and GPx activities and reduction of MDA level. The enhanced antioxidative status is attributed to the role of selenium in forming the selenoproteins which are required for the release of glutathione peroxidase (Karamzadeh et al., 2022).

In contrast, some of these studies found that dietary nano-Se enhanced GPx activity but had no positive effects on other antioxidant enzymes such as CAT and SOD. These data reveal that GPx as a selenoenzyme is more capable of responding to Se supplementation than other antioxidant enzymes. On the other hand, a study on *Oreochromis niloticus* (Dawood et al., 2020) showed

that nano-Se supplementation had no significant effect on GPx activity but enhanced levels of SOD and CAT activities and decreased malondialdehyde (MDA) concentration.

Effects of nano-Se on immunity in fish

Adequate Se-rich feed from the feed industry supports the fish immune system, prevents disease, promotes fast growth, and ensures high meat quality (Sumana et al., 2023; Barchielli et al., 2022). By providing Se-enriched feeds, the feed industry can help prevent disease outbreaks and promote fish welfare. Recently, biogenic nano-Se supplements have been shown to significantly upregulate pro-inflammatory cytokines and enhance immunostimulating factors in fish (Abarike et al., 2019; Vijayaram et al., 2024), by altering the receptors of transferrin on the hematopoietic tissues and increasing the stability and integrity of blood cells in fish due to its potent antioxidant property that protects blood cells from hemolysis and enhances their lifespan (Mohtashempour et al., 2024). Serum biochemical indices provide beneficial diagnostics to monitor the well-being status of cultured fish (Fazio, 2019; Khaled et al., 2024). Therefore, evaluating hematological factors can be used for examining fish health status, and these parameters are susceptible to nutrition, rearing conditions, water quality, stress, or diseases (Khaled et al., 2024). In addition, increasing RBCs and Hb causes oxygen availability in the body tissues owing to the absence of anemic features. The balanced levels of RBCs, Hb, and PCV are also attributed to the role of dietary nano-Se in affording the nutritional requirements for fish, which induced enhanced health status (Abd El-Kader et al., 2021).

The blood total protein is a reliable index to demonstrate fish immunocompetence condition (Mohtashempour et al., 2024). A previous study suggested that the supplement of nano-Se significantly improved the growth, hematological indexes and immune parameters of Nile tilapia (*Oreochromis niloticus*), indicating that nano-Se can improve the nutritional physiology and immunity of Nile tilapia (Rathore et al., 2021). Le and Fotedar (2014) suggested that Se increases the immunocompetence of fish by increasing lymphocyte protein synthesis, which in turn increases the activity of immune cells. In previous studies, the enhancing influence of nutritional nano-Se has demonstrated immune-boosting effects across various species such as common carp (*Cyprinus carpio*) (Rezaei et al., 2024), Nile tilapia (*Oreochromis niloticus*) (Abu-Elala et al., 2021; Ghazi et al., 2021), *Pagrus major* (Dawood et al., 2019), rainbow trout (*Oncorhynchus mykiss*) (Fontagne-Dicharry et al., 2020; Harsij et al., 2020), gilthead seabream (*Sparus aurata*) (Filipa-Silva et al., 2025), European seabass (*Dicentrarchus labrax*) (Mechlaoui et al., 2019), Asian seabass (*Lates calcarifer*) (Mohtashempour et al., 2024), Arabian yellowfin (*Acanthopagrus arabicus*) (Izadpanah et al., 2022; Jafari et al., 2024; Khademzade et al., 2022), and sobaity seabream (*Sparidentex hasta*) (Abdollahi-Mousavi et al., 2024 a,

b). Mohtashemipour et al. (2024) reported that immune responses and immune-related genes of fish improved in fish fed the nano-Se supplemented diet, which coincided with increasing antioxidant capacity and growth rate. Similarly, supplementing the diet with Se-yeast and nano-Se significantly increased serum total protein, globulin, and ALB, as well as increased LYZ, HA, and RBA in meager (Mansour et al., 2017) and common carp (Saffari et al., 2018), respectively. Other studies also reported that supplementing the diet with nano-Se increased serum LYZ and HAs in various farmed fish species such as mahseer (*Tor putitora*) (Khan et al., 2016), rainbow trout (Bai et al., 2019; Harsij et al., 2020), *Piaractus mesopotamicus* (Takahashi et al., 2017), Nile tilapia (Neamat-Allah et al., 2019; Al-Deriny et al., 2020), and red seabream (Dawood et al., 2019).

Previous studies demonstrated positive effects of nano-Se by increasing hematological factors (e.g., HB, Hct, RBC count) that were mainly associated with the increment of GPx activity in various fish species such as mahseer (Khan et al., 2016), common carp (Saffari et al., 2018), red seabream (Dawood et al., 2019), European seabass (Abd El-Kader et al., 2021, 2020) and *Labeo rohita* (Ahmad et al., 2024). Furthermore, Neamat-Allah et al. (2019) reported that dietary nano-Se protected erythrocytes from hemolysis after challenging *Streptococcus iniae* and prohibited anemia due to subsequent hemorrhagic septicemia in Nile tilapia. Zahmatkesh et al., (2020) revealed that supplementing nano-Se at 1 mg/kg diet improved lysozyme, albumin, and globulin levels in *Rutilus caspicus*. In another study in rainbow trout, nano-Se at 0.3 mg/kg diet improved lysozyme, total immunoglobulin, and albumin concentrations (Harsij et al., 2020). Several other studies on various species found that adequate dietary nano-Se improved humoral immune parameters in fish (Abd El-Kader et al., 2020; Keyvanshokoo et al., 2024). Khaled et al. (2024) found that no significant differences were found in serum AST and ALT in fish fed on 1 and 5 mg nano-Se compared to each other or control. These results agree with Ibrahim et al. (2021) who found the lowest activities of plasma ALT and AST in the fish fed diet containing 0.8 mg nano-Se/kg diet as compared with other treatment diets. Also, Abd El-Kader et al. (2021) observed no significant alterations in ALT and AST variables in fish fed with varying levels of Se nanoparticles. According to these results, we conclude that nano-Se with the level of 1 or 5 mg/kg has a protective effect on liver cells, can scavenge free radicals and may also promote cytokine production. Se enhances lymphocyte proliferation and antibody production, promoting a robust immune response in fish (Sumana et al., 2023). Zhai et al. (2018) found that Se supplementation has a positive effect on the immune system and intestinal barrier, reducing permeability and pathogen entry. Se also affects the function of various immune cells in fish, such as macrophages and lymphocytes, as it enhances the phagocytic activity of macrophages so that they can effectively engulf and eliminate pathogens (Avery and

Hoffmann, 2018). It also modulates the production of pro-inflammatory cytokines, such as interleukin-1beta (IL-1 β) and tumor necrosis factor-alpha (TNF- α), which are involved in the immune response against pathogens (Niu et al., 2022).

Additionally, the high total protein in white fish indicates the good metabolism of the diet and improved feed efficiency. Karamzadeh et al. (2022) found that increased lysozyme and phenoloxidase activities enhanced the immune response in white shrimp fed with selenium nanoparticles. Abd El-Kader et al. (2021) reported that the values of RBCs, WBCs, PCV, and Hb were increased in fish fed 0.5–1 mg dietary nano-Se. These results probably are associated with the regulation of the metabolic rate and well-being of fish induced by nano-Se feeding. Similarly, Le and Fotedar (2014) reported that yellowtail fed dietary nano-Se at 0 to 2 mg/kg had enhanced the GPx activity of RBCs. Additionally, the results showed similar enhancements in the Hb, RBCs, and PCV indices with dietary Se in common carp (Saffari et al., 2018). The high count of WBC refers to enhanced adaptive immunity to counteract with pathogens and invaders, which occurs under stressful conditions (Fiúza et al., 2015). WBC functions as the main component of the front lines of body defense, and its number increases rapidly when infections occur (Abd El-Kader et al., 2021). The dietary inclusion of nano-Se supplements at concentrations of 1–2 mg/kg has increased immune parameters such as phagocytic activity, phagocytic index, and lysozyme activity, as well as increased red blood cell counts, globulin levels, and immunoglobulin levels in *Oreochromis niloticus*. This demonstrates the positive impact of nano-Se on the immune system and overall health in fish (Abu-Elala et al., 2021; Ghazi et al., 2021).

WBCs showed an increasing trend with nano-Se supplemented groups might be due to the improved health profile of fish by an improved immune response and several cell-mediated physiological activities (Rathore et al., 2021). Numerous studies reported that nano-Se supplementation exerted immunological effects in various fish species by enhancing the production of antibodies, total Ig, lysozyme, and complements (Abd El-Kader et al., 2020; Zahmatkesh et al., 2020). Indeed, with increased WBCs and platelet counts in fish, diets supplemented with nano-Se strongly supported the improvement of cell-mediated immunity in fish by long-term Se supplementation (Abdollahi-Mousavi et al., 2024 b). These findings suggest that nano-Se enhances immune functions, potentially improving disease resistance in fish (Khaled et al., 2024; Pecoraro et al., 2022). These outcomes could be ascribed to the structural role of Se in the synthesis of selenoproteins supporting the propagation, differentiation, and functional activation of B and T cells (Filippini et al., 2023).

Effects of nano-Se on genes in fish

Recently, dietary Se has been found to regulate the expression of immune-related genes in fish (Sumana et

al., 2023), and to increase the production of immune-related molecules, such as interleukin-10 (IL-10) and immunoglobulin A (IgA), which are critical for immune regulation and defense against infection, and protect against stressors and infectious pathogens in fish (Dawood et al., 2020). Nano-Se stimulates the immune system, leading to increased expression of genes related to TNF- α and IL-1 β , which protect against stressors and infectious pathogens in fish (Vijayaram et al., 2024). For example, studies have shown that dietary Se supplementation promotes the expression of genes involved in the immune response, such as Toll-like receptors (TLRs) and cytokines (Sumana et al., 2023). Similarly, Keyvanshokoo (2024) reported that supplementing nano-Se in aquafeeds can increase the expression of IGF-I in various fish species.

Dawood et al. (2020) found that nano-Se supplementation resulted in upregulated TNF- α and IL-1 β in the liver and spleen of Nile tilapia, resulting in improved blood immunity, antioxidative responses, and general health status. In numerous studies, the upregulated IL-10 and GMCFC genes revealed the immunostimulatory role of nano-Se on *L. calcarifer*, which has also been reported in other species, such as European seabass (Abd El-Kader et al., 2020, 2021). In grass carp (*Ctenopharyngodon idella*), supplementing a high-fat diet with nano-Se significantly down-regulated the expression of proinflammatory genes (IL-6, IL-8, IL-1 β , interferon- γ , and tumor necrosis factor- α , TNF- α) in the gut. It alleviated the oxidative damage of ROS in the gut. Also, Al-Deriny et al. (2020), Mohammady et al. (2023) and Thangarani et al. (2024) reported that dietary nano-Se supplementation upregulated TNF- α in Nile tilapia. Moreover, Abd El-Kader et al. (2023) reported that dietary nano-Se significantly enhanced serum total protein and globulin and increased humoral (i.e., LYZ activity) and cellular (i.e., phagocytosis activity) immune responses in European seabass that were associated with upregulation of IL-8 and IL-1 β in the liver. Se supplementation increased the expression of IL-2 and IL-6 genes in the gills of European seabass, indicating the potential immunomodulatory effects of nano-Se, and promise as a feed supplement for improving immune responses in fish (Montero et al., 2022; Khaled et al., 2024).

Effects of nano-Se on gut health

Morphometric measurement of the width and height of intestinal villi and the number of goblet cells can help in predicting the absorption and digestion mechanisms in the fish gut (Dawood et al., 2020; Lauriano et al., 2016). Dietary nano-Se plays a crucial role in shaping gut microbiota, potentially enhancing immunity and homeostasis in the gut, underscoring its significance in fish health and development. Selenium performs as a pioneer for selenoproteins synthesized in the gut, leading to an enhanced activity of digestive enzymes, and increasing the integrity of gut villi epithelium may enhance the activity of the villous brush border enzymes such as ALP,

resulting in a higher growth rate (Mohtashempour et al., 2024). Besides, fish growth performance promoted by Se supplementation is also correlated to enhanced mucosal length/width, increased number of goblet cells, and augmented cell proliferation and protein synthesis in the intestinal epithelium, which are beneficial for higher nutrient assimilation in fish by enhancing the intestinal surface area (Eissa et al., 2023; Keyvanshokoo et al., 2024; Mohtashempour et al., 2024). A study by Saffari et al. (2018) on common carp also detected that the best feed efficiency ratio and the highest intestinal villi in the foregut and midgut were recorded in the group fed nano-Se diet compared to the inorganic (sodium selenite) and organic (SeMet) groups.

Dawood et al. (2020) found that the measured villous lengths and widths of the three intestinal sections were increased in fish fed nano-Se, which increased cell proliferation and protein synthesis. Furthermore, Se acts as “a co-enzyme in production/activation of intestinal microbes and digestive enzymes” that can improve intestinal morphology and absorptive capacity. Anwar et al. (2024) reported that dietary Se has shown a significant effect on villi height in the fore, mid, and hindgut in fish. Villi length increases as the diet's Se concentration increases. The highest villi height was noticed in the foregut in the 30 mg/kg group followed by the 3 mg/kg group, 0 mg/kg group, and control group. A similar finding was obtained from the study on *Argyrosomus regius* fingerlings supplemented with dietary Se yeast which has increased villi height (Khalil et al., 2019). A similar study reported that dietary Se can significantly increase the villi height in fish in the foregut and mid-section (Saffari et al., 2018). Limited literature is available on the dietary Se impact on gut morphology such as villi height, crypt depth, and muscular thickness. However, some previous studies reported that a Se-supplemented diet significantly affects the gut's developmental morphology in fish (Li et al., 2022).

El-Dahhar et al. (2024) found that *D. labrax* fed diets fortified with selenium nanoparticles, showed significant improvement in their gastrointestinal tract and improvement in the length of folds in the stomach in comparison to the group fed the control diet. Similarly, Dawood et al. (2021) suggests that Se nanoparticles may enhance aquatic animal growth by activating digestive enzymes and improving intestinal villi integrity. Ghazi et al. (2021) reported that Nile tilapia showed improved intestinal morphology, villi length, and goblet cell numbers when given nano-Se. This confirms healthier intestinal promotion by using nano-Se. Ibrahim et al. (2021) demonstrated that including from 0.4 to 0.8 mg/kg of nano-Se in the fish diet enhanced the feed utilization and growth rate of Nile tilapia, and enhanced the histomorphology of the gut by increasing the length and width of villi, goblet cells, and branching and integrity of villi.

Conclusions and future perspective

Environmental factors can have a significant impact on aquaculture production. Therefore, nutrition is a criti-

cal factor, as providing the right balance of nutrients is essential for fish for growth and overall health. Se plays an important role in growth performance and immunity. Recently, these nano-Se supplements have been found to play a vital role in aquaculture and offer a cost-effective, nontoxic, and environmentally friendly approach to improve and sustain aquaculture. However, further research is still needed to determine the supplementation ratios for each fish species, depending on the age stage.

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