



## Selenium toxicity in fishes: A current perspective

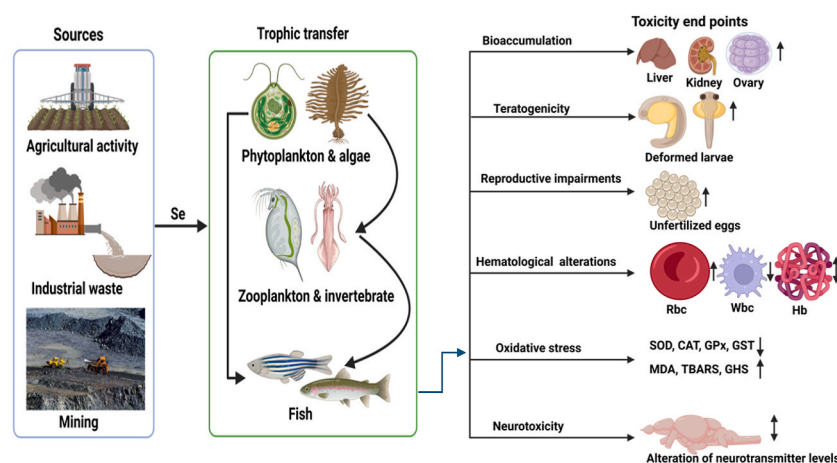
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### GRAPHICAL ABSTRACT



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### ABSTRACT

Anthropogenic activities have led to increased levels of contaminants that pose significant threats to aquatic organisms, particularly fishes. One such contaminant is Selenium (Se), a metalloid which is released by various industrial activities including mining and fossil fuel combustion. Selenium is crucial for various physiological functions, however it can bioaccumulate and become toxic at elevated concentrations. Given that fishes are key predators in aquatic ecosystems and a major protein source for humans, Se accumulation raises considerable ecological and food safety concerns. Selenium induces toxicity at the cellular level by disrupting the balance between reactive oxygen species (ROS) production and antioxidant capacity leading to oxidative damage. Chronic exposure to elevated Se impairs a wide range of critical physiological functions including metabolism, growth and reproduction. Selenium is also a potent teratogen and induces various types of adverse developmental effects in fishes, mainly due to its maternal transfer to the eggs. Moreover, that can persist across generations. Furthermore, Se-induced oxidative stress in the brain is a major driver of its neurotoxicity, which leads

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to impairment of several ecologically important behaviours in fishes including cognition and memory functions, social preference and interactions, and anxiety response. Our review provides an up-to-date and in-depth analysis of the various adverse physiological effects of Se in fishes, while identifying knowledge gaps that need to be addressed in future research for greater insights into the impact of Se in aquatic ecosystems.

## 1. Introduction

Trace elements such as chromium (Cr), copper (Cu), iodine (I), iron (Fe), manganese (Mn), selenium (Se), and zinc (Zn) are essential to fishes, playing a crucial role in their growth, metabolism, reproduction, and overall health when present within physiologically optimum range (Lall and Kaushik, 2021; NRC, 2011). Specifically, Se is a vital micronutrient that helps maintain physiological homeostasis in all vertebrates including fishes (Aramli et al., 2023). However, these elements can become toxic when present in suprphysiological concentrations or in certain chemical forms. For example, Se is essential to fishes within a narrow concentration range, however it becomes extremely toxic when its concentration exceeds the physiological threshold, with toxic effects in fishes observed at dietary concentrations above 3 mg/g dry weight (dw) compared to its essential dietary range of 0.1–0.3 mg/g dw (Thomas and Janz, 2011). Moreover, organic forms of Se (e.g., selenomethionine), which are primarily found in the diet, are considered to be more toxic to fishes than its inorganic counterparts (e.g., selenite and selenate), which occur predominantly in the water (Janz et al., 2010). At optimal physiological concentrations, Se is incorporated into various selenoproteins, such as glutathione peroxidases (GPX1, GPX2, GPX3, GPX4, GPX6), thioredoxin reductases (TXNRD1, TXNRD2, TXNRD3), and iodothyronine deiodinases (DIO1, DIO2, DIO3), which have antioxidant functions that protect cells from oxidative damage (Plateau et al., 2017; Mullur et al., 2014).

Geochemically, Se primarily exists in the crustal rock and phosphate-rich soil and is introduced into aquatic ecosystems by both natural sources and anthropogenic activities (Lemly, 2004). Anthropogenic activities such as mining, coal combustion, oil refining wastewaters, and agricultural drainage waters are the major sources of Se contamination in aquatic systems resulting in elevated concentrations which are toxic to aquatic organisms (Mo et al., 2019; Chapman et al., 2010; Janz et al., 2010). Recent studies have reported varying dissolved Se concentrations in surface water of different geographical locations. For instance, investigations revealed the highest Se concentration recorded in Tonle Sap Lake in Cambodia during the dry season to be 17.6 µg/L, while in Najran city, Saudi Arabia, it was found to be 11.44 µg/L (Haque et al., 2016). Moreover, research conducted in the Ibadan metropolis of Nigeria indicated an average Se content in water as high as  $46.3 \pm 22.4$  µg/L, with the highest recorded Se concentration reaching 258 µg/L in irrigation water in Texas (Etim, 2017; Hudak, 2009). Furthermore, studies have observed Se levels ranging from 45 to 341 µg/L in the underground water of Punjab, North-West India (Bajaj et al., 2011).

Selenium can exist in both inorganic and organic forms. In its inorganic forms, Se is commonly found as selenate and selenite. Its organic forms include selenomethionine (Se-Met) and selenocystine (Se-Cyst) (Janz et al., 2010). In aquatic ecosystems, microorganisms, and primary producers absorb inorganic Se, and bio-transform it into organic forms, primarily Se-Met that can bioaccumulate and bio-magnify in the upper trophic levels and cause toxicity to animals, particularly to oviparous species such as birds (Mo et al., 2020). The most well characterized detrimental effects of Se in fishes include teratogenicity, neurological disorders, cognitive impairment, reproductive failure, cardiovascular complications, and behavioural alterations in fishes (Attaran et al., 2019; Naderi et al., 2018a; Pettem et al., 2017; Thomas and Janz, 2015). Furthermore, previous studies also suggest that excessive Se exposure in freshwater fishes can result in growth inhibition, impaired swimming performance, altered energy homeostasis, visual system impairment, morphological deformities, reproductive impairments, alteration of

hemato-biochemical parameters, and histopathological changes in vital organs (Al-Din et al., 2022; Dhara et al., 2022; Mushtaq et al., 2022a,b). Because of such wide spectrum of toxic effects, Se can pose serious threat to the long-term sustenance of natural fish populations (Rathore et al., 2021b; McPhee and Janz, 2014). Various toxic effects of Se in fishes are presented in Fig. 1.

Selenium can move through aquatic food chains via bio-concentration and biomagnification. Importantly, lower trophic organisms, such as algae, zooplankton, and benthic invertebrates, exhibit high tolerance to elevated Se exposures. Conversely, fishes are among the most sensitive organisms to Se toxicity. Consequently, these prey items can act as vectors, delivering high dietary Se concentrations to fishes (Janz, 2012; Janz et al., 2010).

Given that fishes are top predators in most aquatic ecosystems and provide approximately 60% of the total animal protein consumed by humans (Kim et al., 2021), Se accumulation poses a significant food safety concern. Several reviews have addressed Se toxicity in aquatic organisms with special focus on bioaccumulation (Ohlendorf et al., 2011), growth and survival (Hamilton, 2004), essentiality and toxicity (Janz, 2012; Janz et al., 2010; Hodson and Hilton, 1983), histopathology (Hung, 2018), and neuropathology (Naderi et al., 2021) in aquatic organisms including fishes. However, recent studies have revealed new insights into the various aspects of Se toxicity in fishes that require a renewed focus and an in-depth discussion. To this end, we reviewed the existing literature on Se toxicity in fishes that were published over the last 10 years. This review mainly focuses on the most up-to-date information on critical aspects of Se toxicity in fishes including bioaccumulation, growth and metabolic functions, antioxidant capacity, reproduction and development, and neurobehavioural performance. Moreover, this review also identifies key knowledge gaps that should be addressed in future research for greater insights into the impact of Se in aquatic ecosystems.

## 2. Bioaccumulation of selenium in fishes

Fishes are essential bioindicators in aquatic ecosystems, as they accumulate trace metals that reflect environmental contamination (Burger and Gochfeld, 2005). They are often the tertiary predators in aquatic food chain, which makes them susceptible to accumulating toxic substances from both natural and anthropogenic sources. Thus, they play a key role in understanding trophic transfer and biomagnification of contaminants up through the food chain (Nwani et al., 2010). Moreover, from human health perspective, fishes are globally recognized for their high-quality protein, low saturated fats, and high omega-3 fatty acids, which contribute to reduced cholesterol and lower risks of cancers and cardiovascular diseases (Bosch et al., 2016; Storelli, 2008). Collectively, these two aspects highlight the importance of studying trace metal bioaccumulation in fishes, which have important implications for protecting aquatic and public health (Arulkumar et al., 2017).

Assessment of bioaccumulation serves as a crucial indicator for monitoring the geochemical cycling of heavy metals within aquatic ecosystems (Emon et al., 2023). Among the wide array of metals and metalloids, Se is notably recognized as one of the most accumulative toxic metalloids, which is attributed to its capability to substitute sulfur (S) atoms within proteins, thereby forming stable complexes (Lemly, 2004). The bioaccumulation of Se in fishes is influenced by various factors, including exposure pathways (waterborne or dietary) and habitat characteristics (seawater or freshwater). In both laboratory and field studies, irrespective of waterborne and dietary exposure, Se

bioaccumulation profiles consistently reveal the following order: kidney > liver > gonads > spleen > intestine > gill > brain > muscle (Mushtaq et al., 2022a,b; Pan et al., 2022; Acosta-Lizárraga et al., 2020). Furthermore, bioaccumulation of Se in fishes is significantly influenced by water quality parameters such as pH, temperature, hardness, and the presence of other ions or dissolved organic matter. For instance, lower pH levels can increase the bioavailability of selenite, leading to higher Se accumulation in fish tissues, as observed in studies involving freshwater species (Besser et al., 1993). Elevated temperatures often enhance the metabolic rates of fishes, thereby increasing Se uptake in aquatic organisms (Hilton et al., 1980). Increased water hardness, characterized by higher concentrations of calcium and magnesium in the water, can reduce Se bioaccumulation (Holm et al., 2005). Additionally, the presence of other trace elements like arsenic can antagonistically reduce Se bioaccumulation in rainbow trout (*Oncorhynchus mykiss*) (Jamwal et al., 2019), while higher levels of dissolved organic matter can also reduce Se uptake by complexation and thereby rendering it less bioavailable to fishes (Luoma and Presser, 2009). However, Se accumulation in different organs varies from species to species, depending on their detoxification mechanism. Notably, numerous investigations have consistently highlighted the kidney and liver as sites of highest Se bioaccumulation, attributed to their pivotal roles in detoxification and the elimination of toxic substances from the body (Rathore et al., 2021b; Li et al., 2020; Bergés-Tiznado et al., 2019). Waterborne exposure to Se in fishes results in the highest Se accumulation in the gills (Garnero et al., 2018), whereas dietary exposure has been reported to lead to maximum accumulation in the intestine (Chen et al., 2020).

It is important to note that Se accumulation in specific tissues can be used to predict its toxicity in fishes, regardless of the exposure routes. The United States Environmental Protection Agency (USEPA) and the Canadian Council of Ministers of the Environment (CCME) have established tissue-based toxicity thresholds for assessing Se toxicity in natural fish populations. USEPA recommends Se toxicity thresholds of 15.2 mg/kg dw for egg-ovary, 8.5 mg/kg dw for whole body, and 11.3 mg/kg dw

for muscle tissue in fishes (USEPA, 2016). In comparison, CCME suggests Se toxicity thresholds of 14.7  $\mu\text{g/g dw}$  for egg-ovary and 6.7  $\mu\text{g/g dw}$  for whole body (CCME, 2016). Moreover, the United States Fish and Wildlife Service proposed more conservative Se toxicity thresholds of 10 mg/kg dw for ovaries and 4 mg/kg dw for whole body of fishes (USFWS, 1990). Although these thresholds have been suggested to be overly conservative (Brix et al., 2000), several studies have documented toxic effects in fishes that were associated with tissue-specific Se accumulation that are comparable or lower than the tissue-based Se toxicity threshold established by different regulatory bodies. For example, whole body Se concentrations of 6 mg/kg and 5 mg/kg dw were found to be associated with impaired growth and increased mortality in fathead minnow (*Pimephales promelas*) and bluegill (*Lepomis macrochirus*), respectively (Ogle and Knight, 1989; USFWS, 1990). Additionally, an ovary Se concentration of 10 mg/kg was reported to be associated with reproductive failure in bluegill (Hermanutz et al., 1992). Thomas and Janz (2015) reported that Se concentrations of 12.7  $\mu\text{g/g dw}$  in eggs led to significant larval deformities and mortality in zebrafish (*Danio rerio*). Similarly, Shi et al. (2018) observed significant larval deformities in Japanese medaka (*Oryzias latipes*) when Se concentrations reached 8  $\mu\text{g/g dw}$  in eggs.

Moreover, the accumulation of Se in the muscle tissues of fishes holds significant importance as an indicator of food safety, considering that muscle is the most ingested tissue by humans (Lee et al., 2019). It is to be noted though that Se accumulation in muscle has consistently been reported to be very low compared to other tissues in fishes (Pan et al., 2022; Chen et al., 2020; Khadra et al., 2019). The Se accumulation profiles outlined in Table 1 emphasize specific target organs crucial for assessing the toxic effects of Se in fishes.

### 3. Mechanism of selenium toxicity in fishes

Oxidative stress acts as the primary mechanism underlying Se toxicity in fishes (Misra et al., 2012). Both organic and inorganic forms

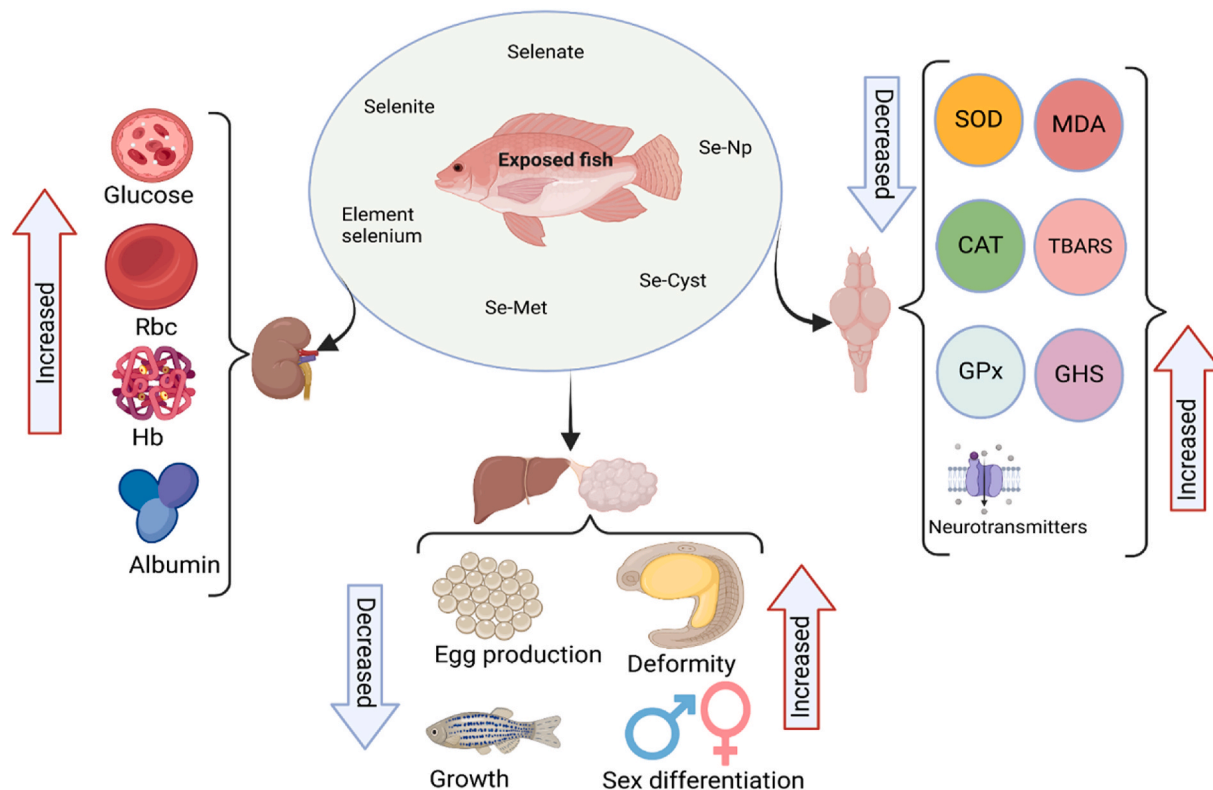


Fig. 1. Toxic effects of selenium in fishes.

**Table 1**  
Bioaccumulation patterns in fishes exposed to selenium.

Laboratory study					
Exposure route	Fish species	Exposure concentration	Exposure periods (days)	Accumulation profiles	Reference
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	kidney > liver > pancreas > muscle	Mushtaq et al. (2022a)
Dietary	<i>Pangasianodon hypophthalmus</i>	0, 0.5, 1, 2 mg/kg	60	liver > whole-body > muscle > gill	El-Sharawy et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 3, 6, 12 µg/g	45	intestine > brain > liver > muscle	Chen et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	0, 3, 6, 12 µg/g	90	intestine > liver > brain > muscle	Chen et al. (2020)
Waterborne	<i>Channa argus</i>	0, 100, 200 mg/L	56	kidney > liver > spleen > intestine > gill > muscle	Li et al. (2020)
Dietary	<i>Acanthopagrus schlegelii</i>	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	liver > muscle	Wang et al. (2019)
Dietary	<i>Carassius auratus</i>	0, 5, 10, 20 mg/kg	30	kidney > liver > muscle	Bai et al., 2019a
Waterborne	<i>Channa argus</i>	0, 50, 100, 200, 400 µg/L	28	kidney > liver > spleen > intestine > gill > muscle	Li et al. (2019)
Waterborne	<i>Channa argus</i>	0, 50, 100, 200 µg/L	56	kidney > liver > spleen > intestine > gill > muscle	Li et al. (2019)
Dietary	<i>Pagrus major</i>	0, 0.5, 1, 2 mg/kg	45	liver > muscle > whole body	Dawood et al. (2019)
Waterborne	<i>Oreochromis mossambicus</i>	0, 5, 10, 25, 50, 100 µg/L	4	liver > gill > brain	Gobi et al. (2018)
Waterborne	<i>Pseudorasbora parva</i>	0, 10, 200, 1000 µg/L	28	liver	Ma et al. (2018)
Dietary	<i>Cyprinus carpio</i>	0, 0.7 mg/kg	56	liver > muscle	Saffari et al. (2017)
Dietary	<i>Oreochromis niloticus</i>	0, 0.25, 0.5, 0.75, 1, 2, 4, 8, 16 mg/kg	70	liver > muscle > gill	Lee et al. (2016)
Waterborne	<i>Danio rerio</i>	0, 1 mg/L	4	liver > kidney > brain	Davis et al., (2016)
Dietary	<i>Oncorhynchus mykiss</i>	0.75, 1.4, 4.46, 8.94 g/kg	70	kidney > liver > muscle > blood	Pacitti et al. (2015)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	liver > muscle	Ashouri et al. (2015)
Field study					
Study area	Fish species		Study periods	Accumulation profiles	Reference
Yellow river, China	Various fish species		July–October 2018	liver > gonads > gill > muscle	Pan et al. (2022)
Northern gulf of California	<i>Merluccius productus</i>		January–March 2017 & 2018	kidney > liver > gonads > gills > muscle	Lizárraga et al., (2020)
Southwestern Atlantic estuaries	<i>Genidens barbuis</i>		November 2016	liver > gills > muscle	Carvalho et al., (2019)
La Plata basin, South America	<i>Prochilodus lineatus</i>		April & June 2017	liver > gills > muscle	Avigliano et al. (2019)
Southeast gulf of California	<i>Coryphaena hippurus</i>		2011–2013	kidney > liver > gonads > muscle	Bergés-Tiznado et al. (2015)
Macedonian rivers	<i>Squalius vardarensis</i>		Spring & Autumn	liver > gill	Dragun et al. (2019)
Lake Saint-Pierre, Quebec, Canada	<i>Perca flavescens</i>		April 2016	gut > liver > gonads > brain > muscle	Khadra et al. (2019)
Vaal dam, South Africa	<i>Labeobarbus aeneus</i> , <i>Labeobarbus kimberleyensis</i> , <i>Labeo umbratus</i> , <i>Labeo capensis</i>		January 2016	liver > muscle	Plessl et al. (2019)
Lakes, Saskatchewan	<i>Catostomus commersonii</i>		October 2014	liver > ovary > testis	Urien et al. (2018)
Río Tercero Reservoir, Argentina	<i>Hoplias malabaricus</i>		Wet & dry season	gills > intestine > brain ≥ liver ≥ muscle	Garnero et al. (2018)
	<i>Oligosarcus jenynsii</i>			gills > intestine > liver ≥ brain ≥ muscle	
	<i>Rhamdia quelen</i>			intestine > gills > liver ≥ brain ≥ muscle	
	<i>Bryconamericus iheringii</i>			intestine > gills > liver ≥ brain ≥ muscle	
	<i>Astyanax fasciatus</i>			intestine ≥ gills > liver ≥ brain > muscle	
	<i>Odontesthes bonariensis</i>			intestine ≥ gills > liver ≥ muscle > brain	
Coast of port Klang, Malaysia	<i>Lates calcarifer</i>		January 2016	liver > muscle	Nasyitah et al. (2018)
	<i>Lutjanus campechanus</i>			liver > muscle	
	<i>Lutjanus griseus</i>			muscle > liver	
East coast of Ireland	<i>Mytilus edulis</i>		August 2012	muscle > skin	McEneff et al. (2017)
Six lakes, North Carolina	Bluegill sunfish, Largemouth bass, Redear sunfish		March–May 2015	liver > ovary > testis > muscle	Brandt et al. (2017)
Eastern Pacific	<i>Istiophorus platypterus</i>		2011–2013	kidney > liver > gonads > muscle	Bergés-Tiznado et al. (2015)

of Se can oxidize cellular thiols (e.g., glutathione; GSH), a phenomenon well-documented over the past two decades. Organic Se, primarily in the form of Se-Met, generates highly reactive metabolites like methylselenol and selenide anion through the action of methioninase enzymes. The redox cycling of methylselenol in the presence of GSH leads to the production of reactive oxygen species (ROS) such as superoxide anion radicals (Palace et al., 2004). Notably, methioninase can also catalyze Se-Met in the absence of thiol groups, producing initial Se radicals that

subsequently form superoxide radicals (Spallholz et al., 2004). In contrast, inorganic Se, primarily in the form of selenite, undergoes reduction by GSH, resulting in the production of hydrogen selenide. This compound is readily oxidized by oxygen, leading to the formation of ROS such as hydrogen peroxide, superoxide, and hydroxyl radicals. Furthermore, selenite's primary metabolite, selenodiglutathione, is highly unstable and is reduced by GSH to form glutathioselenol, which spontaneously dismutates into hydrogen selenide and elemental Se.

Mechanism of Se toxicity in fishes is presented in Fig. 2.

A secondary mechanism of Se toxicity in fishes is the ability of Se to substitute for S in S-containing amino acids, specifically methionine (Met) and cystine (Cyst), forming Se-Met and Se-Cyst during protein synthesis. This occurs due to the chemical similarities between Se and S (Janz et al., 2010). This inappropriate substitution disrupts the formation of disulfide (S-S) bonds, which are crucial for the stabilization of the tertiary structure of proteins (Lemly, 2004; Maier and Knight, 1994), leading to the functional impairment of key enzymes including GPXs, TXNRDs, protein disulfide isomerase, sulfite oxidase, and methionine synthase (Sunde, 1984).

#### 4. Effects of selenium exposure on oxidative stress response

In fishes, the nuclear factor erythroid 2-related factor 2 (Nrf2) signaling pathway plays a crucial role in combating oxidative stress by upregulating key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione S-transferase (GST), and glutathione peroxidase (GPX). These enzymes work synergistically to convert superoxide radicals into hydrogen peroxide, which is then broken down into water and oxygen, serving as the primary defense against highly toxic ROS (Kim and Kang, 2016a). For example, grass carp (*Ctenopharyngodon idella*) fed with Se-supplemented diet at doses of 0, 0.3, 0.6, 0.9 and 1.2 mg/kg for 10 weeks showed significantly elevated hepato-pancreatic expression of Nrf2 gene, which also resulted in the simultaneous upregulation of GPX1 and CAT genes (Yu et al., 2020). Interestingly, dietary interventions, such as the inclusion of *Taraxacum mongolicum* polysaccharide, have been found to enhance the Nrf2-mediated antioxidant response, thereby improving the overall antioxidative and immune status of fishes (Li et al., 2024; Yu et al., 2022). GPX, a Se-dependent enzyme, is particularly important for reducing lipid peroxides, thereby protecting against lipid peroxidation and ferroptosis. However, when Se levels exceed physiological thresholds, this delicate balance is disrupted, leading to oxidative stress as the

production of ROS overwhelms the protective functions of antioxidant enzymes (Kim and Kang, 2017b). This ROS-driven oxidative stress impairs essential biological molecules, including lipids, proteins, and DNA (Kim et al., 2017b, 2021; Lee et al., 2019; Kim and Kang, 2016b). Monitoring the responses of these antioxidant enzymes provides a sensitive and reliable indicator for assessing oxidative stress in fishes exposed to Se. As shown in Table 2, exposure to elevated Se leads to alterations in the activity of SOD, CAT, GST, and GPX in fishes.

SOD is a crucial antioxidant enzyme that catalyzes the conversion of two superoxide anions into hydrogen peroxide ( $H_2O_2$ ) and molecular oxygen ( $O_2$ ), thereby protecting organisms by eliminating excess ROS and maintaining the redox balance of the immune system. Most of the literature reported that chronic exposure to Se at different concentrations ranging from 0.5 to 3.0 mg/kg resulted in increased SOD activities in different organs of fishes including liver (Ghaniem et al., 2022; Wangkahart et al., 2022; Lin et al., 2021), gills (Gobi et al., 2018; Kumar et al., 2018a) and blood (Ghaniem et al., 2022; Abd El-Kader et al., 2021). It has been reported that the increased SOD activities were induced by an antioxidant reaction to prevent oxidative damage caused by ROS production. However, several studies have also reported a decrease in SOD activity in various organs of different fish species exposed to Se, indicating that Se at elevated level can suppress the antioxidant defense system and thereby increase oxidative stress (Li et al., 2020; Kumar and Singh, 2019; Neamat-Allah et al., 2019; Ma et al., 2018).

CAT is another important antioxidant enzyme involved in the detoxification of hydrogen peroxide which minimizes oxidative stress and protects cells from damage. Wangkahart et al. (2022) reported a significant increase in CAT activity in *O. niloticus* exposed to dietary Se. Similarly, CAT activities were noticed to be increased in the liver of *Pangasianodon hypophthalmus* due to increase ROS production (El-Sharawy et al., 2021). In contrast, waterborne exposure of Se to *Channa argus* results in lower CAT activities indicating increased oxidative stress (Li et al., 2020).

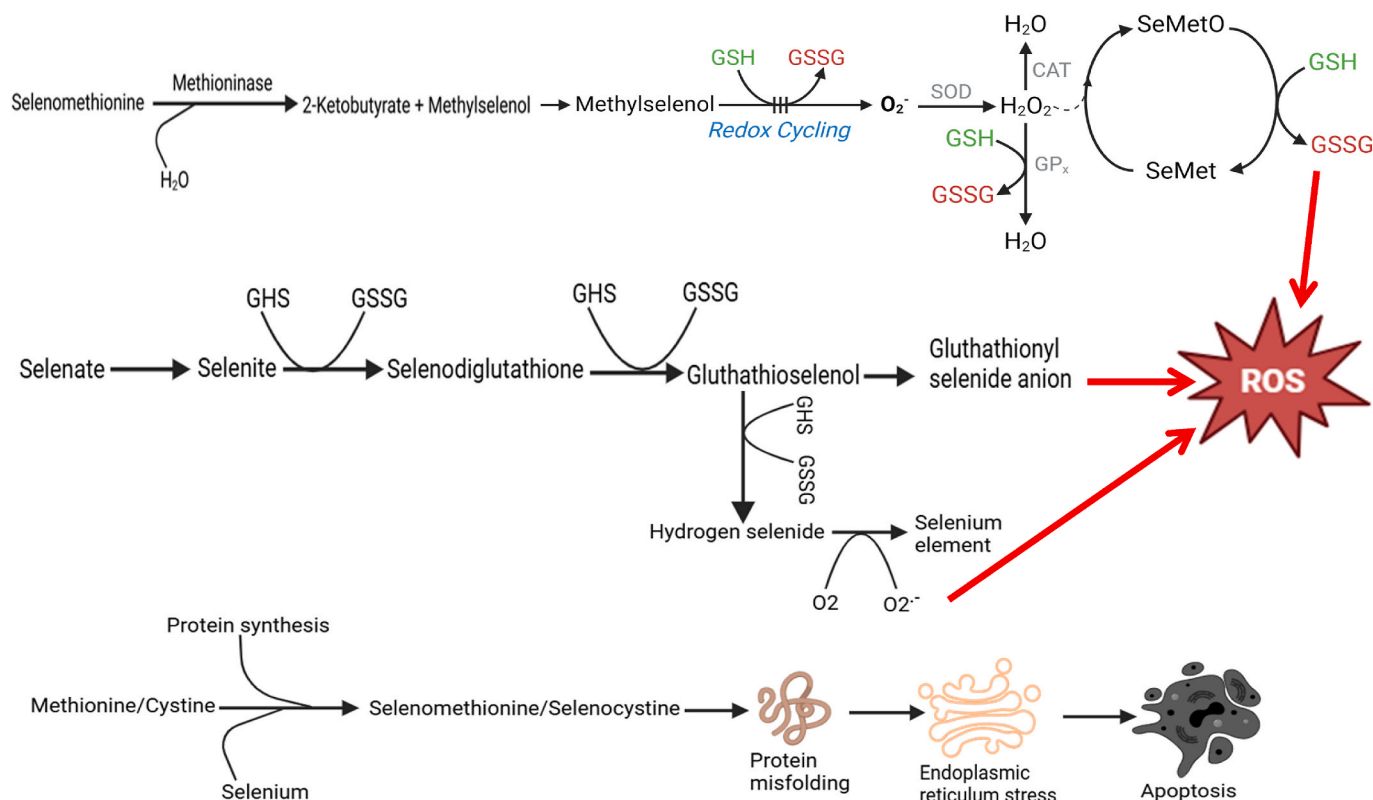


Fig. 2. Mechanism of selenium toxicity in fishes.

**Table 2**  
Antioxidant enzymes response in fishes exposed to selenium.

Exposure route	Fish species	Target organs	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
<b>Superoxide dismutase (SOD)</b>							
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 1, 3, 5 mg/kg	56	1 mg/kg	↑	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	Liver	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
		Whole body	0, 0.5, 1 mg/kg	96	–	x	
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	100 µg/L	↓	Gopi et al. (2021)
Dietary	<i>Nibeia coibor</i>	Liver	0, 10, 100 µg/L	4	100 µg/L	↓	Lin et al. (2021)
		Blood	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.79, 1.11 mg/kg	↑	
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.79, 1.11, 1.45 mg/kg	↑	
Dietary	<i>Dicentrarchus labrax</i>	Blood	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	Liver	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.67, 1.06 mg/kg	↑↓	Jingyuan et al. (2020)
Waterborne	<i>Channa argus</i>	Liver	0, 100, 200 mg/L	56	100, 200 mg/L	↓	Li et al. (2020)
		Spleen	0, 100, 200 mg/L	56	100, 200 mg/L	↓	
Dietary	<i>Danio rerio</i>	Muscle	1.63, 3, 10 mg/kg	28	3, 10 mg/kg	↑↓	Bai et al. (2019a)
Dietary	<i>Acanthopagrus schlegelii</i>	Blood	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	Wang et al. (2019)
		Liver	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 0.7 mg/kg	63	0.7 mg/kg	↓	Neamat-Allah et al. (2019)
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	Kumar and Singh (2019)
		Gill	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
		Kidney	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	25, 50, 100 µg/L	↑	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	25, 50, 100 µg/L	↑	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
		Brain	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	4.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	–	x	
		Brain	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	3, 4 mg/L	↓	
Waterborne	<i>Pseudorasbora parva</i>	Liver	0, 10, 200, 1000 µg/L	28	10, 200, 1000 µg/L	↓	Ma et al. (2018)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.7 mg/kg	56	0.7 mg/kg	↑	Saffari et al. (2017)
Dietary	<i>Argyrosomus regius</i>	Liver	0, 1, 2, 3 mg/kg	63	1, 2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 0.25, 0.5, 0.75, 1, 2, 4, 8, 16 mg/kg	70	8 mg/L	↑	Lee et al. (2016)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.5, 1, 2 mg/kg	56	1, 2 mg/kg	↑	Ashouri et al. (2015)
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 1, 3, 5 mg/kg	56	1, 3 mg/kg	↑	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	Liver	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
		Whole body	0, 0.5, 1 mg/kg	96	–	x	
Dietary	<i>Oreochromis niloticus</i>	Muscle	0, 0.5, 1 mg/kg	96	–	x	Ghaniem et al. (2022)
		Blood	0, 1 mg/kg	65	1 mg/kg	↑	
Waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	100 µg/L	↓	Gopi et al. (2021)
		Liver	0, 10, 100 µg/L	4	100 µg/L	↓	
		Brain	0, 10, 100 µg/L	4	100 µg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↑	Naiel et al. (2021)
Dietary	<i>Nibeia coibor</i>	Blood	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.53, 0.79 mg/kg	↑	Lin et al. (2021)
		Liver	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	–	x	
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 0.5, 1, 2 mg/kg	60	0.5, 1, 2 mg/kg	↑	El-Sharawy et al. (2021)
Dietary	<i>Dicentrarchus labrax</i>	Blood	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 3, 6, 12 µg/g	90	3, 6, 12 µg/g	↑	Chen et al. (2020)
		Liver	0, 3, 6, 12 µg/g	45	6, 12 µg/g	↑	
Waterborne	<i>Channa argus</i>	Liver	0, 100, 200 mg/L	56	100, 200 mg/L	↓	Li et al. (2020)

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Table 2 (continued)

Exposure route	Fish species	Target organs	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
Dietary	<i>Megalobrama amblycephala</i>	Spleen	0, 100, 200 mg/L	56	100, 200 mg/L	↓	Jingyuan et al. (2020)
		Liver	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.67, 1.06 mg/kg	↑	
Dietary	<i>Carassius auratus</i>	Liver	0, 5, 10, 20 mg/kg	30	5, 10, 20 mg/kg	↑	Bai et al. (2019b)
Waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200, 400 µg/L	28	200, 400 µg/L	↑	Li et al. (2019)
		Spleen	0, 50, 100, 200, 400 µg/L	28	200, 400 µg/L	↑	
waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200 µg/L	56	–	x	Li et al. (2019)
		Spleen	0, 50, 100, 200 µg/L	56	–	x	
Dietary	<i>Acanthopagrus schlegelii</i>	Blood	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	Wang et al. (2019)
		Liver	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 0.7 mg/kg	63	0.7 mg/kg	↓	Neamat-Allah et al. (2019)
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	Kumar and Singh (2019)
		Gill	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
		Kidney	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑↓	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑↓	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
		Brain	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	2.5, 3.0, 3.5, 4.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	2.5, 3.0, 3.5, 4.0 mg/L	↑	
		Brain	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	2.5, 3.0, 3.5, 4.0 mg/L	↑	
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.7 mg/kg	56	0.7 mg/kg	↑	Saffari et al. (2017)
Dietary	<i>Piaractus mesopotamicus</i>	Liver	0.72, 0.94, 1.15, 1.57, 2.51 mg/kg	65	–	x	Takahashi et al. (2017)
Dietary	<i>Argyrosomus regius</i>	Liver	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↑	Ashouri et al. (2015)
<b>Glutathione peroxidase (GPX)</b>							
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 1, 3, 5 mg/kg	56	1, 3, 5 mg/kg	↑	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	Liver	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
		Whole body	0, 0.5, 1 mg/kg	96	–	x	
		Muscle	0, 0.5, 1 mg/kg	96	–	x	
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	10, 100 µg/L	↑	Gopi et al. (2021)
		Liver	0, 10, 100 µg/L	4	10, 100 µg/L	↑	
Dietary	<i>Carassius auratus</i>	Blood	0, 0.1, 0.5, 1 mg/kg	60	0.1, 0.5, 1 mg/kg	↑	Seyedi et al. (2021)
Dietary	<i>Dicentrarchus labrax</i>	Blood	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 0.5, 1, 2 mg/kg	60	0.5, 1, 2 mg/kg	↑	El-Sharawy et al. (2021)
Dietary	<i>Nibea coibor</i>	Blood	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	↑	Lin et al. (2021)
		Liver	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	↑	
Waterborne	<i>Channa argus</i>	Liver	0, 100, 200 mg/L	56	200 mg/L	↓	Li et al. (2020)
		Spleen	0, 100, 200 mg/L	56	–	x	
Dietary	<i>Megalobrama amblycephala</i>	Liver	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.42, 0.67, 1.06, 1.46 mg/kg	↑	Jingyuan et al. (2020)
Dietary	<i>Danio rerio</i>	Gill	0, 2.5, 3.0, 3.5, 4.0 mg/kg	4	–	x	Bai et al., 2019a
Dietary	<i>Carassius auratus</i>	Brain	0, 2.5, 3.0, 3.5, 4.0 mg/kg	4	3, 4 mg/kg	↑	Bai et al., 2019a
Waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200, 400 µg/L	28	100, 200, 400 µg/L	↑	Li et al. (2019)
		Spleen	0, 50, 100, 200, 400 µg/L	28	100, 200, 400 µg/L	↑	
Waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200 µg/L	56	50, 100, 200 µg/L	↑	Li et al. (2019)
		Spleen	0, 50, 100, 200 µg/L	56	–	X	
Dietary	<i>Acanthopagrus schlegelii</i>	Blood	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	Wang et al. (2019)
		Liver	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↑	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 0.7 mg/kg	63	0.7 mg/kg	↓	Neamat-Allah et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	Liver	0, 1 mg/kg	56	1 mg/kg	↑	Kohshahi et al. (2019)
		Blood	0, 1 mg/kg	56	1 mg/kg	↑	
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑	

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Table 2 (continued)

Exposure route	Fish species	Target organs	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
Dietary	<i>Piaractus mesopotamicus</i>	Liver	0.72,0.94,1.15, 1.57,2.51 mg/kg	65	1.15,1.57 mg/kg	↑	Takahashi et al. (2017)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.7 mg/kg	56	0.7 mg/kg	↑	Saffari et al. (2017)
Dietary	<i>Tor putitora</i>	Liver	0, 0.68 mg/kg	70	0.68 mg/kg	↑	Khan et al. (2016)
		Muscle	0, 0.68 mg/kg	70	0.68 mg/kg	↑	
		Gill	0, 0.68 mg/kg	70	0.68 mg/kg	↑	
		Brain	0, 0.68 mg/kg	70	0.68 mg/kg	↑	
Dietary	<i>Lates calcarifer</i>	Muscle	2, 3, 4, 5, 7 mg/kg	60	3, 4, 5, 7 mg/kg	↑	Ilham et al. (2016)
Dietary	<i>Pelteobagrus fulvidraco</i>	Liver	0, 0.23, 6.5 mg/kg	56	0.23, 6.5 mg/kg	↑	Hu et al., (2016)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.5, 1, 2 mg/kg	56	1, 2 mg/kg	↑	Ashouri et al. (2015)
<b>Glutathione transferases (GST)</b>							
Waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	10, 100 µg/L	↑	Gopi et al. (2021)
		Liver	0, 10, 100 µg/L	4	10, 100 µg/L	↑	
Waterborne	<i>Channa argus</i>	Liver	0, 100, 200 mg/L	56	100, 200 mg/L	↓	Li et al. (2020)
		Spleen	0, 100, 200 mg/L	56	100, 200 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 3, 6,12 µg/g	90	3, 6,12 µg/g	↑	Chen et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 3, 6,12 µg/g	45	3, 6,12 µg/g	↑	Chen et al. (2020)
Dietary	<i>Carassius auratus</i>	Liver	0, 5, 10, 20 mg/kg	30	5, 10, 20 mg/kg	↓	Bai et al., 2019a
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	10, 25, 50, 100 µg/L	↑↓	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	10, 25, 50, 100 µg/L	↑	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
		Brain	0, 4.5, 5, 5.5, 6.0 mg/L	4	4.5, 5, 5.5, 6.0 mg/L	↑	
Waterborne	<i>Pangasius hypophthalmus</i>	Liver	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	2.5, 3.0, 3.5, 4.0 mg/L	↑	Kumar et al. (2018a)
		Gill	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	4.0 mg/L	↑	
		Brain	0, 2.5, 3.0, 3.5, 4.0 mg/L	4	2.5, 3.0, 3.5, 4.0 mg/L	x	
Waterborne	<i>Pseudorasbora parva</i>	Liver	0, 10, 200, 1000 µg/L	28	10, 200, 1000 µg/L	↓	Ma et al. (2018)
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	Kumar et al. (2018b)
		Gill	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
		Kidney	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	
Dietary	<i>Piaractus mesopotamicus</i>	Liver	0.72,0.94,1.15, 1.57,2.51 mg/kg	65	0.94,1.15, 1.57 mg/kg	↑	Takahashi et al. (2017)

↑ = increased; ↓ = decreased; x = no changed.

GST is usually triggered in fishes by exposure to environmental toxins (Kim and Kang, 2016c). GST functions in the second stage of detoxification metabolism by conjugating to xenobiotics and clearing them from the cells. Thus, GST plays a key role in homeostasis and foreign body dissociation, protecting tissues from oxidative stress (Mushtaq et al., 2022a,b). GPX is an enzyme that assists peroxide conversion to less toxic hydroxyl compounds that protect cells from damage caused by oxygen. Many authors have reported that exposure to Se alters GST and GPX activities by inducing oxidative stress (El-Sharawy et al., 2021; Gopi et al., 2021; Gobi et al., 2018; Ma et al., 2018; Takahashi et al., 2017).

Malondialdehyde (MDA), thiobarbituric acid reactive substances (TBARS), and reduced glutathione levels (GHS) are recognized as crucial indicators of oxidative damage in fishes exposed to environmental toxins (Shah and Mraz, 2020). Table 3 summarizes the oxidative damage indicators (MDA, TBARS, and GHS) in fishes exposed to Se. Oxidative stress triggers lipid peroxidation of cell membranes and DNA damage, quantified by MDA levels. Elevated ROS signify toxic reactions, inducing oxidative stress by disrupting the balance between ROS generation and antioxidant capacity. Excessive ROS can escalate lipid peroxidation, leading to MDA production, serving as direct evidence of free radical-induced damage in fishes (Lin et al., 2021). Changes in MDA content indirectly gauge the disruption level of the biofilm system. Chronic dietary Se exposure below 1 mg/kg enhances antioxidant enzyme activities and diminishes MDA content in the serum, liver, gill, and muscle, indicating improved antioxidant capacity in fishes (Ghaniem et al., 2022; Wang et al., 2019). However, MDA content shows an upward trajectory with increasing dietary Se levels beyond 1.11 mg/kg, likely due to oxidative stress (Bai et al., 2019a). Additionally, waterborne Se exposure ranging from 50 µg/L to 200 mg/L leads to increased MDA levels in the liver, spleen, and serum of various fishes, attributed to increased ROS generation and lipid peroxidation (Li et al., 2019; Ma et al., 2018).

TBARS level serves as a widely used indicator of lipid peroxidation in fishes experiencing oxidative stress induced by environmental toxins, including Se above the physiological threshold (Kumar and Singh, 2019; Ponton et al., 2016). Fishes, with their high content of polyunsaturated fatty acids (PUFA), are particularly prone to oxidative damage, making TBARS a valuable biomarker of oxidative stress (Lauriano et al., 2016). Both waterborne and dietary exposure to Se in *O. mossambicus* and *O. niloticus*, respectively, have been linked to increased TBARS levels, indicating lipid peroxidation and oxidative damage in the liver and gills (Gopi et al., 2021; Chen et al., 2020). The level of GHS is also recognized as an indicator of oxidative damage in fishes exposed to Se. Most studies report that various fish species exposed to Se up to 1 mg/kg or 1 mg/L exhibit increased GHS levels in different internal organs, indicating higher antioxidative capacity and lower oxidative stress (Naiel et al., 2021; Gobi et al., 2018; Ma et al., 2018).

## 5. Effects of selenium on metabolic functions

Metabolic markers are critical for assessing the health and physiological stress in fishes, influenced by internal and external factors (Uddin et al., 2023). Blood biochemical alterations are key indicators of pollutant exposure (Kucukbay et al., 2009). As an accessible biological fluid, blood reflects changes in physiological states. Thus, hematological investigations are vital for monitoring fish health, with trace elements in the blood significantly affecting physiological functions (Shahjahan et al., 2018). Metal stress has been shown to alter metabolic markers, including enzyme levels, lipid peroxidation products, and hematological parameters (Ates et al., 2008). These changes are influenced by factors such as the type of metal or fish species, water quality, and exposure duration (Orun et al., 2008). Primary stress responses due to metals exposure are characterized by the release of catecholamines and corticosteroids, whereas the secondary stress responses to hematological changes and its associated biochemistry as reliable biomarkers in fishes



**Table 3**  
Oxidative damage indicators in fishes exposed selenium.

Exposure route	Fish species	Target organs	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
<b>Malondialdehyde (MDA)</b>							
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 1, 3, 5 mg/kg	56		x	Wangkahart et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 1 mg/kg	65	1 mg/kg	↓	Ghaniem et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	Blood	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↓	Abd El-Kader et al. (2021)
Dietary	<i>Pangasianodon hypophthalmus</i>	Liver	0, 0.5, 1, 2 mg/kg	60	0.5, 1, 2 mg/kg	↓	El-Sharawy et al. (2021)
Dietary	<i>Nibea coibor</i>	Blood	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.79 mg/kg	↓	Lin et al. (2021)
		Liver	0.21, 0.53, 0.79, 1.11, 1.45, 1.72 mg/kg	56	0.79 mg/kg	↓	
Waterborne	<i>Channa argus</i>	Liver	0, 100, 200 mg/L	56	100, 200 mg/L	↑	Li et al. (2020)
Waterborne	<i>Channa argus</i>	Spleen	0, 100, 200 mg/L	56	100, 200 mg/L	↑	
Dietary	<i>Megalobrama amblycephala</i>	Liver	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.42, 0.67, 1.06, mg/kg	↓↑	Jingyuan et al. (2020)
Dietary	<i>Carassius auratus</i>	Liver	0, 5, 10, 20 mg/kg	30	5, 10, 20 mg/kg	↑	Bai et al., 2019b
Waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200 µg/L	56	50, 100, 200 µg/L	↑	Li et al. (2019)
Waterborne	<i>Channa argus</i>	Liver	0, 50, 100, 200, 400 µg/L	28	200, 400 µg/L	↑	Li et al. (2019)
Waterborne	<i>Channa argus</i>	Spleen	0, 50, 100, 200, 400 µg/L	28	200, 400 µg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 0.7 mg/kg	63		x	Neamat-Allah et al. (2019)
Dietary	<i>Acanthopagrus schlegelii</i>	Blood	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.68, 0.91, 1.08, 3.06 mg/kg	↓	Wang et al. (2019)
		Liver	0, 0.34, 0.52, 0.68, 0.91, 1.08, 3.06 mg/kg	56	0.34, 0.68, 0.91, 1.08, 3.06 mg/kg	↓	
Dietary	<i>Oreochromis niloticus</i>	Liver	0.53,0.86,1.04,1.22 mg/kg	42	–	x	Durigon et al. (2019)
		Gill	0.53,0.86,1.04,1.22 mg/kg	42	1.04,1.22 mg/kg	↓	
		Muscle	1.04,1.22 mg/kg	42	0.86, 1.04,1.22 mg/kg	↓	
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	5, 10, 25, 50, 100 µg/L	↑	
Waterborne	<i>Pseudorasbora parva</i>	Liver	0, 10, 200, 1000 µg/L	28	10, 200, 1000 µg/L	↑	Ma et al. (2018)
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.7 mg/kg	56	0.7 mg/kg	↓	Saffari et al. (2017)
Dietary	<i>Pelteobagrus fulvidraco</i>	Liver	0, 0.23, 6.5 mg/kg	56	0.23, 6.5 mg/kg	x	Hu et al., (2016)
Waterborne	<i>Carassius auratus</i>	Blood	0, 2, 3, 4 mg/L	5	4 mg/L	↑	Choi et al. (2015)
Waterborne	<i>Channa argus</i>	Spleen	0, 50, 100, 200 µg/L	56	50, 100, 200 µg/L	↑	
Dietary	<i>Cyprinus carpio</i>	Liver	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↓	Ashouri et al. (2015)
<b>Thio-barbituric acid reactive substances (TBARES level)</b>							
Dietary	<i>Hypophthalmichthys molitrix</i>	Liver	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
		Blood	0, 0.5, 1 mg/kg	96	–	x	
		Muscle	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↑	
Waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	10, 100 µg/L	↑	Gopi et al. (2021)
		Liver	0, 10, 100 µg/L	4	10, 100 µg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 3, 6,12 µg/g	90	6,12 µg/g	↑	Chen et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	Liver	0, 3, 6,12 µg/g	45	6,12 µg/g	↑	Chen et al. (2020)
Dietary	<i>Argyrosomus regius</i>	Liver	0, 1, 2, 3 mg/kg	63	1, 2, 3 mg/kg	↓	Mansour et al. (2017)
<b>Glutathione (GSH levels)</b>							
Waterborne	<i>Oreochromis mossambicus</i>	Gill	0, 10, 100 µg/L	4	10, 100 µg/L	↑	Gopi et al. (2021)
		Liver	0, 10, 100 µg/L	4	10, 100 µg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	Blood	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↑	Naiel et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	Liver	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.67,1.06 mg/kg	↓↑	Jingyuan et al. (2020)
Waterborne	<i>Pseudorasbora parva</i>	Liver	0, 10, 200, 1000 µg/L	28	10, 200, 1000 µg/L	↑	Ma et al. (2018)
Waterborne	<i>Oreochromis mossambicus</i>	Liver	0, 5, 10, 25, 50, 100 µg/L	4	10, 25, 50, 100 µg/L	↑	Gobi et al. (2018)
		Gill	0, 5, 10, 25, 50, 100 µg/L	4	10, 25, 50, 100 µg/L	↑	
Dietary	<i>Piaractus mesopotamicus</i>	Liver	0.72,0.94,1.15, 1.57,2.51 mg/kg	65	–	x	Takahashi et al. (2017)
Waterborne	<i>Danio rerio</i>	Liver	0, 1 mg/L	4	1 mg/L	↑	Davis et al., (2016)
		Kidney	0, 1 mg/L	4	1 mg/L	↑	
		Brain	0, 1 mg/L	4	1 mg/L	↑	

↑ = increased; ↓ = decreased; x = no changed.

has been well documented (Rebl et al., 2021).

Hematological properties [red blood cell (RBC), white blood cell (WBC), hematocrit (Hct), hemoglobin (Hb), glucose, cholesterol, total protein, aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP)] are important metabolic

markers for evaluating the health status of fishes following exposure to various environmental stresses, chemical toxicity, and bacterial infections (Kim et al., 2020; Kim and Kang, 2017a). Se above the physiological optimum results in alteration of metabolic markers in fishes including RBC, WBC, Hb, Hct, AST, ALT, ALP, albumin, globulin, and

total protein. Alterations of metabolic markers of fishes in relation to Se exposure route (waterborne and dietary) are presented in Table 4. Several studies have consistently reported that chronic dietary exposure to Se within the range of 0.5–1 mg/kg for a duration of 30–90 days leads to increase levels of RBCs, Hb, and Hct in different fish species (Al-Din et al., 2022; Ghaniem et al., 2022; Abd El-Kader et al., 2021). These elevated parameters signify an enhancement in the health status of the fishes, attributed to improved oxygen availability in cellular tissues, thereby preventing anemia.

The antioxidant properties of Se contribute to the protection of RBC membranes, thereby prolonging their lifespan and defending against oxidative damage caused by ROS. This mechanism aids in reducing anemia, membrane disruption, cell hemolysis, and degeneration (Khan et al., 2016). Similar enhancements in hematological parameters have been observed in fishes fed with nano-Se, including Common carp (Saffari et al., 2017), European seabass (Dawood et al., 2019), and Nile tilapia (Rathore et al., 2021a). The elevated levels of Hb and Hct resulting from nano-Se exposure are attributed to the increased oxygen-carrying capacity to meet the higher respiratory and metabolic demands (de Azevedo et al., 2015).

Several studies have reported an increased in WBCs counts in various fish species exposed to Se (Al-Din et al., 2022; Mushtaq et al., 2022a,b; Yeganeh et al., 2016). This elevation in WBCs indicates the activation of cell-mediated immunity, particularly under stressful conditions (Fiúza et al., 2015). However, it is noteworthy that exposure to waterborne Se has shown contrasting effects, including a significant decrease in RBC count, Hct, and Hb levels (Dhara et al., 2022). Such decreases may be an indication of an increasing rate of erythrocyte destruction in the hematopoietic organ, potentially leading to anemia (Yeganeh et al., 2016).

Blood glucose is used as a stress indicator in fishes; high glucose levels often indicate high stress because high cortisol levels stimulate the dissolution of liver glycogen to provide energy during the stress process. The significant utilization of blood glucose in Se treated fishes may be due to enhanced energy demand by releasing more glucose via glycogenolysis (Dhara et al., 2022). The activity of transaminases (ALT and AST) in serum serves as an indicator of stress in fishes, with increased concentrations reflecting responses to stressful conditions (Bitiren et al., 2004). Moreover, elevated liver enzyme activities can lead to liver and kidney damage, resulting in necrosis and higher ALP levels in blood, which can cause skeletal disorders such as osteoporosis and hepatic cell ruptures (Bitiren et al., 2004). AST and ALT also play essential roles in nitrogen metabolism within cells, facilitating the transfer of amino acids to liver cells and monitoring toxic effects (Abdel-Tawwab, 2016). Additionally, ALP is involved in the transport of phosphorylated intermediates through cells and carbohydrate metabolism (Yousef et al., 2003).

Several studies have indicated that the observed increase in AST, ALT, and ALP serum activities in Se-exposed fishes may be attributed to cellular cytotoxicity and damage to liver and kidney tissues. However, contradictory findings have been reported, with no significant differences found in AST, ALT, and ALP activities in various fish species fed different levels of Se (Abd El-Kader et al., 2021; Ziaei-Nejad et al., 2021; Jingyuan et al., 2020). Conversely, Se supplementation led to decrease activities of AST, ALT, and ALP in certain fish species, indicating a potential positive influence on liver health (Mushtaq et al., 2022a,b; Naiel et al., 2021; Saffari et al., 2017). These findings underscore that feeding fishes with Se supplemented diets could positively influence the health of liver.

Detecting total protein levels in fish blood is vital for assessing overall health and immunity status, as proteins play critical roles in cell function, metabolism, hormone secretion, and regulating physiological processes within the fish body. *O. niloticus* exposed to Se for 65 days exhibited an increase in total protein levels (Ghaniem et al., 2022; Naiel et al., 2021). This elevation may be attributed to the high protein content induced by Se's role in increasing selenoprotein levels intracellularly. Conversely, other species of fishes exposed to different

concentrations of Se showed lower levels of total protein (Dhara et al., 2022; Yeganeh et al., 2016). This reduction in total protein levels may be associated with hypoalbuminemia, which could be related to cellular degradation, imperfect protein synthesis, and protein loss due to pathological changes in the kidney (Hamed, 2015).

Among serum proteins, albumin and globulin are crucial indicators of the immune status of experimental animals (Naderi et al., 2017a). Elevated levels of albumin can help protect blood vessels from leaking during times of stress, while globulins contain various immunological components (Uribe et al., 2011). An increase in albumin and globulin levels is associated with higher organic Se levels in fish diets, which can enhance their production in the liver (Abdel-Tawwab et al., 2007).

Studies have shown that increasing the amount of Se up to 2 mg/kg in the diet significantly increases total protein and globulin levels, consistent with findings on African catfish and Common carp by Abdel-Tawwab et al. (2007) and Ashouri et al. (2015), respectively. Furthermore, triglycerides serve as a source of energy for various metabolic processes, with excess amounts being stored as fat in adipose tissue. Therefore, the observed elevation in serum triglyceride levels in Se-treated fishes could be attributed to the degradation of stored fats to produce the required energy to counteract the toxic effects of Se (Dhara et al., 2022; Naderi et al., 2017b).

## 6. Effects of selenium on growth and reproduction

Appropriate nutrition is essential for maintaining the overall growth, reproductive performance, and health status of fishes (Rohani et al., 2022; Islam et al., 2021; Jahan et al., 2021). Food deprivation can lead to physiological impairments in fishes, potentially resulting in reproductive issues such as reduced fertility and hatching rates due to nutrient deficiencies (Wu, 2022; Volkoff and London, 2018). Among various nutrients, trace metals play a significant role in fulfilling the nutritional demands of fishes for various physiological processes, including growth and reproduction (Taslina et al., 2022). Se is a key trace element that plays essential roles in regulating reproductive hormones, growth, and metabolism within physiological thresholds in animals, including fishes (Abdollahi-Mousavi et al., 2024; Mushtaq et al., 2022a,b; Saffari et al., 2022).

The dietary requirement of Se in fishes are highly species-specific (Jahanbakhshi et al., 2021). For example, the dietary requirement of Se for *Oncorhynchus mykiss*, *O. niloticus*, *Ictalurus punctatus*, and *Carassius auratus* is reported to be 0.15–0.38, 1.06–2.06, 0.25, and 0.73–1.19 µg/g diet dw, respectively (Jahanbakhshi et al., 2021; Khalil et al., 2019; Nazari et al., 2017; Zhu et al., 2017). Prabhu et al. (2016) reported that diets containing varying levels of Se, ranging from 0.2 to 12 mg/kg, exhibited beneficial effects on the physiological and immunological responses of fishes. Environmentally relevant waterborne exposure to inorganic Se (selenite) can also affect the fish growth. For example, freshly hatched zebrafish embryos exposed to waterborne selenite concentrations of 10–100 µg/L for 30 days exhibited reduced length and body weight compared to their counterparts which were raised in normal water (Uddin et al., 2023; unpublished data).

In contrast, Se exposure above dietary requirements level can lead to Se accumulation, causing adverse effects on reproductive performance, growth inhibition, tissue damage, and mortality (Zhu et al., 2017). Cheng et al. (2022) reported that long-term exposure to 57.01 or 117.67 µg/L of sodium selenite for 4 months markedly inhibited the growth of adult zebrafish. Similarly, dietary Se-Met at 58.63 µg/g (dw) disturbed the sexual differentiation and development of zebrafish larvae after 90 days of exposure (Mo et al., 2020). Dietary exposure to high Se levels (30.02 and 59.76 mg/kg dw) caused significant Se accumulation in the ovaries of female *Procambarus clarkii*, reducing their spawning rate by inhibiting the secretion of 17β-estradiol (Mo et al., 2019). Additionally, Mo et al. (2020) reported that exposure to high dietary Se-Met levels (10.80 mg/kg dw) interfered with the growth hormone/insulin-like growth factors (GH/IGFs) and hypothalamus-pituitary-gonad-liver

**Table 4**  
Alterations of metabolic markers in fishes exposed to selenium.

Exposure route	Fish species	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
<b>Red blood cell (RBC)</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	1 mg/kg	↓	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	0.5, 1 mg/kg	↑	Al-Din et al. (2022)
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↓	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Dietary	<i>Labeo rohita</i>	0, 0.5 mg/kg	60	0.5 mg/kg	↑	Pavithra et al., (2021)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	–	x	Neamat-Allah et al. (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 2, 4, 8 mg/kg	90	2, 8 mg/kg	↑, ↓	Iqbal et al. (2017)
Dietary	<i>Piaractus mesopotamicus</i>	0.72, 0.94, 1.15, 1.57, 2.51 mg/kg	65	1.15, 1.57 mg/kg	↑	Takahashi et al. (2017)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	–	x	Mansour et al. (2017)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↓	Yeganeh et al. (2016)
Dietary	<i>Tor putitora</i>	0, 0.68 mg/kg	70	0.68 mg/kg	↑	Khan et al. (2016)
<b>White blood cell (WBC)</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↑	Mushtaq et al. (2022a)
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	–	x	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	1 mg/kg	↑	Al-Din et al. (2022)
Dietary	<i>Labeo rohita</i>	0, 0.5 mg/kg	60	0.5 mg/kg	↓	Pavithra et al., (2021)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	1, 2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Oreochromis niloticus</i>	0, 2, 4, 8 mg/kg	90	–	x	Iqbal et al. (2017)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↑	Yeganeh et al. (2016)
<b>Hemoglobin (Hb)</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	1 mg/kg	↓	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	1 mg/kg	↑	Mushtaq et al. (2022a)
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↓	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	1 mg/kg	↑	Al-Din et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Labeo rohita</i>	0, 0.5 mg/kg	60	0.5 mg/kg	↑	Pavithra et al., (2021)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	0.53, 0.86, 1.04, 1.22 mg/kg	42	–	x	Durigon et al. (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 2, 4, 8 mg/kg	90	4, 8 mg/kg	↓	Iqbal et al. (2017)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	–	x	Mansour et al. (2017)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↓	Yeganeh et al. (2016)
Dietary	<i>Tor putitora</i>	0, 0.68 mg/kg	70	0.68 mg/kg	↑	Khan et al. (2016)
Dietary	<i>Lates calcarifer</i>	2, 3, 4, 5, 7 mg/kg	60	–	x	Ilham et al. (2016)
<b>Glucose</b>						
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	–	x	Mushtaq et al. (2022a)
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↑	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	0.5 mg/kg	↑	Al-Din et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↓	Ghaniem et al. (2022)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	–	x	Jahanbakhshi et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	–	x	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Pangasianodon hypophthalmus</i>	0, 1, 2 mg/kg	60	1, 2 mg/kg	↓	Kumar and Singh (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	–	x	Neamat-Allah et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	–	x	Nazari et al., 2017
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	0.23, 6.5 mg/kg	↑↓	Hu et al., (2016)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↑	Yeganeh et al. (2016)
<b>Alkaline phosphatase (ALP)</b>						
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↓	Mushtaq et al. (2022a)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	0.3, 0.6, 0.9 mg/kg	↑	Jahanbakhshi et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	0.5 mg/kg	↓	Ziaei-Nejad et al. (2021)

(continued on next page)

Table 4 (continued)

Exposure route	Fish species	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	–	x	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Danio rerio</i>	1.63, 3, 10 mg Se/kg	28	3, 10 mg Se/kg	↑	Bai et al., 2019b
Dietary	<i>Carassius auratus</i>	0, 5, 10, 20 mg/kg	30	5, 10, 20 mg/kg	↑	Bai et al., 2019b
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	0.7 mg/kg	↑	Neamat-Allah et al. (2019)
Dietary	<i>Cyprinus carpio</i>	0, 0.7 mg/kg	56	0.7 mg/kg	↓	Saffari et al. (2017)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↑	Yeganeh et al. (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	–	x	Ashouri et al. (2015)
Waterborne	<i>Carassius auratus</i>	0, 2, 3, 4 mg/L	5	3, 4 mg/L	↑	Choi et al. (2015)
<b>Aspartate transaminase (AST)</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	0.5, 1 mg/kg	↑	Al-Din et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↓	Mushtaq et al. (2022a)
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	1 mg/kg	↓	Wangkahart et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	–	x	Abd El-Kader et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↓	Naiel et al. (2021)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	–	x	Jahanbakhshi et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	–	x	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	–	x	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Carassius auratus</i>	0, 5, 10, 20 mg/kg	30	10, 20 mg/kg	↑	Bai et al., 2019b
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	0.7 mg/kg	↑	Neamat-Allah et al. (2019)
Dietary	<i>Cyprinus carpio</i>	0, 0.7 mg/kg	56	0.7 mg/kg	↓	Saffari et al. (2017)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	1, 2, 3 mg/kg	↑	Mansour et al. (2017)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	–	x	Yeganeh et al. (2016)
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	–	x	Hu et al., (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	1, 2 mg/kg	↑	Ashouri et al. (2015)
Waterborne	<i>Carassius auratus</i>	0, 2, 3, 4 mg/L	5	3, 4 mg/L	↑	Choi et al. (2015)
<b>Alanine transaminase (ALT)</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	0.5, 1 mg/kg	↑	Al-Din et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	–	x	Ghaniem et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↓	Mushtaq et al. (2022a)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	3 mg/kg	↓	Wangkahart et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	–	x	Abd El-Kader et al. (2021)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	–	x	Jahanbakhshi et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↓	Naiel et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	0.5, 2 mg/kg	↓ ↑	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	–	x	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Carassius auratus</i>	0, 5, 10, 20 mg/kg	30	10, 20 mg/kg	↑	Bai et al., 2019b
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	0.7 mg/kg	↑	Neamat-Allah et al. (2019)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	1, 2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Cyprinus carpio</i>	0, 0.7 mg/kg	56	0.7 mg/kg	↓	Saffari et al. (2017)
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	–	x	Hu et al., (2016)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↑	Yeganeh et al. (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↑	Ashouri et al. (2015)
<b>Hematocrit (Hct)</b>						
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↓	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	–	x	Al-Din et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Hypophthalmichthys molitrix</i>	0, 0.5, 1 mg/kg	96	0.5, 1 mg/kg	↑	Mushtaq et al. (2022a)
Dietary	<i>Labeo rohita</i>	0, 0.5 mg/kg	60	0.5 mg/kg	↑	Pavithra et al., (2021)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	1 mg/kg	↑	Zahmatkesh et al. (2020)
Dietary	<i>Pagrus major</i>	0, 0.5, 1, 2 mg/kg	45	1, 2 mg/kg	↑	Dawood et al. (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	–	x	Neamat-Allah et al. (2019)
Dietary	<i>Piaractus mesopotamicus</i>	0.72, 0.94, 1.15, 1.57, 2.51 mg/kg	65	1.15, 1.57 mg/kg	↑	Takahashi et al. (2017)
Dietary	<i>Tor putitora</i>	0, 0.68 mg/kg	70	0.68 mg/kg	↑	Khan et al. (2016)
Dietary	<i>Lates calcarifer</i>	2, 3, 4, 5, 7 mg/kg	60	5, 7 mg/kg	↓	Ilham et al. (2016)
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↓	Yeganeh et al. (2016)

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Table 4 (continued)

Exposure route	Fish species	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↑	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↓	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	3 mg/kg	↓	Wangkahart et al. (2022)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	0.5 mg/kg	↓	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	1.06, 1.46 mg/kg	↓	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Oreochromis niloticus</i>	0.53, 0.86, 1.04, 1.22 mg/kg	42	–	x	Durigon et al. (2019)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↓	Khalil et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	–	x	Nazari et al., 2017
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	–	x	Hu et al., (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↓	Ashouri et al. (2015)
<b>Albumin</b>						
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↑	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	–	x	Al-Din et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	–	x	Abd El-Kader et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↑	Naiel et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	1, 2 mg/kg	↑↓	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	1.06 mg/kg	↑	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Pangasianodon hypophthalmus</i>	0, 1, 2 mg/kg	60	1, 2 mg/kg	↑	Kumar and Singh (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	–	x	Neamat-Allah et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	–	x	Nazari et al., 2017
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	–	x	Hu et al., (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↓	Ashouri et al. (2015)
<b>Globulin</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	–	x	Al-Din et al. (2022)
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↓	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Dicentrarchus labrax</i>	0, 0.25, 0.5, 1 mg/kg	90	0.25, 0.5, 1 mg/kg	↑	Abd El-Kader et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↑	Naiel et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	–	x	Ziaei-Nejad et al. (2021)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Pangasianodon hypophthalmus</i>	0, 1, 2 mg/kg	60	1, 2 mg/kg	↑	Kumar and Singh (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	0.7 mg/kg	↑	Neamat-Allah et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	1 mg/kg	↓	Nazari et al., 2017
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Pelteobagrus fulvidraco</i>	0, 0.23, 6.5 mg/kg	56	–	x	Hu et al., (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↑	Ashouri et al. (2015)
<b>Total protein</b>						
Dietary	<i>Oreochromis niloticus</i>	0, 0.5, 1 mg/kg	70	–	x	Al-Din et al. (2022)
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↓	Dhara et al. (2022)
	<i>Ctenopharyngodon idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↓	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	1 mg/kg	↑	Ghaniem et al. (2022)
Dietary	<i>Oreochromis niloticus</i>	0, 1, 3, 5 mg/kg	56	–	x	Wangkahart et al. (2022)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	–	x	Jahanbakhshi et al. (2021)
Dietary	<i>Oreochromis niloticus</i>	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	56	0.2, 0.3, 0.4, 0.5, 0.6 mg/kg	↑	Naiel et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	1, 2 mg/kg	↑	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.67, 1.06 mg/kg	↑	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Pangasianodon hypophthalmus</i>	0, 1, 2 mg/kg	60	1, 2 mg/kg	↑	Kumar and Singh (2019)
Dietary	<i>Oreochromis niloticus</i>	0, 0.7 mg/kg	63	0.7 mg/kg	↑	Neamat-Allah et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	–	x	Nazari et al., 2017
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↑	Mansour et al. (2017)
Dietary	<i>Tor putitora</i>	0, 0.68 mg/kg	70	0.68 mg/kg	↑	Khan et al. (2016)

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Table 4 (continued)

Exposure route	Fish species	Exposure concentration	Exposure periods (days)	Response concentration	Response	Reference
Waterborne	<i>Cyprinus carpio</i>	0, 0.054 mg/L	28	0.054 mg/L	↓	Yeganeh et al. (2016)
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	2 mg/kg	↑	Ashouri et al. (2015)
<b>Triglyceride (TG)</b>						
Waterborne	<i>Channa punctata</i>	0, 1.5, 3 mg/L	30	1.5, 3 mg/L	↑	Dhara et al. (2022)
	<i>Ctenopharyngodon Idella</i>	0, 0.798, 1.596 mg/L	30	0.798, 1.596 mg/L	↑	
Dietary	<i>Oreochromis niloticus</i>	0, 1 mg/kg	65	–	x	Ghaniem et al. (2022)
Dietary	<i>Carassius auratus</i>	0, 0.3, 0.6, 0.9 mg/kg	63	–	x	Jahanbakhshi et al. (2021)
Dietary	<i>Acanthopagrus latus</i>	0, 0.5, 1, 2 mg/kg	56	–	x	Ziaei-Nejad et al. (2021)
Dietary	<i>Megalobrama amblycephala</i>	0.10, 0.42, 0.67, 1.06, 1.46 mg/kg	56	0.67 mg/kg	↓	Jingyuan et al. (2020)
Dietary	<i>Rutilus caspicus</i>	0, 1 mg/kg	28	–	x	Zahmatkesh et al. (2020)
Dietary	<i>Pagrus major</i>	0, 0.5, 1, 2 mg/kg	45	1, 2 mg/kg	↓	Dawood et al. (2019)
Dietary	<i>Oreochromis niloticus</i>	0.53, 0.86, 1.04, 1.22 mg/kg	42	–	x	Durigon et al. (2019)
Dietary	<i>Argyrosomus regius</i>	0, 1, 2, 3 mg/kg	63	2, 3 mg/kg	↓	Khalil et al. (2019)
Dietary	<i>Oncorhynchus mykiss</i>	0, 1 mg/kg	60	1 mg/kg	↑	Nazari et al., 2017
Dietary	<i>Cyprinus carpio</i>	0, 0.5, 1, 2 mg/kg	56	–	x	Ashouri et al. (2015)

↑ = increased; ↓ = decreased; x = no changed.

(HPGL) systems in zebrafish, resulting reduction of the percent early vitellogenic oocyte and spermatid in female and male individuals respectively. Berntssen et al. (2018) noted that Se consumption exceeding 5 µg/g diet (dw) in fishes increases the potential for physiological toxicities and reduces overall growth and reproductive fitness. Naiel et al. (2023) reported that treatment with diet containing 1 mg/kg selenium-nanoparticle (SeNP) for 6 months resulted in increased eggs production and frequency of spawning in red tilapia (*Oreochromis* sp.). In contrast, male catfish *Sorubim cuspidus* fed with 2.57 mg/kg Se-Met diet for a period of 14 weeks showed no significant difference in length and weight gain (Hoya-Flórez et al., 2024). Se is a crucial dietary component that significantly impacts the growth and reproduction in fishes, thus understanding the dietary requirements of Se in terms of essentiality and toxicity is very important for sustainable aquaculture practices and maintaining the sustainability of aquatic ecosystems (Sumana et al., 2023).

## 7. Developmental effects of selenium

The early developmental stages of fishes, particularly embryos and larvae, are notably susceptible to pollutants such as heavy metals and metalloids. Consequently, they are widely recognized as significant bio-indicators for evaluating the toxicity of these substances on aquatic organisms (Rahman et al., 2020; Jezierska et al., 2009). Se is an essential trace element and a well-documented teratogen at supra-nutritional levels in oviparous vertebrates, including fishes (Massé et al., 2015; Thomas & Janz, 2014, 2015). Among various endpoints, teratogenicity is considered a crucial indicator of Se toxicity in fishes (Witeska et al., 2014).

Selenium induced developmental toxicity primarily occurs in fishes due to the maternal deposition of Se from the liver into eggs during vitellogenesis, followed by the metabolism of Se from egg albumen or yolk by the embryo and fish larvae. Maternal exposure to Se-Met, the predominant dietary form of Se, results in developmental toxicity in fishes, manifesting as spinal curvatures (lordosis, kyphosis, scoliosis), craniofacial malformations, incidences of edema (yolk sac, pericardial), in developing larvae (Cheng et al., 2022; Mo et al., 2020, 2021; Penglase et al., 2014; Thomas and Janz, 2014). The deposition of protein bound Se-Met in embryos through maternal transfer is subsequently utilized in energy production and/or protein synthesis in the larvae. The gradual release of Se-Met during protein catabolism could potentially delay the onset and progression of Se toxicity in early life stages, resulting in developmental deformities rather than immediate mortality (Thomas and Janz, 2016). Additionally, Se-Met catabolism has been associated with oxidative stress in developing embryos, potentially impacting

embryo hatchability.

Waterborne exposure to Se-Met induces malformations including the absence of fins, pericardial edema, spinal deformities, and defects in cardiovascular and ocular development (Zhao et al., 2022; Janz, 2012). However, several field, and laboratory-based studies have reported that maternal Se transfer results in increased mortality and/or deformities in F1 generation fishes (Thomas and Janz, 2015; Janz et al., 2010). Uddin et al. (2023; unpublished data) found embryonic and larval deformities in zebrafish following waterborne exposure to Se-Met. Additionally, high mortality and/or deformities were observed after microinjection of excess Se-Met in pallid sturgeon (*Scaphirhynchus albus*), shovelnose sturgeon (*Scaphirhynchus platyrhynchus*), and white sturgeon (*Acipenser transmontanus*) (Papoulias et al., 2014; Lin et al., 2021). Mo et al. (2021) found that exposing female zebrafish to selenite resulted in adverse developmental effects on their offspring. On the contrary, zebrafish embryos exposed to waterborne selenite at concentrations of 10–100 µg/L did not show any larval deformities (Uddin et al., 2023; unpublished study). Moreover, waterborne exposure to SeNP in zebrafish embryos at concentrations of 15–25 µg/mL, led to the development of pericardial edema, tail malformation, and decreased heart rate (Kalishwaralal et al., 2016a). It is important to note that larvae are typically more sensitive to Se than embryos since embryos possess protective hard chorion layers and perivitelline fluid that can impede Se entry (Kong et al., 2013; Mhadhbi et al., 2010). Table 5 illustrates Se-induced developmental toxicity in fishes. These developmental deformities in fishes hold ecotoxicological relevance due to their potential to directly impair swimming, feeding, and reproductive capacities, ultimately contributing to the reduction in population size and diversity over time (Lemly, 2002).

## 8. Neurobehavioural effects of selenium

Fish behaviours serve as a critical indicator in eco-toxicology for monitoring water pollution (Brodin et al., 2013). Previous research has demonstrated that various environmental toxicants can significantly alter behaviours of fishes, affecting their learning and memory functions, exploration tendencies, predator-prey interactions, swimming abilities, and overall activity levels (Hong and Zha, 2019; Sandoval-Herrera et al., 2019). These behavioural changes are closely linked to growth, reproduction, and population dynamics in fishes (Jacquin et al., 2020). However, it is essential to understand that changes in behaviours at individual levels can have long-term adverse effects on population and community structures, potentially increasing their susceptibility to extinction (Ward et al., 2017, 2020).

Although Se has neuroprotective properties, high concentrations can

**Table 5**  
Effect of selenium on embryonic and larval development of fishes.

Fish species	Exposure concentration	Exposure periods (days)	Response concentration	Phenotypic alterations	Reference
<i>Danio rerio</i>	0, 12.5, 25, 50, 100 µg/L	120	100 µg/L	ROS levels & apoptotic cells increased	Cheng et al. (2023)
<i>Danio rerio</i>	0, 12.5, 25, 50, 100 µg/L	120	100 µg/L	increased mortality, elevated malformation rate, reduced body length	Cheng et al. (2022)
<i>Danio rerio</i>	0, 0.25, 0.5, 1, 2 µM	4	0.5, 1, 2 µM	lower hatching rate, high mortality & deformities	Zhao et al. (2022)
<i>Danio rerio</i>	0.15, 0.2, 0.3, 0.4 mg/L	5	0.2, 0.3, 0.4 mg/L	delayed hatchability with pericardial edema and tail malformation	Vaishnavi et al. (2019)
<i>Pimephales promelas</i>	30, 90, 270, 810, 2430, 7290, 21,870, 65,610 µg/L	6	810, 2430, 7290, 21870, 65610 µg/L	reduced hatchability and survival, increased severity of deformities	Gerhart et al. (2019)
<i>Oryzias latipes</i>	0, 10, 20 µg/g	7	20 µg/g	pericardial edema and craniofacial changes	Shi et al. (2018)
<i>Danio rerio</i>	0, 8, 16, 32 µg/g	6	16, 32 µg/g	increased deformities, mortality, decreased hatchability	Thomas and Janz (2016)
<i>Danio rerio</i>	0, 10 µg/g	57	10 µg/g	reduced fitness, survivability, lower hatching rate	Raine et al. (2016)
<i>Oryzias latipes</i>	0, 0.5, 5, 50 µM	1	5, 50 Mm	significantly reduced larval survival and hatching rate	Kupsco and Schlenk (2016)
<i>Oryzias latipes</i>	0, 12.5, 25, 50 µg/g	6	12.5, 25, 50 µg/g	lower hatching success with high mortality	Chernick et al. (2016)
<i>Danio rerio</i>	0, 5, 25 µg/mL	1	5, 25 µg/mL	increased mortality, pericardial edema, cardiac arrhythmia	Kalishwaralal et al. (2016b)
<i>Oncorhynchus mykiss</i>	0, 0.5, 1.2 mg/kg	72	–	no significant difference in hatching and mortality	Dicharry et al., (2015)
<i>Danio rerio</i>	0, 3.4, 9.8, 27.5 µg/g	90	9.8, 27.5 µg/g	increased mortality & deformities	Thomas and Janz (2015)

cause neuronal damage and neurotoxicity (Naderi et al., 2017a). The primary mechanism of Se-induced neurotoxicity is its ability to increase ROS production, leading to oxidative stress, which can adversely affect the brain and central nervous system (CNS) (Ellwanger et al., 2016). Given the brain's high oxygen consumption and lipid-rich composition, it is particularly vulnerable to oxidative stress, which can disrupt various neural signaling pathways and thereby alter fish behaviours (Salim, 2017).

Neurotoxicity of Se can manifest through alterations in monoamine neurotransmitter systems, such as dopamine and serotonin, which are crucial for regulating social behaviour, anxiety, stress responses, and learning and memory functions in vertebrates (Naderi et al., 2017a; Vinceti et al., 2014). For example, adult zebrafish (*Danio rerio*) exposed to environmentally relevant concentrations of Se-Met (3.6–34.1 µg/g dw) for 90 days exhibited dysregulations in serotonergic systems in the brain, which was associated with impairments in social learning, reduced group preference, and increased anxiety-like behaviours, mainly in the highest treatment group (Attaran et al., 2020). Interestingly, offspring of female zebrafish treated with dietary Se (34.1 µg/g dw) also demonstrated similar behavioural impairments and disruption of serotonergic signaling in the brain (Attaran et al., 2021). In addition, Attaran et al. (2019) reported that chronic dietary exposure to Se-Met at a concentration of 31.5 µg/g dw for 60 days resulted in disruption of serotonergic neurotransmission, and impaired antipredator and social behaviours in zebrafish. Furthermore, adult zebrafish chronically exposed to different concentrations of dietary Se (0, 3.5, 11.1, 27.4, 63.4 µg/g) showed impaired latent learning performance and associative learning behaviour, which were likely mediated by the alterations in the dopaminergic neurotransmission in the brain (Naderi et al., 2017, 2018b). Interestingly, chronic maternal (60 days) exposure to dietary Se was also reported to alter the latent learning performance in adult zebrafish offspring likely via the dysregulation of the dopaminergic system (Naderi et al., 2018a). These studies indicate that environmentally relevant exposure to dietary Se can adversely affect the cognitive and social behaviours in fishes and these effects can be transmitted intergenerationally affecting the next generation even without direct exposure to elevated Se. It is important to note though that behavioural effects of Se can be dependent of species tested and exposure dose. For example, fathead minnows (*Pimephales promelas*) fed with diets containing Se (2.9–6.8 µg/g wet weight) for 70 days did not show any significant alterations in their escape responses - a routine behaviour

critical to predator-prey interactions (Anderson et al., 2019).

Direct waterborne exposure to elevated Se can also cause adverse neurobehavioural effects in embryonic and larval fish. For example, Uddin et al. (2023; unpublished data) found that zebrafish embryos at 1-h post-fertilization (hpf) exposed to Se-Met at concentrations of 5 µg/L and 10 µg/L exhibited impaired light-dark preference, following dysregulation of key genes in the dopaminergic and serotonergic pathways. Additionally, 1 hpf zebrafish embryos exposed to selenite at environmentally relevant concentrations (0, 10, 50, 100 µg/L) for 30 days showed reflexive movement impairment at 5 days post-fertilization (dpf), thigmotactic disruption at 15 dpf, social preference interruption at 21 dpf, and reduced novel object recognition ratio at 30 dpf (Uddin et al., 2023; unpublished data). Social preference behaviour is crucial for obtaining updated information about the habitat, which directly relates to fish fitness, as it plays a vital role in foraging, mating, territorial defense, and predator avoidance (Hoppitt and Laland, 2013). Scototaxis and thigmotaxis are well established index of anxiety like behaviours in fishes (Maximino et al., 2010). Various behavioural effects in fishes exposed to elevated Se are summarized in Table 6.

Brain acetylcholinesterase (AChE) activity serves as a notable biomarker of neurotoxicity, essential for the deactivation of acetylcholine at nerve endings and the proper functioning of sensory and neuromuscular systems (Song et al., 2006), thus playing a pivotal role in locomotion (Drever et al., 2011). Locomotor activity, a fundamental behaviour, is integral to various fitness-related functions such as feeding, social interactions, reproduction, and responses to predation threats. Consequently, alterations in locomotor activity induced by toxicants can negatively impact fitness (Salahinejad et al., 2023). Moreover, fishes with impaired locomotor activity may struggle to effectively respond to challenges in aquaculture environments (José et al., 2007). Hariharan et al. (2024) observed that zebrafish larvae exposed to SeNp at concentrations ranging from 0 to 0.6 µg/mL and selenite at concentrations from 0 to 10 µg/mL for 6 days exhibited reduced locomotor activity and increased anxiety levels, although these concentrations are not environmentally relevant. Thomas and Janz (2011) reported a significant reduction in critical swimming speed in adult zebrafish following a 60-day dietary exposure to environmentally relevant concentrations of Se (3.7, 9.6, and 26.6 µg/g dw). Li et al. (2021) found that two-month-old zebrafish exposed to environmentally relevant concentrations of Se exhibited disruptions in dopamine, serotonin, and acetylcholine signaling pathways, accompanied by altered

**Table 6**  
Summary of studies on effects of selenium on various behaviours of fishes.

Selenium species	Fish species	Developmental stages	Exposure concentration	Exposure period (days)	Environmentally relevant study	Behaviour affected	Effect direction	Reference
Selenite	<i>Danio rerio</i>	larvae	0, 0.2, 0.4, 0.6 µg/mL	6	no	Light preference locomotion	↓	Hariharan et al. (2024)
SeNp	<i>Danio rerio</i>	larvae	0, 1, 5, 10 µg/mL	6	no	Anxiety	↑	Hariharan et al. (2024)
						Light preference locomotion	↓	
SeMet	<i>Danio rerio</i>	adult	0, 3.6, 12.8, 34.1 µg/g	90	yes	Anxiety	↑	Attaran et al. (2021)
						Group preference	↓	
SeMet	<i>Danio rerio</i>	adult	0, 3.6, 12.8, 34.1 µg/g	90	yes	Social learning preference	↓	Attaran et al. (2020)
Ph <sub>2</sub> Se <sub>2</sub>	<i>Ctenopharyngodon</i>	juvenile	0, 3 mg/kg	30	no	locomotion	x	Baldissera et al. (2020)
Ph <sub>2</sub> Se <sub>2</sub>	<i>Danio rerio</i>	adult	0, 0.1, 0.25, 0.5, 1, 2 Mm	30	no	locomotion	x	Ferreira et al. (2019)
						thigmotaxis	↓	
SeMet	<i>Danio rerio</i>	adult	2.1, 11.6, 31.5 µg/g	60	yes	Fear response	↓	Attaran et al. (2019)
						Group preference	↓	
SeMet	<i>Danio rerio</i>	adult	0, 3.5, 11.1, 27.4 µg/g	60	yes	Latent learning performance	↓	Naderi et al. (2018a)
SeMet	<i>Danio rerio</i>	adult	0, 2.3, 9.7, 32.5, 57.7 µg/g	30	no	Latent learning performance	↓	Nazari et al., 2017
SeMet	<i>Danio rerio</i>	adult	0, 3.5, 11.1, 27.4, 63.4 µg/g	60	no	Associated learning performance	↓	Naderi et al. (2018b)

SeMet: Selenomethionine; SeNp: Selenium-nano particle; Ph<sub>2</sub>Se<sub>2</sub>: Diphenyl diselenide; ↑ = increased; ↓ = decreased; x = no changed.

locomotor activity and novel area preference. Similarly, 20-day post-hatch fathead minnows exposed to various concentrations of Se in the form of Se-Met in their diet for 60 days exhibited reduced swimming speeds (McPhee and Janz, 2014). Additionally, zebrafish (*Danio rerio*) embryos exposed to a 0.5 µM concentration of Se from 1 hpf to 96 hpf exhibited decreased swimming speed and distance, as well as a diminished touch response (Zhao et al., 2022). Adult zebrafish showed alterations in their repeated swimming performance upon exposure to different concentrations of Se (1.3, 3.4, 9.8 or 27.5 µg/g dw) through diet for 90 days (Thomas et al., 2013). Notably, a significant reduction in AChE activity is commonly observed in fishes exposed to Se (Modesto and Marinez, 2010), and the accumulation of acetylcholine resulting from AChE inhibition may influence fleeing and reproductive behaviour in fishes (Bretaud et al., 2000).

## 9. Conclusions and future directions

Selenium is an essential micronutrient to aquatic organisms but poses significant risks to aquatic ecosystems when present above threshold levels. This review examined the diverse detrimental effects of Se in fishes, including metabolic effects, reproductive failures and teratogenicity, and neurobehavioural impairments. Bioaccumulation of Se emerges as a pivotal indicator for monitoring its geochemical cycling within aquatic environments. Regardless of exposure routes, be it through diet or waterborne sources, fishes exhibit the highest Se accumulation in their kidney, liver, and gonads. Maternal transfer of Se from the liver to eggs during vitellogenesis induces developmental toxicity, leading to spinal curvatures, craniofacial malformations, and incidences of edema in the offspring. Moreover, Se disrupts different metabolic markers of fishes, impacting oxygen carrying capacity and overall immunity. Oxidative stress ensues from Se accumulation, attributed to the generation of ROS. To counteract oxidative damage, fishes activate antioxidant responses involving SOD, CAT, GST, GPX. Additionally, Se alters behaviours by perturbing neurotransmitter systems, including dopamine and serotonin, and inhibiting AChE, leading to behavioural and cognitive disorders. In summary, Se exposure in fishes results in a spectrum of toxicities encompassing bioaccumulation, reproductive toxicity, teratogenicity, alterations of metabolic and oxidative stress markers, and neuro-behavioural toxicity, underscoring the importance

of understanding its impacts on aquatic ecosystems.

Despite significant advancements in understanding Se toxicity in fishes, critical gaps remain in the existing literature. Many studies use Se exposure concentrations that are not environmentally relevant, failing to reflect real-world scenarios in aquatic environments. Additionally, research often relies on model organisms to establish toxicity thresholds, which may not apply to other species due to the species-specific nature of the essentiality and toxicity of Se. The uptake and depuration of Se in fishes are highly species-specific and depend on their diet and feeding habits. Therefore, a single toxicity threshold cannot sufficiently protect all fish species. Moreover, the essentiality and toxicity thresholds vary among freshwater, brackish water, and marine fishes. Furthermore, most studies focus on early developmental stages and reproductive toxicity, neglecting the fact that nutritional requirements and sensitivity to Se can vary significantly across different developmental stages of fishes. Additionally, the speciation of Se needs to be accounted for in toxicity thresholds for aquatic life, as organic Se is significantly more toxic than inorganic Se. In most studies, the no observed effect concentration (NOEC) and low observed effect concentration (LOEC) of Se have been determined based solely on developmental endpoints in fishes, often neglecting behavioural endpoints. Recent research, however, indicates that even lower concentrations of Se can significantly alter behavioural endpoints without affecting developmental endpoints. Moreover, dietary exposure studies typically involve spiking commercial diets with Se, which does not accurately represent natural environmental conditions. The USEPA has established chronic Se water quality criteria values for the protection of aquatic organisms, which are 1.5 µg/L for lentic and 3.1 µg/L for lotic water environment. In contrast, the CCME has set a more stringent guideline for the protection of aquatic life, with a threshold of 1 µg Se/L for freshwater, while no specific guideline exists for saltwater. However, due to anthropogenic activities, Se concentrations in the environment frequently exceed these established guidelines, posing a significant threat to aquatic ecosystems.

To address these limitations, we propose the following future research directions—future studies should reflect realistic environmental conditions to better understand Se-induced toxicity in fishes; research should determine essential and toxicity thresholds for fishes on a species-specific basis, independent of their taxonomic relationships; conduct studies across different life stages of fishes, including larvae, fry,



juveniles, and adults, to identify potential Se toxicity thresholds; design experiments that better mimic natural conditions by exposing different prey organisms, such as black worms, to Se and subsequently feeding these to fishes; develop tissue-based toxicity thresholds of Se for fishes to safeguard the health and well-being of aquatic organisms. Behavioural end points should be taken into consideration during revising national water quality guidelines. All environmental biologist and toxicologist should move together to enhance the ecological relevance and accuracy of future research on Se toxicity in fishes, ultimately contributing to the conservation and management of aquatic ecosystems.

### CRedit authorship contribution statement

**Md Helal Uddin:** Writing – original draft, Resources, Investigation, Data curation, Conceptualization. **Jinnath Rehana Ritu:** Writing – review & editing, Conceptualization. **Sravan Kumar Putnala:** Writing – review & editing. **Mahesh Rachamalla:** Writing – review & editing. **Douglas P. Chivers:** Writing – review & editing, Supervision. **Som Niyogi:** Writing – review & editing, Supervision.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: MD HELAL UDDIN reports was provided by University of Saskatchewan. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

No data was used for the research described in the article.

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### References

- Abd El-Kader, M.F., Fath El-Bab, A.F., Abd-Elghany, M.F., Abdel-Warith, A.W.A., Younis, E.M., Dawood, M.A.O., 2021. Selenium nanoparticles act potentially on the growth performance, hemato-biochemical indices, antioxidative, and immune-related genes of European Seabass (*Dicentrarchus labrax*). *Biol. Trace Elem. Res.* 199, 3126–3134. <https://doi.org/10.1007/s12011-020-02431-1>.
- Abdel-Tawwab, M., 2016. Effect of feed availability on susceptibility of Nile tilapia, (*Oreochromis niloticus*) (L.) to environmental zinc toxicity: growth performance, biochemical response, and zinc bioaccumulation. *Aquaculture* 464, 309–315. <https://doi.org/10.1016/j.aquaculture.2016.07.009>.
- Abdel-Tawwab, M., Mousa, M.A., Abbass, F.E., 2007. Growth performance and physiological response of African catfish, *Clarias gariepinus* (B.) fed organic selenium prior to the exposure to environmental copper toxicity. *Aquaculture* 272, 335–345. <https://doi.org/10.1016/j.aquaculture.2007.09.004>.
- Abdollahi-Mousavi, S.E., Keyvanshokoo, S., Torfi Mozanzadeh, M., Ghasemi, A., 2024. Efficacy of nutritional selenium nanoparticles on growth performance, immune response, antioxidant capacity, expression of growth and immune-related genes, and post-stress recovery in juvenile Sobaita seabream (*Sparidentex hasta*). *Fish Shellfish Immunol.* 147, 109452 <https://doi.org/10.1016/j.fsi.2024.109452>.
- Acosta-Lizárraga, L.G., Bergés-Tiznado, M.E., Bojórquez-Sánchez, C., Osuna-Martínez, C., Páez-Osuna, F., 2020. Bioaccumulation of mercury and selenium in tissues of the mesopelagic fish Pacific hake (*Merluccius productus*) from the northern Gulf of California and the risk assessment on human health. *Chemosphere* 255, 126941. <https://doi.org/10.1016/j.chemosphere.2020.126941>.
- Al-Din, A.S., Ibrahim, S., Omar, A., Refaey, M., 2022. Growth, feed efficiency, hemato-biochemical indices, and flesh quality of adult Nile tilapia, *Oreochromis niloticus*, fed a diet supplemented with nano-selenium. *Egypt. J. Aquat. Biol. Fish.* 26, 653–676. <https://doi.org/10.21608/EJABF.2022.275456>.
- Anderson, P.J., Mitchell, M.D., Fedoroff, K.J., Chivers, D.P., Ferrari, M.C., 2019. The effects of selenomethionine on the escape behaviours of fathead minnows. *Arch. Environ. Contam. Toxicol.* 77, 62–67. <https://doi.org/10.1007/s00244-019-00604-1>.
- Aramli, M.S., Moghanlou, K.S., Imani, A., 2023. Effect of dietary antioxidant supplements (selenium forms, alpha-tocopherol, and coenzyme Q10) on growth performance, immunity, and physiological responses in rainbow trout (*Oncorhynchus mykiss*) using orthogonal array design. *Fish Shellfish Immunol.* 134, 108615 <https://doi.org/10.1016/j.fsi.2023.108615>.
- Arulkumar, A., Paramasivam, S., Rajaram, R., 2017. Toxic heavy metals in commercially important food fishes collected from Palk Bay, Southeastern India. *Mar. Pollut. Bull.* 119, 454–459. <https://doi.org/10.1016/j.marpolbul.2017.03.045>.
- Ashouri, S., Keyvanshokoo, S., Salati, A.P., Johari, S.A., Pasha-Zanoosi, H., 2015. Effects of different levels of dietary selenium nanoparticles on growth performance, muscle composition, blood biochemical profiles and antioxidant status of common carp (*Cyprinus carpio*). *Aquaculture* 446, 25–29. <https://doi.org/10.1016/j.aquaculture.2015.04.021>.
- Ates, B., Orun, I., Talas, Z.S., Durmaz, G., Yilmaz, I., 2008. Effects of sodium selenite on some biochemical and hematological parameters of rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) exposed to Pb<sup>2+</sup> and Cu<sup>2+</sup>. *Fish Physiol. Biochem.* 34, 53–59. <https://doi.org/10.1007/s10695-007-9146-5>.
- Attaran, A., Salahinejad, A., Crane, A.L., Niyogi, S., Chivers, D.P., 2019. Chronic exposure to dietary selenomethionine nanoparticles on growth performance, muscle composition, serotoninergic neurotransmission and alters social and antipredator behaviours in zebrafish (*Danio rerio*). *Environ. Pollut.* 246, 837–844. <https://doi.org/10.1016/j.envpol.2018.12.090>.
- Attaran, A., Salahinejad, A., Naderi, M., Crane, A.L., Chivers, D.P., Niyogi, S., 2021. Transgenerational effects of selenomethionine on behaviour, social cognition, and the expression of genes in the serotoninergic pathway in zebrafish. *Environ. Pollut.* 286, 117289 <https://doi.org/10.1016/j.envpol.2021.117289>.
- Attaran, A., Salahinejad, A., Naderi, M., Crane, A.L., Niyogi, S., Chivers, D.P., 2020. Effects of chronic exposure to selenomethionine on social learning outcomes in zebrafish (*Danio rerio*): serotoninergic dysregulation and oxidative stress in the brain. *Chemosphere* 247, 125898. <https://doi.org/10.1016/j.chemosphere.2020.125898>.
- Avigliano, E., Maichak de Carvalho, B., Invernizzi, R., Olmedo, M., Jasan, R., Volpedo, A.V., 2019. Arsenic, selenium, and metals in a commercial and vulnerable fish from southwestern Atlantic estuaries: distribution in water and tissues and public health risk assessment. *Environ. Sci. Pollut. Res.* 26, 7994–8006. <https://doi.org/10.1007/s11356-019-04258-3>.
- Bai, Z., Ren, T., Han, Y., Hu, Y., Schohel, M.R., Jiang, Z., 2019a. Effect of dietary biofermented selenium on growth performance, nonspecific immune enzyme, proximate composition and bioaccumulation of zebrafish (*Danio rerio*). *Aquac. Rep.* 13, 100180 <https://doi.org/10.1016/j.aqrep.2019.100180>.
- Bai, Z., Ren, T., Han, Y., Rahman, M.M., Hu, Y., Li, Z., Jiang, Z., 2019b. Influences of dietary selenomethionine exposure on tissue accumulation, blood biochemical profiles, gene expression and intestinal microbiota of *Carassius auratus*. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 218, 21–29. <https://doi.org/10.1016/j.cbpc.2018.12.001>.
- Bajaj, M., Eiche, E., Neumann, T., Winter, J., Gallert, C., 2011. Hazardous concentrations of selenium in soil and groundwater in North-West India. *J. Hazard Mater.* 189, 640–646. <https://doi.org/10.1016/j.jhazmat.2011.01.086>.
- Baldissera, M.D., Souza, C.F., da Silva, A.S., Henn, A.S., Flores, E.M.M., Baldisserotto, B., 2020. Diphenyl diselenide dietary supplementation alleviates behavior impairment and brain damage in grass carp (*Ctenopharyngodon idella*) exposed to methylmercury chloride. *Biochem. Physiol. C Toxicol. Pharmacol.* 229, 108674 <https://doi.org/10.1016/j.cbpc.2019.108674>.
- Bergés-Tiznado, M.E., Fernando Márquez-Farías, J., Cristina Osuna-Martínez, C., Torres-Rojas, Y.E., Galván-Magaña, F., Páez-Osuna, F., 2019. Patterns of mercury and selenium in tissues and stomach contents of the dolphinfish *Coryphaena hippurus* from the SE Gulf of California, Mexico: concentrations, biomagnification and dietary intake. *Mar. Pollut. Bull.* 138, 84–92. <https://doi.org/10.1016/j.marpolbul.2018.11.023>.
- Bergés-Tiznado, M.E., Fernando Márquez-Farías, J., Torres-Rojas, Y., Galván-Magaña, F., Páez-Osuna, F., 2015. Mercury and selenium in tissues and stomach contents of the migratory sailfin, *Istiophorus platypterus*, from the Eastern Pacific: concentration, biomagnification, and dietary intake. *Mar. Pollut. Bull.* 101, 349–358. <https://doi.org/10.1016/j.marpolbul.2015.10.021>.
- Berntssen, M.H., Betancor, M., Caballero, M.J., Hillestad, M., Rasinger, J., Hamre, K., Sele, V., Amlund, H., Ørnsrud, R., 2018. Safe limits of selenomethionine and selenite supplementation to plant-based Atlantic salmon feeds. *Aquaculture* 495, 617–630. <https://doi.org/10.1016/j.aquaculture.2018.06.041>.
- Besser, J.M., Canfield, T.J., La Point, T.W., 1993. Bioaccumulation of organic and inorganic selenium in a laboratory food chain. *Environ. Toxicol. Chem.* 12, 57–72. <https://doi.org/10.1002/etc.5620120108>.
- Bitiren, M., Karakılıç, A.Z., Zerim, M., Aksoy, N., Musa, D., 2004. Effects of selenium on histopathological and enzymatic changes in experimental liver injury of rats. *Exp. Toxicol. Pathol.* 56, 59–64. <https://doi.org/10.1016/j.etp.2004.05.001>.
- Bosch, A.C., O'Neill, B., Sigge, G.O., Kerwath, S.E., Hoffman, L.C., 2016. Mercury accumulation in Yellowfin tuna (*Thunnus albacares*) with regards to muscle type, muscle position and fish size. *Food Chem.* 190, 351–356. <https://doi.org/10.1016/j.foodchem.2015.05.109>.
- Brandt, J.E., Bernhardt, E.S., Dwyer, G.S., Giulio, R.T.D., 2017. Selenium ecotoxicology in freshwater lakes receiving coal combustion residual effluents: a North Carolina example. *Environ. Sci. Technol.* 51, 2418–2426. <https://doi.org/10.1021/acs.est.6b05353>.
- Brethead, S., Toutant, J.P., Saglio, P., 2000. Effects of carbofuran, diuron and nicosulfuron on acetylcholinesterase activity in goldfish (*Carassius auratus*). *Ecotoxicol. Environ. Saf.* 47, 117–124. <https://doi.org/10.1006/eesa.2000.1954>.

- Brix, K.V., DeForest, D.K., Fairbrother, A., Adams, W.J., 2000. Critical review of tissue-based selenium toxicity thresholds for fish and birds. *British Columbia Mine Reclamation Symposium*. <https://doi.org/10.14288/1.0302701>.
- Brodin, T., Fick, J., Jonsson, M., Klaminder, J., 2013. Dilute concentrations of a psychiatric drug alter behavior of fish from natural populations. *Science* 339, 814–815. <https://doi.org/10.1126/science.1226850>.
- CCME, 2016. *Canadian Water Quality Guidelines for the Protection of Aquatic Life: Selenium*. Canadian Council of Ministers of the Environment, Winnipeg.
- Chapman, P.M., Adams, W.J., Brooks, M.L., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., Shaw, D.P. (Eds.), 2010. *Ecological Assessment of Selenium in the Aquatic Environment*, vol. 339. CRC Press, Boca Raton, FL. ISBN: 9781439826775.
- Chen, H., Li, J., Yan, L., Cao, J., Li, D., Huang, G.Y., Shi, W.J., Dong, W., Zha, J., Ying, G., Zhong, H., Wang, Z., Huang, Y., Luo, Y., Xie, L., 2020. Sub-chronic effects of dietary selenium yeast and selenite on growth performance and the immune and antioxidant systems in Nile tilapia *Oreochromis niloticus*. *Fish Shellfish Immunol.* 97, 283–293. <https://doi.org/10.1016/j.fsi.2019.12.053>.
- Cheng, R., Zhang, J., He, Y., Liao, C., Wang, L., Zhang, X., 2022. Parental exposure to waterborne selenite induces transgenerational developmental toxicity in zebrafish offspring. *Chemosphere* 303, 134838. <https://doi.org/10.1016/j.chemosphere.2022.134838>.
- Cheng, R., Zhang, Z., Zhan, C., Qin, T., Wang, L., Zhang, X., 2023. Environmentally relevant concentrations of selenite trigger reproductive toxicity by affecting oocyte development and promoting larval apoptosis. *Environ. Pollut.* 316, 120648. <https://doi.org/10.1016/j.envpol.2022.120648>.
- Chernick, M., Ware, M., Albright, E., Kwok, K.W.H., Dong, W., Zheng, N., Hinton, D.E., 2016. Parental dietary seleno-L-methionine exposure and resultant offspring developmental toxicity. *Aquat. Toxicol.* 170, 187–198. <https://doi.org/10.1016/j.aquatox.2015.11.004>.
- Choi, Y.J., Yang, S.G., Jung, M.M., Kim, B.S., Yun, S.G., Choi, C.Y., 2015. Effects of waterborne selenium on toxic and physiological stress response in goldfish, *Carassius auratus*. *Mol. Cell. Toxicol.* 11, 35–46. <https://doi.org/10.1007/s13273-015-0005-7>.
- Dawood, M.A.O., Koshio, S., Zaineldin, A.I., Doan, H.V., Ahmed, H.A., Elsbagh, M., Abdel-Daim, M.M., 2019. An evaluation of dietary selenium nanoparticles for red sea bream (*Pagrus major*) aquaculture: growth, tissue bioaccumulation, and antioxidant responses. *Environ. Sci. Pollut. Res.* 26, 30876–30884. <https://doi.org/10.1007/s11356-019-06223-6>.
- De Azevedo, R.V., De Oliveira, K.F., Flores-Lopes, F., Teixeira-Lanna, E.A., Takishita, S., Tavares-Braga, L.G., 2015. Responses of Nile tilapia to different levels of water salinity. *Lat. Am. J. Aquat. Res.* 43, 828–835. <https://doi.org/10.3856/vol43-issue5-fulltext-3>.
- Dhara, K., Chukwuka, A.V., Saha, S., Saha, N.C., Faggio, C., 2022. Effects of short-term selenium exposure on respiratory activity and proximate body composition of early-life stages of *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*. *Environ. Toxicol. Pharmacol.* 90, 103805. <https://doi.org/10.1016/j.etap.2021.103805>.
- Dragun, Z., Tepić, N., Ramani, S., Krasnić, N., Filipović Marijić, V., Valić, D., Kapetanović, D., Erk, M., Rebok, K., Kostov, V., Jordanova, M., 2019. Mining waste as a cause of increased bioaccumulation of highly toxic metals in liver and gills of Vardar chub (*Squalius vardarensis* Karaman, 1928). *Environ. Pollut.* 247, 564–576. <https://doi.org/10.1016/j.envpol.2019.01.068>.
- Drever, B.D., Riedel, G., Platt, B., 2011. The cholinergic system and hippocampal plasticity. *Behav. Brain Res.* 221, 505–514. <https://doi.org/10.1016/j.bbr.2010.11.037>.
- Durigon, E.G., Kunz, D.F., Peixoto, N.C., Uczay, J., Lazzari, R., 2019. Diet selenium improves the antioxidant defense system of juveniles Nile tilapia (*Oreochromis niloticus* L.). *Braz. J. Biol.* 79, 527–532. <https://doi.org/10.1590/1519-6984.187760>.
- Ellwanger, J.H., Franke, S.I., Bordin, D.L., Pra, D., Henriques, J.A., 2016. Biological functions of selenium and its potential influence on Parkinson's disease. *An. Acad. Bras. Cienc.* 88, 1655e1674. <https://doi.org/10.1590/0001-3765201620150595>.
- El-Sharawy, M.E., Hamouda, M., Soliman, A.A., Amer, A.A., El-Zayat, A.M., Sewilam, H., Younis, E.M., Abdel-Warith, A.W.A., Dawood, M.A.O., 2021. Selenium nanoparticles are required for the optimum growth behavior, antioxidative capacity, and liver wellbeing of striped catfish (*Pangasianodon hypophthalmus*). *Saudi J. Biol. Sci.* 28, 7241–7247. <https://doi.org/10.1016/j.sjbs.2021.08.023>.
- Emon, F.J., Rohani, M.F., Sumaiya, N., Tuj Jannat, M.F., Akter, Y., Shahjahan, M., Abdul Kari, Z., Tahluddin, A.B., Goh, K.W., 2023. Bioaccumulation and bioremediation of heavy metals in fishes-A review. *Toxics* 11, 510. <https://doi.org/10.3390/toxics11060510>.
- Etim, E.U., 2017. Occurrence and distribution of arsenic, antimony and selenium in shallow groundwater systems of Ibadan metropolis, southwestern Nigerian. *J. Heal. Pollut.* 7, 32–41. <https://doi.org/10.5696/2156-9614-7-13.32>.
- Ferreira, L.M., da Rosa, L.V.C., Müller, T.E., de Menezes, C.C., Marcondes Sari, M.H., Loro, V.L., Nogueira, C.W., Rosemberg, D.B., Cruz, L., 2019. Zebrafish exposure to diphenyl diselenide-loaded polymeric nanoparticles caused no behavioral impairments and brain oxidative stress. *J. Trace Elem. Med. Biol.* 5, 62–68. <https://doi.org/10.1016/j.jtemb.2019.02.005>.
- Fiúza, L.S., Aragão, N.M., Ribeiro, J.H.P., de Moraes, M.G., Rocha, Í.R.C.B., Lustosa Neto, A.D., de Sousa, R.R., Madrid, R.M.M., de Oliveira, E.G., Costa, F.H.F., 2015. Effects of salinity on the growth, survival, haematological parameters and osmoregulation of tambaqui *Colossoma macropomum* juveniles. *Aquacult. Res.* 46, 1–9. <https://doi.org/10.1111/are.12224>.
- Garnero, P.L., Monferran, M.V., González, G.A., Griboff, J., de los Angeles, B.M., 2018. Assessment of exposure to metals, as and Se in water and sediment of a freshwater reservoir and their bioaccumulation in fish species of different feeding and habitat preferences. *Ecotoxicol. Environ. Saf.* 163, 492–501. <https://doi.org/10.1016/j.ecoenv.2018.07.023>.
- Gerhart, A.K., Hecker, M., Janz, D.M., 2019. Toxicity of aqueous l-selenomethionine exposure to early life-stages of the Fathead Minnow (*Pimephales promelas*). *Bull. Environ. Contam. Toxicol.* 102, 323–328. <https://doi.org/10.1007/s00128-018-02537-2>.
- Ghaniem, S., Nassef, E., Zaineldin, A.I., Bakr, A., Hegazi, S., 2022. A Comparison of the beneficial effects of inorganic, organic, and elemental nano-selenium on Nile Tilapia: growth, immunity, oxidative status, gut morphology, and immune gene expression. *Biol. Trace Elem. Res.* 200, 5226–5241. <https://doi.org/10.1007/s12011-021-03075-5>.
- Gobi, N., Vaseeharan, B., Rekha, R., Vijayakumar, S., Faggio, C., 2018. Bioaccumulation, cytotoxicity and oxidative stress of the acute exposure selenium in *Oreochromis mossambicus*. *Ecotoxicol. Environ. Saf.* 162, 147–159. <https://doi.org/10.1016/j.ecoenv.2018.06.070>.
- Gopi, N., Rekha, R., Vijayakumar, S., Liu, G., Monserrat, J.M., Faggio, C., Nor, S.A.M., Vaseeharan, B., 2021. Interactive effects of freshwater acidification and selenium pollution on biochemical changes and neurotoxicity in *Oreochromis mossambicus*. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 250, 109161. <https://doi.org/10.1016/j.cbpc.2021.109161>.
- Hamed, H.S., 2015. Impact of a short-term malathion exposure of Nile Tilapia, (*Oreochromis niloticus*): the protective role of selenium. *Inter. J. Environ. Monit. Assess.* 3, 30–37. <https://doi.org/10.11648/j.ijema.s.2015030501.15>.
- Hamilton, S.J., 2004. Review of selenium toxicity in the aquatic food chain. *Sci. Total Environ.* 326, 1–31. <https://doi.org/10.1016/j.scitotenv.2004.01.019>.
- Haque, M.M., Al Attas, H.A., Hassan, M.A., 2016. Health risk assessment of trace elements in drinking water from Najran City, southwestern Saudi Arabia. *Arabian J. Geosci.* 9, 1–12. <https://doi.org/10.1007/s12517-016-2501-z>.
- Hariharan, S., Chauhan, S., Marcharla, E., Alphonse, C.R.W., Rajaretnam, R.K., Ganesan, S., 2024. Developmental toxicity and neurobehavioral effects of sodium selenite and selenium nanoparticles on zebrafish embryos. *Aquat. Toxicol.* 266, 106791. <https://doi.org/10.1016/j.aquatox.2023.106791>.
- Hermanutz, R.O., Allen, K.N., Roush, T.H., Hedtke, S.F., 1992. Effects of elevated selenium concentrations on bluegills (*Lepomis macrochirus*) in outdoor experimental streams. *Environ. Toxicol. Chem.* 11, 217–224. <https://doi.org/10.1002/etc.5620110211>.
- Hilton, J.W., Hodson, P.V., Slinger, S.J., 1980. The requirement and toxicity of selenium in rainbow trout (*Salmo gairdneri*). *J. Nutr.* 110, 2527–2535. <https://doi.org/10.1093/jn/110.12.2527>.
- Hodson, P.V., Hilton, J.W., 1983. The nutritional requirements and toxicity to fish of dietary and waterborne selenium. *Ecol. Bull.* 35, 335–340. <https://www.jstor.org/stable/20112868>.
- Holm, J., Palace, V., Siwik, P., Sterling, G., Evans, R., Baron, C., Werner, J., Wautier, K., 2005. Developmental effects of bioaccumulated selenium in eggs and larvae of two salmonid species. *Environ. Toxicol. Chem.* 24, 2373–2381. <https://doi.org/10.1897/04-402R1.1>.
- Hong, X., Zha, J., 2019. Fish behavior: a promising model for aquatic toxicology research. *Sci. Total Environ.* 686, 311–321. <https://doi.org/10.1016/j.scitotenv.2019.06.028>.
- Hoppitt, W., Laland, K.N., 2013. *Social Learning: an Introduction to Mechanisms, Methods, and Models*. Princeton University Press. <https://doi.org/10.1515/9781400846504>.
- Hoya-Florez, J., Atencio-García, V., Gutiérrez-Espinoza, M., Estrada-Posada, A., Chaparro-Gutiérrez, J., Yepes-Blandón, J., 2024. Effect of selenium on physiological and reproductive parameters in males of the catfish *Sorubim cuspidatus*. *Aquac. Rep.* 35, 102013. <https://doi.org/10.1016/j.aqrep.2024.102013>.
- Hudak, P.F., 2009. Elevated fluoride and selenium in west Texas groundwater. *Bull. Environ. Contam. Toxicol.* 82, 39–42. <https://doi.org/10.1007/s00128-008-9583-6>.
- Hung, P.D., 2018. Selenium deficiency, toxicity and its requirement in marine fish: a research review. *Tạp chí Khoa học-Công nghệ Thủy Sản. Trường Đại học Nha Trang* 30, 60–68. <https://doi.org/10.53818/jst.04.2018.418>.
- Ilham, I., Siddik, M.A.B., Fotedar, R., 2016. Effects of organic selenium supplementation on growth, accumulation, haematology and histopathology of juvenile Barramundi (*Lates calcarifer*) fed high soybean meal diets. *Biol. Trace Elem. Res.* 174, 436–447. <https://doi.org/10.1007/s12011-016-0708-1>.
- Iqbal, S., Atique, U., Sharif Mughal, M., Khan, N., Sultan Haider, M., Iqbal, K.J., Akmal, M., 2017. Effect of selenium incorporated in feed on the hematological profile of Tilapia (*Oreochromis niloticus*). *J. Aquacult. Res. Dev.* 8, 513. <https://doi.org/10.4172/2155-9546.1000513>.
- Islam, S.M.M., Rohani, M.F., Shahjahan, M., 2021. Probiotic yeast enhances growth performance of Nile tilapia (*Oreochromis niloticus*) through morphological modifications of intestine. *Aquac. Reports* 21, 100800. <https://doi.org/10.1016/j.aqrep.2021.100800>.
- Jacquin, L., Petitjean, Q., Côte, J., Laffaille, P., Jean, S., 2020. Effects of pollution on fish behavior, personality, and cognition: some research perspectives. *Front. Ecol. Evol.* 8, 86. <https://doi.org/10.3389/fevo.2020.00086>.
- Jahan, N., Islam, S.M.M., Rohani, M.F., Hossain, M.T., Shahjahan, M., 2021. Probiotic yeast enhances growth performance of rohu (*Labeo rohita*) through upgrading hematology, and intestinal microbiota and morphology. *Aquaculture* 545, 737243. <https://doi.org/10.1016/j.aquaculture.2021.737243>.
- Jahanbakhshi, A., Pourmozaffar, S., Adeshina, I., Mahmoudi, R., Erfanfifar, E., Ajdari, A., 2021. Selenium nanoparticle and selenomethionine as feed additives: effects on growth performance, hepatic enzymes' activity, mucosal immune parameters, liver histology, and appetite-related gene transcript in goldfish (*Carassius auratus*). *Fish Physiol. Biochem.* 47, 639–652. <https://doi.org/10.1007/s10695-021-00937-6>.

- Jamwal, A., Saibu, Y., MacDonald, T.C., George, G.N., Niyogi, S., 2019. The effects of dietary selenomethionine on tissue-specific accumulation and toxicity of dietary arsenite in rainbow trout (*Oncorhynchus mykiss*) during chronic exposure. *Metallomics* 11, 643–655. <https://doi.org/10.1039/c8mt00309b>.
- Janz, D.M., DeForest, D.K., Brooks, M.L., Chapman, P.M., Gilron, G., Hoff, D., Hopkins, W.D., McIntyre, D.O., Mebane, C.A., Palace, V.P., Skorupa, J., Wayland, M., 2010. In: Chapman, P.M., Adams, W.J., Brooks, M.L., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., Shaw, D.P. (Eds.), *Selenium Toxicity to Aquatic Organisms*. CRC Press, Pensacola, FL, USA, pp. 141–231.
- Janz, D.M., 2012. In: Wood, C.M., Farrell, A.P., Brauner, C.J. (Eds.), *Fish Physiology: Homeostasis and Toxicology of Essential Metals*, 31A. Elsevier, San Diego, pp. 327–373.
- Jezińska, B., Ługowska, K., Witeska, M., 2009. The effects of heavy metals on embryonic development of fish (a review). *Fish Physiol. Biochem.* 35, 625–640. <https://doi.org/10.1007/s10695-008-9284-4>.
- Jingyuan, H., Yan, L., Wenjing, P., Wenqiang, J., Bo, L., Linghong, M., Qunlang, Z., Hualiang, L., Xianping, G., 2020. Dietary selenium enhances the growth and anti-oxidant capacity of juvenile blunt snout bream (*Megalobrama amblycephala*). *Fish Shellfish Immunol.* 101, 115–125. <https://doi.org/10.1016/j.fsi.2020.03.041>.
- José, L., Barcellos, G., Ritter, F., Carlos, L., Mezzalana, R., Bolognesi, L., Calliari, A., Finco, J., Cericato, L., 2007. Whole-body cortisol increases after direct and visual contact with a predator in zebrafish, *Danio rerio*. *Aquaculture* 272, 774–778. <https://doi.org/10.1016/j.aquaculture.2007.09.002>.
- Kalishwaralal, K., Jayabharathi, S., Sundar, K., Muthukumaran, A., 2016a. A novel one-pot green synthesis of selenium nanoparticles and evaluation of its toxicity in zebrafish embryos. *Artif. Cells. Nanomed. Biotechnol.* 44, 471–477. <https://doi.org/10.3109/21691401.2014.962744>.
- Kalishwaralal, K., Jayabharathi, S., Sundar, K., Muthukumaran, A., 2016b. Comparative analysis of cardiovascular effects of selenium nanoparticles and sodium selenite in zebrafish embryos. *Artif. Cells. Nanomed. Biotechnol.* 44, 990–996. <https://doi.org/10.3109/21691401.2015.1008507>.
- Khadra, M., Planas, D., Brodeur, P., Amyot, M., 2019. Mercury and selenium distribution in key tissues and early life stages of Yellow Perch (*Perca flavescens*). *Environ. Pollut.* 254, 112963. <https://doi.org/10.1016/j.envpol.2019.112963>.
- Khalil, H.S., Mansour, A.T., Goda, A.M.A., Omar, E.A., 2019. Effect of selenium yeast supplementation on growth performance, feed utilization, lipid profile, liver and intestine histological changes, and economic benefit in meagre, *Argyrosomus regius*, fingerlings. *Aquaculture* 501, 135–143. <https://doi.org/10.1016/j.aquaculture.2018.11.018>.
- Khan, K.U., Zuberi, A., Nazir, S., Fernandes, J.B.K., Jamil, Z., Sarwar, H., 2016. Effects of dietary selenium nanoparticles on physiological and biochemical aspects of juvenile *Tor putitora*. *Turk. J. Zool.* 4, 704–712. <https://doi.org/10.3906/zoo-1510-5>.
- Kim, J.H., Kang, J.C., 2016a. Oxidative stress, neurotoxicity, and metallothionein (MT) gene expression in juvenile rockfish *Sebastes schlegelii* under the different levels of dietary chromium (Cr<sup>6+</sup>) exposure. *Ecotoxicol. Environ. Saf.* 125, 78–84. <https://doi.org/10.1016/j.ecoenv.2015.12.001>.
- Kim, J.H., Kang, J.C., 2016b. The immune responses in juvenile rockfish, *Sebastes schlegelii* for the stress by the exposure to the dietary lead (II). *Environ. Toxicol. Pharmacol.* 46, 211–216. <https://doi.org/10.1016/j.etap.2016.07.022>.
- Kim, J.H., Kang, J.C., 2016c. The chromium accumulation and its physiological effects in juvenile rockfish, *Sebastes schlegelii*, exposed to different levels of dietary chromium (Cr<sup>6+</sup>) concentrations. *Environ. Toxicol. Pharmacol.* 41, 152–158. <https://doi.org/10.1016/j.etap.2015.12.001>.
- Kim, J.H., Kang, J.C., 2017a. Effects of dietary chromium exposure to rockfish, *Sebastes schlegelii* are ameliorated by ascorbic acid. *Ecotoxicol. Environ. Saf.* 139, 109–115. <https://doi.org/10.1016/j.ecoenv.2017.01.029>.
- Kim, J.H., Kang, J.C., 2017b. Effects of sub-chronic exposure to lead (Pb) and ascorbic acid in juvenile rockfish: antioxidant responses, MT gene expression, and neurotransmitters. *Chemosphere* 171, 520–527. <https://doi.org/10.1016/j.chemosphere.2016.12.094>.
- Kim, J.H., Sohn, S., Kim, S.K., Hur, Y.B., 2020. Effects on hematological parameters, antioxidant and immune responses, AChE, and stress indicators of olive flounders, *Paralichthys olivaceus*, raised in bio-floc and seawater challenged by *Edwardsiella tarda*. *Fish Shellfish Immunol.* 97, 194–203. <https://doi.org/10.1016/j.fsi.2019.12.011>.
- Kim, J.H., Yu, Y.B., Choi, J.H., 2021. Toxic effects on bioaccumulation, hematological parameters, oxidative stress, immune responses and neurotoxicity in fish exposed to microplastics: a review. *J. Hazard Mater.* 413, 125423. <https://doi.org/10.1016/j.jhazmat.2021.125423>.
- Kohshahi, A.J., Sourinejad, I., Sarkheil, M., Johari, S.A., 2019. Dietary cosupplementation with curcumin and different selenium sources (nanoparticulate, organic, and inorganic selenium): influence on growth performance, body composition, immune responses, and glutathione peroxidase activity of rainbow trout (*Oncorhynchus mykiss*). *Fish Physiol. Biochem.* 45, 793–804. <https://doi.org/10.1007/s10695-018-0585-y>.
- Kong, X., Jiang, H., Wang, S., Wu, X., Fei, W., Li, L., Nie, G., Li, X., 2013. Effects of copper exposure on the hatching status and antioxidant defense at different developmental stages of embryos and larvae of goldfish *Carassius auratus*. *Chemosphere* 92, 1458–1464. <https://doi.org/10.1016/j.chemosphere.2013.04.004>.
- Kucukbay, F.Z., Yazlak, H., Karaca, I., Sahin, N., Tuzcu, M., Cakmak, M.N., Sahin, K., 2009. The effects of dietary organic or inorganic selenium in rainbow trout (*Oncorhynchus mykiss*) under crowding conditions. *Aquacult. Nutr.* 15, 569–576. <https://doi.org/10.1111/j.1365-2095.2008.00624.x>.
- Kumar, N., Krishnani, K.K., Gupta, S.K., Sharma, R., Baitra, R., Singh, D.K., Singh, N.P., 2018a. Immuno-protective role of biologically synthesized dietary selenium nanoparticles against multiple stressors in *Pangasinodon hypophthalmus*. *Fish Shellfish Immunol.* 78, 289–298. <https://doi.org/10.1016/j.fsi.2018.04.051>.
- Kumar, N., Krishnani, K.K., Singh, N.P., 2018b. Comparative study of selenium and selenium nanoparticles with reference to acute toxicity, biochemical attributes, and histopathological response in fish. *Environ. Sci. Pollut. Res.* 25, 8914–8927. <https://doi.org/10.1007/s11356-017-1165-x>.
- Kumar, N., Singh, N.P., 2019. Effect of dietary selenium on immuno-biochemical plasticity and resistance against *Aeromonas veronii biovar sobria* in fish reared under multiple stressors. *Fish Shellfish Immunol.* 84, 38–47. <https://doi.org/10.1016/j.fsi.2018.09.065>.
- Kupsco, A., Schlenk, D., 2016. Stage susceptibility of Japanese medaka (*Oryzias latipes*) to selenomethionine and hypersaline developmental toxicity. *Environ. Toxicol. Chem.* 35, 1247–1256. <https://doi.org/10.1002/etc.3268>.
- Lall, S.P., Kaushik, S.J., 2021. Nutrition and metabolism of minerals in fish. *Animals* 11, 2711. <https://doi.org/10.3390/ani11092711>.
- Lauriano, E., Pergolizzi, S., Capillo, G., Kuciel, M., Alecci, A., Faggio, C., 2016. Immunohistochemical characterization of toll-like receptor 2 in gut epithelial cells and macrophages of goldfish *Carassius auratus* fed with a high-cholesterol diet. *Fish Shellfish Immunol.* 59, 250–255. <https://doi.org/10.1016/j.fsi.2016.11.003>.
- Lee, J.W., Choi, H., Hwang, U.K., Kang, J.C., Kang, Y.J., Kim, K.I., Kim, J.H., 2019. Toxic effects of lead exposure on bioaccumulation, oxidative stress, neurotoxicity, and immune responses in fish: a review. *Environ. Toxicol. Pharmacol.* 68, 101–108. <https://doi.org/10.1016/j.etap.2019.03.010>.
- Lee, S., Nambi, R.W., Won, S., Katya, K., Bai, S.C., 2016. Dietary selenium requirement and toxicity levels in juvenile Nile tilapia, *Oreochromis niloticus*. *Aquaculture* 464, 153–158. <https://doi.org/10.1016/j.aquaculture.2016.06.027>.
- Lemly, A.D., 2004. Aquatic selenium pollution is a global environmental safety issue. *Ecotoxicol. Environ. Saf.* 59, 44e56. [https://doi.org/10.1016/S0147-6513\(03\)00095-2](https://doi.org/10.1016/S0147-6513(03)00095-2).
- Lemly, D.A., 2002. Symptoms and implications of selenium toxicity in fish: the Bevels Lake case example. *Aquat. Toxicol.* 57, 39–49. [https://doi.org/10.1016/S0166-445X\(01\)00264-8](https://doi.org/10.1016/S0166-445X(01)00264-8).
- Li, M.Y., Gao, C.S., Du, X.Y., Zhao, L., Niu, X.T., Wang, G.Q., Zhang, D.M., 2020. Effect of sub-chronic exposure to selenium and astaxanthin on *Channa argus*: bioaccumulation, oxidative stress and inflammatory response. *Chemosphere* 244. <https://doi.org/10.1016/j.chemosphere.2019.125546>.
- Li, M.Y., Guo, W.Q., Guo, G.L., Zhu, X.M., Niu, X.T., Shan, X.F., Tian, J.X., Wang, G.Q., Zhang, D.M., 2019. Effect of sub-chronic exposure to selenium and lillium mongolicum Regel flavonoids on *Channa argus*: bioaccumulation, oxidative stress, immune responses and immune-related signaling molecules. *Fish Shellfish Immunol.* 91, 122–129. <https://doi.org/10.1016/j.fsi.2019.05.002>.
- Li, M.Y., Shi, Y.C., Xu, W.X., Zhao, L., Zhang, A.Z., 2024. Exploring Cr (VI)-induced blood-brain barrier injury and neurotoxicity in zebrafish and snakehead fish, and inhibiting toxic effects of astaxanthin. *Environ. Pollut.* 355, 124280. <https://doi.org/10.1016/j.envpol.2024.124280>.
- Li, X., Liu, H., Li, D., Lei, H., Wei, X., Schlenk, D., Mu, J., Chen, H., Yan, B., Xie, L., 2021. Dietary seleno-L-methionine causes alterations in neurotransmitters, ultrastructure of the brain, and behaviors in zebrafish (*Danio rerio*). *Environ. Sci. Technol.* 55, 11894–11905. <https://doi.org/10.1021/acs.est.1c03457>.
- Lin, F., Zhang, H., Yu, J., Yu, C., Chen, C., Sun, Z., Wang, S., Wen, X., 2021. Effects of dietary selenium on growth performance, antioxidant status and tissue selenium deposition of juvenile Chu's croaker (*Nibea coibor*). *Aquaculture* 536, 736439. <https://doi.org/10.1016/j.aquaculture.2021.736439>.
- Luoma, S.N., Presser, T.S., 2009. Emerging opportunities in management of selenium contamination. *Environ. Sci. Technol.* 43, 8483–8487. <https://doi.org/10.1021/es900828h>.
- Ma, S., Zhou, Y., Chen, H., Hou, L., Zhao, J., Cao, J., Geng, S., Luo, Y., Schlenk, D., Xie, L., 2018. Selenium accumulation and the effects on the liver of topmouth gudgeon *Pseudorasbora parva* exposed to dissolved inorganic selenium. *Ecotoxicol. Environ. Saf.* 160, 240–248. <https://doi.org/10.1016/j.ecoenv.2018.05.047>.
- Maier, K.J., Knight, A.W., 1994. *Ecotoxicology of selenium in freshwater systems*. Rev. Environ. Contam. T. Springer 31–48.
- Mansour, A.T.E., Goda, A.A., Omar, E.A., Khalil, H.S., Esteban, M.Á., 2017. Dietary supplementation of organic selenium improves growth, survival, antioxidant and immune status of meagre, *Argyrosomus regius*, juveniles. *Fish Shellfish Immunol.* 68, 516–524. <https://doi.org/10.1016/j.fsi.2017.07.060>.
- Massé, A.J., Muscatello, J.R., Janz, D.M., 2015. Dose-dependent early life stage toxicities in *Xenopus laevis* exposed in ovo to selenium. *Environ. Sci. Technol.* 49, 13658–13666. <https://doi.org/10.1021/acs.est.5b04303>.
- Maximino, C., Marques de Brito, T., Dias, C.A.G.D.M., Gouveia Jr, A., Morato, S., 2010. Scototaxis as anxiety-like behavior in fish. *Nat. Protoc.* 5, 209–216. <https://doi.org/10.1038/nprot.2009.225>.
- McEneff, G., Quinn, B., Bennion, M., Dolan, S., O'Rourke, K., Morrison, L., 2017. Bioaccumulation of metals in juvenile rainbow trout (*Oncorhynchus mykiss*) via dietary exposure to blue mussels. *Chemosphere* 188, 548–556. <https://doi.org/10.1016/j.chemosphere.2017.08.141>.
- McPhee, D.L., Janz, D.M., 2014. Dietary selenomethionine exposure alters swimming performance, metabolic capacity and energy homeostasis in juvenile fathead minnow. *Aquat. Toxicol.* 155, 91e100. <https://doi.org/10.1016/j.aquatox.2014.06.012>.
- Mhadhbi, L., Boumaiza, M., Beiras, R., 2010. A standard ecotoxicological bioassay using early life stages of the marine fish *Psetta maxima*. *Aquat. Living Resour.* 23, 209–216. <https://doi.org/10.1051/alr/2010014>.
- Misra, S., Hamilton, C., Niyogi, S., 2012. Induction of oxidative stress by selenomethionine in isolated hepatocytes of rainbow trout (*Oncorhynchus mykiss*). *Toxicol. Vitro* 26, 621e629. <https://doi.org/10.1016/j.tiv.2012.02.001>.

- Mo, A.J., Wang, J.H., Yuan, M.R., Zhao, D.X., Gu, Z.M., Liu, Y., Huang, H.Y., Yuan, Y.C., 2019. Effect of sub-chronic dietary L-selenomethionine exposure on reproductive performance of Red Swamp Crayfish, (*Procambarus clarkii*). *Environ. Pollut.* 253, 749e758 <https://doi.org/10.1016/j.envpol.2019.07.082>.
- Mo, A., Dang, Y., Wang, J., Liu, C., Yuan, Y., Yang, H., 2020. Sex differences, growth, reproduction and zinc ion homeostasis of zebrafish after chronic dietary L-selenomethionine exposure. *Chemosphere* 259, 127455. <https://doi.org/10.1016/j.chemosphere.2020.127455>.
- Mo, A., Wang, X., Yuan, Y., Liu, C., Wang, J., 2021. Effects of waterborne exposure to environmentally relevant concentrations of selenite on reproductive function of female zebrafish: a life cycle assessment. *Environ. Pollut.* 270, 116237 <https://doi.org/10.1016/j.envpol.2020.116237>.
- Modesto, K.A., Marinez, C.B.R., 2010. Roundup causes oxidative stress in liver and inhibits acetylcholinesterase in muscle and brain of the fish *Prochilodus lineatus*. *Chemosphere* 78, 294–299. <https://doi.org/10.1016/j.chemosphere.2009.10.047>.
- Mullur, R., Liu, Y.Y., Brent, G.A., 2014. Thyroid hormone regulation of metabolism. *Physiol. Rev.* 94, 355e382 <https://doi.org/10.1152/physrev.00030.2013>.
- Mushtaq, M., Fatima, M., Shah, S.Z.H., Khan, N., Naveed, S., Khan, M., 2022a. Evaluation of dietary selenium methionine levels and their effects on growth performance, antioxidant status, and meat quality of intensively reared juvenile *Hypophthalmichthys molitrix*. *PLoS One* 17, e0274734. <https://doi.org/10.1371/journal.pone.0274734>.
- Mushtaq, M., Fatima, M., Shah, S.Z.H., Khan, N., Naveed, S., Khan, M., 2022b. Effects of sodium selenite, selenium methionine, and selenium yeast on growth performance, carcass composition, blood biochemistry, and antioxidant status of intensively reared *Hypophthalmichthys molitrix*. *Aquac. Rep.* 24, 101182 <https://doi.org/10.1016/j.aqrep.2022.101182>.
- Naderi, M., Ferrari, M.C.O., Chivers, D.P., Niyogi, S., 2018a. Maternal exposure to dietary selenium causes dopaminergic hyperfunction and cognitive impairment in zebrafish offspring. *Environ. Sci. Technol.* 52, 13574–13583. <https://doi.org/10.1021/acs.est.8b04768>.
- Naderi, M., Keyvanshokoo, S., Salati, A.P., Ghaedi, A., 2017a. Combined or individual effects of dietary vitamin E and selenium nanoparticles on humoral immune status and serum parameters of rainbow trout (*Oncorhynchus mykiss*) under high stocking density. *Aquaculture* 474, 40–47. <https://doi.org/10.1016/j.aquaculture.2017.03.036>.
- Naderi, M., Puar, P., Zonouzi-Marand, M., Chivers, D.P., Niyogi, S., Kwong, R.W., 2021. A comprehensive review on the neuropathophysiology of selenium. *Sci. Total Environ.* 767, 144329 <https://doi.org/10.1016/j.scitotenv.2020.144329>.
- Naderi, M., Salahinejad, A., Ferrari, M.C.O., Niyogi, S., Chivers, D.P., 2018b. Dopaminergic dysregulation and impaired associative learning behavior in zebrafish during chronic dietary exposure to selenium. *Environ. Pollut.* 237, 174–185. <https://doi.org/10.1016/j.envpol.2018.02.033>.
- Naderi, M., Salahinejad, A., Jamwal, A., Chivers, D.P., Niyogi, S., 2017b. Chronic dietary selenomethionine exposure induces oxidative stress, dopaminergic dysfunction, and cognitive impairment in adult zebrafish (*Danio rerio*). *Environ. Sci. Technol.* 51, 12879–12888. <https://doi.org/10.1021/acs.est.7b03937>.
- Naiel, M.A.E., Negm, S.S., Abd El-hameed, S.A.A., Abdel-Latif, H.M.R., 2021. Dietary organic selenium improves growth, serum biochemical indices, immune responses, antioxidative capacity, and modulates transcription of stress-related genes in Nile tilapia reared under sub-optimal temperature. *J. Therm. Biol.* 99, 102999 <https://doi.org/10.1016/j.jtherbio.2021.102999>.
- Naiel, M.A., Eissa, E.S.H., Abd El-Aziz, Y.M., Saadony, S., Abd Elnabi, H.E., Sakr, S.E.S., 2023. The assessment of different dietary selenium resources on reproductive performance, spawning indicators, and larval production of red tilapia (*Oreochromis mossambicus* x *O. niloticus*) broodfish. *Aquac. Nutr.* 1, 5596619. <https://doi.org/10.1155/2023/5596619>.
- Nasyitah, S.N., Zaharin, A.A., Nizam, M.K., Juen, L.L., Woong, K.K., 2018. Bioaccumulation of heavy metals in maricultured fish, *Lates calcarifer* (Barramudi), *Lutjanus campechanus* (red snapper) and *Lutjanus griseus* (grey snapper). *Chemosphere* 197, 318–324. <https://doi.org/10.1016/j.chemosphere.2017.12.187>.
- Nazari, K., Shamsaie, M., Eila, N., Kamali, A., Sharifpour, I., 2017. The effects of different dietary levels of organic and inorganic selenium on some growth performance and proximate composition of juvenile rainbow trout (*Oncorhynchus mykiss*). *Iran. J. Fish. Sci.* 16, 238–251. <http://dori.net/dor/20.1001.1.15622916.2017.16.1.20.1>.
- Neamat-Allah, A.N.F., Mahmoud, E.A., Abd El Hakim, Y., 2019. Efficacy of dietary nano-selenium on growth, immune response, antioxidant, transcriptomic profile and resistance of Nile tilapia, *Oreochromis niloticus* against *Streptococcus iniae* infection. *Fish Shellfish Immunol.* 94, 280–287. <https://doi.org/10.1016/j.fsi.2019.09.019>.
- NRC, 2011. *Nutrient Requirements of Fish and Shrimp*. The National Academies Press, Washington, DC, USA.
- Ogle, R.S., Knight, A.W., 1989. Effects of elevated foodborne selenium on growth and reproduction of the fathead minnow (*Pimephales promelas*). *Arch. Environ. Contam. Toxicol.* 18, 795–803. <https://doi.org/10.1007/BF01160293>.
- Ohlendörfer, H.M., Covington, S.M., Byron, E.R., Arenal, C.A., 2011. Conducting site-specific assessments of selenium bioaccumulation in aquatic systems. *Integr. Environ. Assess. Manag.* 7, 314–324. <https://doi.org/10.1002/ieam.157>.
- Orun, I., Talas, Z.S., Ozdemir, I., Alkan, A., Erdogan, K., 2008. Antioxidative role of selenium on some tissues of (Cd<sup>2+</sup>), (Cr<sup>3+</sup>)-induced rainbow trout. *Ecotox. Environ. Safe.* 71, 71–75. <https://doi.org/10.1016/j.ecoenv.2007.07.008>.
- Pacitti, D., Lawan, M.M., Sweetman, J., Martin, S.A.M., Feldmann, J., Secombes, C.J., 2015. Selenium supplementation in fish: a combined chemical and biomolecular study to understand Sel-Plex assimilation and impact on selenoproteome expression in rainbow trout (*Oncorhynchus mykiss*). *PLoS One* 10, e0127041. <https://doi.org/10.1371/journal.pone.0127041>.
- Palace, V.P., Spallholz, J.E., Holm, J., Wautier, K., Evans, R.E., Baron, C.L., 2004. Metabolism of selenomethionine by rainbow trout (*Oncorhynchus mykiss*) embryos can generate oxidative stress. *Ecotoxicol. Environ. Saf.* 58, 17–21. <https://doi.org/10.1016/j.ecoenv.2003.08.019>.
- Pan, B., Wang, Y., Li, D., Wang, T., Du, L., 2022. Tissue-specific distribution and bioaccumulation pattern of trace metals in fish species from the heavily sediment-laden Yellow River, China. *J. Hazard Mater.* 425, 128050 <https://doi.org/10.1016/j.jhazmat.2021.128050>.
- Pengglase, S., Hamre, K., Rasinger, J.D., Ellingsen, S., 2014. Selenium status affects selenoprotein expression, reproduction, and F1 generation locomotor activity in zebrafish (*Danio rerio*). *Br. J. Nutr.* 111, 1918–1931. <https://doi.org/10.1017/S000711451300439x>.
- Pettem, C.M., Weber, L.P., Janz, D.M., 2017. Cardiac and metabolic effects of dietary selenomethionine exposure in adult zebrafish. *Toxicol. Sci.* 159, 449e460 <https://doi.org/10.1017/S000711451300439x>.
- Plateau, P., Saveanu, C., Lestini, R., Dauplais, M., Decourty, L., Jacquier, A., Blanquet, S., Lazard, M., 2017. Exposure to selenomethionine causes selenocysteine misincorporation and protein aggregation in *Saccharomyces cerevisiae*. *Sci. Rep.* 7, 44761 <https://doi.org/10.1038/srep44761>.
- Plessl, C., Gilbert, B.M., Sigmund, M.F., Theiner, S., Avenant-Oldewage, A., Keppler, B.K., Jirsa, F., 2019. Mercury, silver, selenium and other trace elements in three cyprinid fish species from the Vaal Dam, South Africa, including implications for fish consumers. *Sci. Total Environ.* 659, 1158–1167. <https://doi.org/10.1016/j.scitotenv.2018.12.442>.
- Ponton, D.E., Caron, A., Hare, L., Campbell, P.G.C., 2016. Hepatic oxidative stress and metal subcellular partitioning are affected by selenium exposure in wild yellow perch (*Perca flavescens*). *Environ. Pollut.* 214, 608–617. <https://doi.org/10.1016/j.envpol.2016.04.051>.
- Prabhu, P.A.J., Schrama, J.W., Kaushik, S.J., 2016. Mineral requirements of fish: a systematic review. *Rev. Aquac.* 8, 172–219. <https://doi.org/10.1111/raq.12090>.
- Rahman, M.S., Islam, S.M.M., Haque, A., Shahjahan, M., 2020. Toxicity of the organophosphate insecticide sumithion to embryo and larvae of zebrafish. *Toxicol. Reports* 7, 317–323. <https://doi.org/10.1016/j.toxrep.2020.02.004>.
- Raine, J.C., Lallemand, L., Pettem, C.M., Janz, D.M., 2016. Effects of chronic dietary selenomethionine exposure on the visual system of adult and F1 generation zebrafish (*Danio rerio*). *Bull. Environ. Contam. Toxicol.* 97, 331–336. <https://doi.org/10.1007/s00128-016-1849-9>.
- Rathore, S.S., Murthy, H.S., Girisha, S.K., Nithin, M.S., Nasren, S., Mamun, M.A.A., Puneeth, T.G., Rakesh, K., Kumar, B.T.N., Pai, M., 2021a. Supplementation of nano-selenium in fish diet: impact on selenium assimilation and immune-regulated selenoproteome expression in monosex Nile tilapia (*Oreochromis niloticus*). *Physiol. C Toxicol. Pharmacol.* 240, 108907 <https://doi.org/10.1016/j.cbpc.2020.108907>.
- Rathore, S.S., Murthy, H.S., Mamun, M.A.A., Nasren, S., Rakesh, K., Kumar, B.T.N., Abhiman, P.B., Khandagale, A.S., 2021b. Nano-selenium supplementation to ameliorate nutrition physiology, immune response, antioxidant system and disease resistance against *Aeromonas hydrophila* in monosex Nile tilapia (*Oreochromis niloticus*). *Biol. Trace Elem. Res.* 199, 3073–3088. <https://doi.org/10.1007/s12011-020-02416-0>.
- Rebl, A., Seibel, H., Baßmann, B., 2021. Blood will tell: what haematological analyses can reveal about fish welfare. *Front. Vet. Sci.* 8, 194. <https://doi.org/10.3389/fvets.2021.616955>.
- Rohani, M.F., Islam, S.M., Hossain, M.K., Ferdous, Z., Siddik, M.A., Nuruzzaman, M., Padeniya, U., Brown, C., Shahjahan, M., 2022. Probiotics, prebiotics and synbiotics improved the functionality of aquafeed: upgrading growth, reproduction, immunity and disease resistance in fish. *Fish Shellfish Immunol.* 120, 569–589. <https://doi.org/10.1016/j.fsi.2021.12.037>.
- Saffari, S., Keyvanshokoo, S., Mozanzadeh, M.T., Shahriari, A., 2022. Maternal supplementation of nano-selenium in a plant-based diet improves antioxidant competence of female Arabian yellowfin sea bream (*Acanthopagrus arabicus*) breeders and their progeny. *Anim. Reprod. Sci.* 247, 107157 <https://doi.org/10.1016/j.anireprosci.2022.107157>.
- Saffari, S., Keyvanshokoo, S., Zakeri, M., Johari, S.A., Pasha-Zanoosi, H., 2017. Effects of different dietary selenium sources (sodium selenite, selenomethionine and nanoselenium) on growth performance, muscle composition, blood enzymes and antioxidant status of common carp (*Cyprinus carpio*). *Aquacult. Nutr.* 23, 611–617. <https://doi.org/10.1111/anu.12428>.
- Salahinejad, A., Meuthen, D., Attaran, A., Chivers, D.P., Ferrari, M.C.O., 2023. Effects of common antiepileptic drugs on teleost fishes. *Sci. Total Environ.* 866, 161324 <https://doi.org/10.1016/j.scitotenv.2022.161324>.
- Salim, S., 2017. Oxidative stress and the central nervous system. *J. Pharmacol. Exp. Ther.* 360, 201e205 <https://doi.org/10.1124/jpet.116.237503>.
- Sandoval-Herrera, N., Mena, F., Espinoza, M., Romero, A., 2019. Neurotoxicity of organophosphate pesticides could reduce the ability of fish to escape predation under low doses of exposure. *Sci. Rep.* 9, 10530 <https://doi.org/10.1038/s41598-019-46804-6>.
- Seyed, J., Kalbassi, M.R., Esmailbeigi, M., Tayemeh, M.B., Amiri Moghadam, J., 2021. Toxicity and deleterious impacts of selenium nanoparticles at supranutritional and imbalance levels on male goldfish (*Carassius auratus*) sperm. *J. Trace Elem. Med. Biol.* 66, 126758 <https://doi.org/10.1016/j.jtemb.2021.126758>.
- Shah, B.R., Mraz, J., 2020. Advances in nanotechnology for sustainable aquaculture and fisheries. *Rev. Aquac.* 12, 925–942. <https://doi.org/10.1111/raq.12356>.
- Shahjahan, M., Uddin, M.H., Bain, V., et al., 2018. Increased water temperature altered hemato-biochemical parameters and structure of peripheral erythrocytes in striped catfish *Pangasianodon hypophthalmus*. *Fish Physiol. Biochem.* 44, 1309–1318. <https://doi.org/10.1007/s10695-018-0522-0>.

- Shi, M., Zhang, C., Xia, I.F., Cheung, S.T., Wong, K.S., Wong, K.H., Au, D.W.T., Hinton, D. E., Kwok, K.W.H., 2018. Maternal dietary exposure to selenium nanoparticle led to malformation in offspring. *Ecotoxicol. Environ. Saf.* 156, 34–40. <https://doi.org/10.1016/j.ecoenv.2018.02.073>.
- Song, S.B., Xu, Y., Zhou, B.S., 2006. Effects of hexachlorobenzene on antioxidant status of liver and brain of common carp (*Cyprinus carpio*). *Chemosphere* 65, 699–706. <https://doi.org/10.1016/j.chemosphere.2006.01.033>.
- Spallholz, J.E., Palace, V.P., Reid, T.W., 2004. Methioninase and selenomethionine but not Se-methylselenocysteine generate methylselenol and superoxide in an in vitro chemiluminescent assay: implications for the nutritional carcinostatic activity of selenoamino acids. *Biochem. Pharmacol.* 67, 547–554. <https://doi.org/10.1016/j.bcp.2003.09.004>.
- Storelli, M.M., 2008. Potential human health risks from metals (Hg, Cd, and Pb) and polychlorinated biphenyls (PCBs) via seafood consumption: estimation of target hazard quotients (THQs) and toxic equivalents (TEQs). *Food Chem. Toxicol.* 46, 2782–2788. <https://doi.org/10.1016/j.fct.2008.05.011>.
- Sumana, S.L., Chen, H., Shui, Y., Zhang, C., Yu, F., Zhu, J., Su, S., 2023. Effect of dietary selenium on the growth and immune systems of fish. *Animals* 13, 2978. <https://doi.org/10.3390/ani13182978>.
- Sunde, R.A., 1984. The biochemistry of selenoproteins. *J. Am. Oil Chem. Soc.* 12, 1891–1900. <https://doi.org/10.1007/BF02540827>.
- Takahashi, L.S., Biller-Takahashi, J.D., Mansano, C.F.M., Urbinati, E.C., Gimbo, R.Y., Saita, M.V., 2017. Long-term organic selenium supplementation overcomes the trade-off between immune and antioxidant systems in pacu (*Piaractus mesopotamicus*). *Fish Shellfish Immunol.* 60, 311–317. <https://doi.org/10.1016/j.fsi.2016.11.060>.
- Taslina, K., Al-Emran, M., Rahman, M.S., Hasan, J., Ferdous, Z., Rohani, M.F., Shahjahan, M., 2022. Impacts of heavy metals on early development, growth and reproduction of fish-A review. *Toxicol Rep* 9, 858–868. <https://doi.org/10.1016/j.toxrep.2022.04.013>.
- Thomas, J.K., Janz, D.M., 2011. Dietary selenomethionine exposure in adult zebrafish alters swimming performance, energetics and the physiological stress response. *Aquat. Toxicol.* 102, 79e86. <https://doi.org/10.1016/j.aquatox.2010.12.020>.
- Thomas, J.K., Janz, D.M., 2014. In ovo exposure to selenomethionine via maternal transfer increases developmental toxicities and impairs swim performance in F<sub>1</sub> generation zebrafish (*Danio rerio*). *Aquat. Toxicol.* 152, 20–29. <https://doi.org/10.1016/j.aquatox.2014.03.022>.
- Thomas, J.K., Janz, D.M., 2015. Developmental and persistent toxicities of maternally deposited selenomethionine in zebrafish (*Danio rerio*). *Environ. Sci. Technol.* 49, 10182–10189. <https://doi.org/10.1021/acs.est.5b02451>.
- Thomas, J.K., Janz, D.M., 2016. Embryo microinjection of selenomethionine reduces hatchability and modifies oxidant responsive gene expression in zebrafish. *Sci. Rep.* 6, 26520. <https://doi.org/10.1038/srep26520>.
- Thomas, J.K., Wiseman, S., Giesy, J.P., Janz, D.M., 2013. Effects of chronic dietary selenomethionine exposure on repeat swimming performance, aerobic metabolism and methionine catabolism in adult zebrafish (*Danio rerio*). *Aquat. Toxicol.* 130, 112–122. <https://doi.org/10.1016/j.aquatox.2013.01.009>.
- Uddin, M.H., Khatun, M.F., Islam, M.J., Niyogi, S., Haque, M.M., Rashid, H., 2023. Effects of increasing salinity on growth performance, hemato-biochemical parameters, and erythrocyte structure of freshwater Gourami (*Trichogaster fasciata*). *Aquac. Stud.* 24, AQUAST1466. <https://doi.org/10.4194/AQUAST1466>.
- Uribe, C., Folch, H., Enriquez, R., Moran, G., 2011. Innate and adaptive immunity in teleost fish: a review. *Vet. Med.* 56, 486–503. <https://doi.org/10.17221/3294-VETMED>.
- Urien, N., Cooper, S., Caron, A., Sonnenberg, H., Rozon-Ramilo, L., Campbell, P.G.C., Couture, P., 2018. Subcellular partitioning of metals and metalloids (As, Cd, Cu, Se and Zn) in liver and gonads of wild white suckers (*Catostomus commersonii*) collected downstream from a mining operation. *Aquac. Toxicol.* 202, 105–116. <https://doi.org/10.1016/j.aquatox.2018.07.001>.
- USEPA, 2016. Aquatic Life Ambient Water Quality Criterion for Selenium – Freshwater 2016. EPA 822-R-16-006. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.
- USFWS, 1990. Agricultural irrigation drainwater studies in support of the san joaquin valley drainage program. Final report. In: U.S. Department of the Interior, Fish and Wildlife Service. National Fisheries Contaminant Research Center, Columbia, Missouri, p. 309.
- Vaishnavi, A.S., Baskaran, D., Gowri, M., Valli, C., 2019. Assessment of nano selenium effect in developing zebra fish embryos. *J. Entomol. Zool. Stud.* 7, 914–917.
- Vinceti, M., Mandrioli, J., Borella, P., Michalke, B., Tsatsakis, A., Finkelstein, Y., 2014. Selenium neurotoxicity in humans: bridging laboratory and epidemiologic studies. *Toxicol. Lett.* 230, 295–303. <https://doi.org/10.1016/j.toxlet.2013.11.016>.
- Volkoff, H., London, S., 2018. Nutrition and reproduction in fish. *Environ. Reprod.* 9, 743–748. <https://doi.org/10.1016/B978-0-12-809633-8.20624-9>.
- Wang, L., Xiao, J.X., Hua, Y., Xiang, X.W., Zhou, Y.F., Ye, L., Shao, Q.J., 2019. Effects of dietary selenium polysaccharide on growth performance, oxidative stress and tissue selenium accumulation of juvenile black sea bream, *Acanthopagrus schlegelii*. *Aquaculture* 503, 389–395. <https://doi.org/10.1016/j.aquaculture.2019.01.033>.
- Wangkahart, E., Bruneel, B., Chantiratikul, A., de Jong, M., Pakdeearong, N., Subramani, P.A., 2022. Optimum dietary sources and levels of selenium improve growth, antioxidant status, and disease resistance: re-evaluation in a farmed fish species, Nile tilapia (*Oreochromis niloticus*). *Fish Shellfish Immunol.* 12, 172–182. <https://doi.org/10.1016/j.fsi.2021.12.003>.
- Ward, J.L., Cox, M.K., Schoenfluss, H., 2017. Thermal modulation of anthropogenic estrogen exposure on a freshwater fish at two life stages. *Horm. Behav.* 94, 21–32. <https://doi.org/10.1016/j.yhbeh.2017.05.015>.
- Ward, J.L., Korn, V., Auxier, A.N., Schoenfluss, H.L., 2020. Temperature and estrogen alter predator-prey interactions between fish species. *Integr. Organism. Biol.* 2, 1–11. <https://doi.org/10.1093/iob/obaa008>.
- Wu, G., 2022. Nutrition and metabolism: foundations for animal growth, development, reproduction, and health (Scopus). *Adv. Exp. Med. Biol.* 1354, 1–24. [https://doi.org/10.1007/978-3-030-85686-1\\_1](https://doi.org/10.1007/978-3-030-85686-1_1).
- Yeganeh, S., Adel, M., Ahmadvand, S., Ahmadvand, S., Velisek, J., 2016. Toxicity of organic selenium (Selemax) and its effects on haematological and biochemical parameters and histopathological changes of common carp (*Cyprinus carpio* L., 1758). *Toxin. Rev.* 35, 207–213. <https://doi.org/10.1080/15569543.2016.1213749>.
- Yousef, M.I., El-Demerdash, F.M., Kamel, K.I., Al-Salhen, K.S., 2003. Changes in some hematological and biochemical indices of rabbits induced by isoflavones and cypermethrin. *Toxicology* 189, 223–234. [https://doi.org/10.1016/S0300-483X\(03\)00145-8](https://doi.org/10.1016/S0300-483X(03)00145-8).
- Yu, H., Zhang, C., Zhang, X., Wang, C., Li, P., Liu, G., Yan, X., Xiong, X., Zhang, L., Hou, J., Liu, S., 2020. Dietary nano-selenium enhances antioxidant capacity and hypoxia tolerance of grass carp *Ctenopharyngodon idella* fed with high-fat diet. *Aquacult. Nutr.* 26, 545–557. <https://doi.org/10.1111/anu.13016>.
- Yu, Z., Zhao, L., Zhao, J.L., Xu, W., Guo, Z., Zhang, A.Z., Li, M.Y., 2022. Dietary *Taraxacum mongolicum* polysaccharide ameliorates the growth, immune response, and antioxidant status in association with NF- $\kappa$ B, Nrf2 and TOR in Jian carp (*Cyprinus carpio* var. Jian). *Aquaculture* 547, 737522. <https://doi.org/10.1016/j.aquaculture.2021.737522>.
- Zahmatkesh, A., Karimzadeh, K., Faridnia, M., 2020. Effect of dietary selenium nanoparticles and chitosan oligosaccharide on biochemical parameters of caspian roach (*Rutilus caspius*) under malathion stress. *Casp. J. Environ. Sci.* 18, 59–71. <https://doi.org/10.22124/cjes.2020.3979>.
- Zhao, G., Zhu, Y., Hu, J., Gao, M., Hong, Y., 2022. L-selenomethionine induces zebrafish embryo cardiovascular defects via down-regulating expression of Irf2b. *Chemosphere* 29, 133351. <https://doi.org/10.1016/j.chemosphere.2021.133351>.
- Zhu, L., Han, D., Zhu, X.M., Yang, Y.X., Jin, J.Y., Liu, H.K., Xie, S.Q., 2017. Dietary selenium requirement for on growing gibel carb (*Carassius auratus gibelio* var. CAS III). *Aquacult. Res.* 48, 2841–2851. <https://doi.org/10.1111/are.13118>.
- Ziaei-Nejad, S., Hosseini, S.M., Mortezaei, S.R.S., 2021. Effects of selenium nanoparticles supplemented feed on biochemical indices, growth and survival of Yellow-Tail Seabream (*Acanthopagrus latus*). *J. Agr. Sci. Tech.* 23, 1001–1011. <http://jast.modares.ac.ir/article-23-44533-en.html>.