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Significance of macro and micro-minerals in fish diet: An overview

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ABSTRACT

Aquatic animals possess specialized physiological mechanisms enabling the absorption and retention of essential minerals from their diet and surrounding water. However, significant knowledge gaps persist regarding the trace element requirements, bioavailability, and underlying physiological processes in aquaculture species. Research on the mineral nutrition of farmed fish and crustaceans has been relatively limited, despite the critical role of these elements in supporting growth, metabolism, and overall health. Trace and inorganic minerals are indispensable for sustaining physiological functions and optimal development in aquatic organisms. Therefore, precise mineral requirements must be considered in feed formulations to prevent deficiencies and reduce the environmental impact. Excessive release of minerals from uneaten feed or excretion can contribute to eutrophication, posing a challenge to sustainable aquaculture practices. Bridging these research gaps is essential for advancing aquafeed development and promoting environmentally responsible aquaculture.

Key words: Fish, macro-minerals, metabolism, micro/trace minerals, nutrition

INTRODUCTION

Minerals play a vital role in supporting the physiological and biochemical functions essential for maintaining normal life processes in both terrestrial and aquatic species. Fish, living in freshwater and marine environments, possess the ability to absorb inorganic elements from their diet and surroundings (Suttle, 2022). The essential roles of macrominerals such as calcium, phosphorus, magnesium, sodium, potassium, and chloride, as well as trace elements like cobalt, copper, iodine, iron, manganese, selenium, and zinc, have been well-established in fish. However, other trace elements such as arsenic, boron, chromium, fluorine, nickel, lithium, lead, molybdenum, silicon, and vanadium which are considered essential for humans and other animals due to their role in specific physiological functions, have not been documented in fish. Compared to other nutrients, mineral nutrition in fish has received relatively limited attention. Notably, trace minerals such as iron, manganese, zinc, copper, cobalt, selenium, chromium, and iodine are present in only small quantities in aquatic organisms (NRC, 2011; Antony et al., 2016).

Minerals are known to interact with other nutrients due to their reactive nature and ability to form chemical bonds. O'Dell (1997) defined mineral interactions as "interrelationships among mineral elements as revealed by physiological or biochemical consequences." These interactions are generally categorized as either positive (synergistic) or negative (antagonistic). Positive interactions often involve cooperative roles in physiological structures and processes for instance, copper (Cu) and iron (Fe) are essential for hemoglobin synthesis; calcium (Ca), phosphorus (P), and magnesium (Mg) are jointly required for the formation of bone hydroxyapatite; and manganese (Mn) works with zinc (Zn) to maintain the structural integrity of RNA molecules in the liver. Conversely, antagonistic interactions occur when elements with similar electronic configurations and ionic radii compete for the same binding sites. Examples include the competition between Zn and cadmium (Cd) for metallothionein binding, or the substitution of Mg and Mn at enzyme active sites. In the gastrointestinal tract, antagonism may also arise through the formation of insoluble complexes, for example, copper and sulfur (S) forming copper sulfide, or zinc binding with phytic acid to form phytates (Erdman, 1979). Various mineral-mineral and mineral–vitamin interactions have also been documented in fish species (Hilton, 1989). Specific interactions involving individual trace elements are discussed in their respective sections.

MECHANISMS OF MINERAL ABSORPTION AND NUTRITIONAL DYNAMICS IN FISH

The mineral nutrition of fish has received less attention compared to other nutrients. At the cellular level, it is generally believed that the molecular mechanisms of mineral metabolism in fish are similar to those in terrestrial animals. However, estimating the quantitative dietary requirement is complex due to the ions' passage across fish skin and gills from the surrounding water (Lall, 2002). Fish gills are thought to be the primary site for absorbing waterborne minerals in freshwater (FW). According to Evans and Claiborne (2009), in seawater (SW), fish drink water as part of their osmoregulatory system, keeping their internal body fluids significantly less saline than the external saltwater environment. Therefore, dietary mineral absorption from the digestive tract becomes more significant in freshwater fish. Anadromous fish, like salmonids, undergo transitions between FW and SW phases during their lives, where they gradually acclimatize to the marine environment and acquire inorganic elements by drinking SW, similar to marine fish. Differences may exist in how fish absorb minerals due to variations in gastric acid secretion between fish with stomachs and those without, as well as differences in mineral uptake from water (Lall, 2002).

Minerals released into the aquatic environment from uneaten feed, as well as from fecal and urinary waste produced in hatcheries and aquaculture systems, significantly impact the water quality (Lall and Milley, 2008). These minerals are excreted in both soluble and particulate forms. While soluble minerals directly affect water chemistry, particulate matter may settle at the bottom of ponds and tanks, accumulate at the downstream ends of raceways, or deposit in sediments beneath fish cages (Fig. 1). The composition of feed ingredients and the type of mineral supplements whether inorganic or organic greatly influence the release of mineral-bound fecal matter and the concentration of soluble mineral compounds excreted in urine. Environmental conditions, including water flow, temperature, dissolved oxygen, pH, salinity, and microbial activity, also play a critical role in the breakdown and mobilization of minerals from waste. Studies have shown that elevated levels of Zn and Cu found in sediments beneath sea cages, resulting from feed inputs, can decline to background levels following appropriate chemical remediation (Brooks et al., 2003; Dean et al., 2007). Additionally, certain trace elements such as Cu, Zn, and cadmium (Cd) may associate with naturally occurring organic matter. These metal-bound organic particles can be remobilized into the dissolved phase, forming complexes with organic ligands in pore water (Ponce et al., 2004).

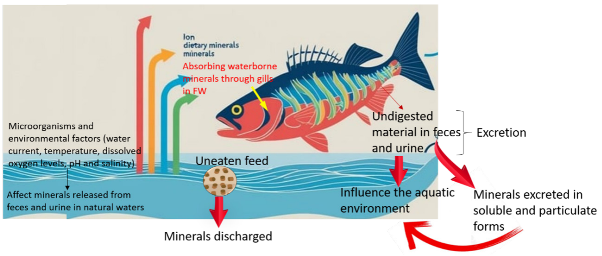

Fig. 1. Mechanism of minerals absorption and nutritional dynamics in fish

Macro-minerals

Macrominerals are essential nutrients required by fish in relatively large amounts, playing pivotal roles in their physiological and biochemical processes. The primary macrominerals in fish include calcium, phosphorus, magnesium, sodium, potassium, chlorine, and sulfur. These minerals are integral to growth, metabolism, and overall health, influencing key functions such as skeletal development, osmoregulation, enzyme activation, and nerve and muscle function. Table 1 outlines the key minerals required by fish along with their recommended levels for optimal growth and performance. These requirements vary depending on the species, age, environmental conditions, and dietary factors. It serves as a guide for formulating balanced aquafeeds to meet the nutritional needs of fish while ensuring efficient production and maintaining water quality. Understanding these requirements is crucial for enhancing the sustainability of aquaculture systems.

Table 1. Macro-minerals requirement of fish and crustaceans

Macro-minerals	Fishes	Dietary requirements (per kg feed)	Crustaceans	
Calcium (g)	Trouts and salmon	0.2-0.3	Prawns	10-18
	Common carp	0.28		
	Indian and Chinese carp	5-18		
	Red sea bream	3.4		
	Japanese eel	2.7		
	Other fishes	5		
Phosphorus (g)	Trouts and salmon	7-8	Prawns	9
	Common carp	6-7		
	Tilapia	9		
	Red sea bream	6.8		
	Sea bass & sea bream	7-8		
	Japanese eel	2.9		
	Channel catfish	4-7		
	Indian and Chinese carp	5-7		
Magnesium (g)	Trouts and salmon	0.5-0.7	Prawns	0.8-1.0
	Carps	0.4-0.5		
	Other fishes	0.5		
Sodium (g)	Fishes	1-3	Prawns	6
Potassium (g)	Fishes	1-3	Prawns	9

Source: ADCP (1983); Cho et al. (1985); New (1987)

Phosphorus and Calcium

Calcium and phosphorus play crucial roles in the development and maintenance of the skeletal system (Lall and Lewis-McCrea, 2007). While fish can absorb calcium from the water, the concentration of phosphorus is typically low in freshwater, making it necessary to supply phosphorus through their diet (Lall, 2002). When fish suffer from phosphorus deficiency, they may exhibit poor bone mineralization and skeletal abnormalities, such as deformed bones, curved spines, and ribs (Yang et al., 2016; Yuan et al., 2021). To address this deficiency, phosphorus supplements are commonly used in fish feed, often in the form of phytase to hydrolyze phytate-bound phosphorus found in plant-based feed ingredients (Pandey et al., 2015; Hossain et al., 2020). For example, studies have reported that species-specific dietary phosphorus requirements must be met to support optimal growth, feed efficiency, and haematological parameters (Yang et al., 2016; Yuan et al., 2021). However, carp growth was observed in the presence of dietary phosphorous levels and was not related to calcium levels. In rainbow trout fry, the dietary levels of phosphorus and calcium have an impact on skeletal development and mineral deposition. Moreover, as dietary phosphorus levels increase, the retention of phosphorus decreases (Fontagné et al., 2009).

Magnesium

Magnesium is a vital mineral required for normal growth, reproduction, and the prevention of skeletal abnormalities in fish (Lall, 2002; Liang et al., 2015; Liu et al., 2018). Magnesium is an essential intracellular divalent cation that plays a crucial role in numerous physiological processes within the body. It forms stable complexes with ATP, thereby participating in vital biological functions such as protein synthesis, cell division, and energy metabolism. Additionally, magnesium regulates ion channels, serves as a key intracellular signaling molecule, and contributes to nerve impulse transmission, muscle contraction, potassium transport, and the modulation of oxidative phosphorylation. It acts as a cofactor for crucial enzymes like manganese superoxide dismutase (Mn-SOD) and pyruvate carboxylase, which are involved in cellular physiological mechanisms such as the metabolism of proteins, fats, and carbohydrates. Magnesium deficiency can cause calcinosis of the kidney, vertebra deformities, degradation of muscle fibres, and damage to epithelial cells of the pyloric cecum and gill filaments (Liang et al., 2012). A significant portion of magnesium (50-70%) in the fishbodyis located in skeletal tissue and scales, while the remaining 20% is found within soft tissue cells (Lall, 2021). For farmed fish, the magnesium requirement is approximately 0.4 to 0.6 kg per diet (NRC, 2011).

Micro-minerals

The micro or trace elements serve four major biochemical functions: catalytic, structural, physiological, and regulatory (NRC, 2011). Additionally, numerous metalloenzymes play vital roles in various metabolic functions, such as energy synthesis, protein digestion, cell reproduction, and antioxidant action. More than one-third of all proteins require a trace element cofactor for proper functioning (Andreiniet al., 2009; Maret, 2010). Deficiencies or suboptimal levels of trace elements may lead to a decline or loss of enzyme activity (Lall, 2010). In recent times, certain micronutrients and immunostimulants have received increased attention to reduce vulnerability to various stresses and diseases and to improve the overall health of fish and other animals (Richards et al., 2010; Lehman et al., 2011; Mohan et al., 2019). Table 2 provides a summary of the dietary requirements of trace minerals in some fish species.In aquatic organisms, particularly fish, a positive relationship has been observed between dietary mineral content and growth performance indicators. While existing studies on trace minerals remain relatively limited, research in this area continues to expand as their significance in aquaculture nutrition becomes increasingly recognized.

Table 2. Dietary requirement of the trace minerals in fish species

Trace minerals	Fish species	Requirement level (mg kg^{-1} diet)	References
Iron	Atlantic salmon Channel catfish Red sea bream Eel	33 – 100 30 150 170	Gatlin and Wilson (1986) Sakamoto and Yone (1976, 1978) Nose and Arai (1979)
Copper	Rainbow trout and Carp Channel catfish Atlantic salmon	3 5	Ogino and Yang (1980) Gatlin and Wilson (1986)
Manganese	Channel catfish Rainbow trout and Carp Juvenile stage fish Salmon and Trout broodstock	2.4 12 – 13 2 – 15 >30	Gatlin and Wilson (1984) Ogino and Yang (1980) Satoh et al. (1987) Lall (2002)
Zinc	Rainbow trout and Common carp Atlantic salmon Blue tilapia Red drum	15 – 30 37 – 67 20 20 – 25	Ogino and Yang (1978) Maage and Julshamn (1993) McLain and Gatlin (1988) Gatlin et al. (1991)
Iodine	Atlantic salmon	4.5	Lall (2021)
Selenium	Rainbow trout Channel catfish Gibel carp	0.15 – 0.38 0.25 1.18	Hilton et al. (1989) Gatlin and Wilson (1984) Han et al. (2011)
Cobalt	All general fishes	0.05 – 1.0	Watanabe et al. (1997)
Molybdenum Chromium Fluorine	Trace amounts (µg)	0.1– 0.2	ADCP (1983); Cho et al. (1985)

Copper

Copper (Cu) is recognized as an essential trace element necessary for the proper cellular functioning of all living organisms. Its biological importance stems from its ability to alternate between different redox states, primarily the oxidized form (Cu^{2+}) and less commonly, the reduced form (Cu^{+}). In animals, including fish, copper plays a vital role as a cofactor in several key enzymes, such as tyrosinase, cytochrome c oxidase, superoxide dismutase, lysyl oxidase, and dopamine β-hydroxylase (Gundogdu et al., 2009). The metabolism of copper in fish is comparable to that in mammals, with elevated concentrations of copper and copper-dependent enzymes found in tissues like the liver, brain, heart, and ocular regions (e.g., iris and choroid) (Kamunde et al., 2002). Fish acquire copper through both the gills and the gastrointestinal tract, although dietary intake is generally considered the primary source supporting growth, development, and physiological processes (Kamunde et al., 2002; Bury et al., 2003). The extent of copper absorption through the gills can vary depending on the concentration of copper in the surrounding water (Taylor et al., 2003) and this pathway becomes more prominent when dietary copper levels are insufficient. For instance, in rainbow trout maintained on a copper-deficient diet, approximately 60% of the body's copper was derived from waterborne sources, whereas fish provided with copper-rich diets obtained up to 99% of their copper from dietary sources (Kamunde et al., 2002). The mechanisms of copper uptake from water and its associated toxicity have been the subject of extensive research and critical reviews (Grosell, 2012).

Manganese

Manganese is an essential element crucial for appropriate brain function and plays a vital role in lipid and glucose metabolism (Liu et al., 2013). Its uptake mechanisms from water and the gastrointestinal system are not widely recognized. In fish, manganese is important for broodstock nutrition, and its deficiency often leads to slower growth. For instance, both rainbow trout and carp show poor growth when fed with an insufficient manganese diet (Liu et al., 2013). Tan et al. (2012) reported that manganese deficiency in rainbow trout and carp led to dwarfism and disturbances in bone formation, as well as cataracts in the eye lens. The deficiency also resulted in a reduction of skeletal manganese content due to insufficient dietary supply. Previous studies have indicated that brook trout and rainbow trout eggs had poor hatchability when fed manganese-deficient fish meal diets (Lall, 2002). However, improved growth was observed in carp fed with manganous sulfate, which also enhanced protein synthesis and inhibited fat production in the liver (Liu et al., 2013). A manganese supplement of 10 mg kg^{-1} was found to be necessary for healthy growth without deficient symptoms (NRC, 2011).

Zinc

Zinc is a crucial trace mineral in fish nutrition, as it is involved in prostaglandin metabolism and plays a structural role in nucleoproteins. Clinical signs of zinc deficiency in fish may result from disruptions in protein and nucleic acid metabolism (Fountoulaki et al., 2010). Zinc intake in fish can occur from both feed and water, but dietary supplementation is more effective. The gills and the gastrointestinal tract are the primary sources of zinc intake in fish. Hossain and Furuichi (2000) observed that the entire digestive tract of flounder fish is capable of absorbing zinc, with the uppermost route of the intestine having the highest capacity and the stomach having the lowest. Additionally, K€uc€ukbay et al. (2006) revealed that the gills of rainbow trout play an essential role in excreting dietary zinc. Zinc is generally eliminated by the kidney and chloride cells of the gills. Interestingly, even when fish have an adequate dietary zinc supplement, uptake of water-dissolved zinc still occurs. Zinc deficiency in fish leads to poor development and lowered protein and carbohydrate digestibility, possibly due to decreased carboxy peptidase activity (Viegas et al., 2021).

Iodine

Iodine is essential for thyroid hormones, which regulate the level of metabolic activity in fish. Thyroid hormones significantly impact growth, cellular oxidation, neuromuscular control, circulatory dynamics, and food metabolism (Lall and Kaushik, 2021). Fish differ from mammals in their use of iodine and additional thyroidal metabolism of triiodothyronine (T3) and thyroxine (T4). T3 has a stronger interaction with plasma proteins than T4, and its turnover rate in trout is lower than that of T4. T3 and T4 are primarily excreted through bile, with the gills and kidneys are also involved (Eales, 2019). Iodine shortage has been shown to cause thyroid hyperplasia in salmonid fish (NRC, 2011). Iodine can be taken up by the gills from the surrounding water, and the rate of uptake is inversely proportional to the calcium concentration of the water. Dietary iodine is readily absorbed in the digestive tract (Lall and Kaushik, 2021). Freshwater fish exhibit higher iodine deficiency symptoms and rely more on dietary sources for iodine due to the lower iodine content in freshwater compared to seawater.

Selenium

Selenium (Se) is widely acknowledged as both an essential micronutrient and a potential toxicant in fish diets and aquatic environments, particularly in salmonids (Lall and Kaushik, 2021). Its importance in aquaculture has been demonstrated across several farmed fish species reared in both freshwater (FW) and seawater (SW) systems (Lall, 2002; NRC, 2011; Antony et al., 2016). In the environment, selenium exists in four primary inorganic oxidation states: selenate, selenite, elemental selenium, and selenide. Within biological systems, these inorganic forms are metabolized into bioavailable organic compounds, chiefly the seleno-amino acids selenocysteine (SeC) and selenomethionine (SeMet). Selenoproteins, which incorporate SeC, play critical roles in a range of physiological processes (Labunsky et al., 2014; Roman et al., 2014). The dietary selenium requirements of fish have been determined using various response parameters such as growth rate, glutathione peroxidase (GPx) activity in liver and plasma, and selenium concentrations in whole body and tissues like liver and muscle. These requirements vary depending on the chemical form of selenium (organic or inorganic), its bioavailability from different dietary sources, vitamin E levels in the diet, and selenium concentrations in the rearing water (Mohanta and Garg, 2014). Deficiency symptoms due to inadequate dietary selenium intake have been observed in several fish species and are commonly marked by reduced GPx enzyme activity in plasma and liver (Liu et al., 2010; Han et al., 2011; Zhu et al., 2011; Zhu et al., 2016; Domínguez et al., 2019; Wang et al., 2019; Ning et al., 2020).

Cobalt

The dietary requirement of cobalt (Co) in fish varies depending on species and physiological needs. For instance, an estimated requirement of approximately 100 mg Co kg^{-1} of diet has been reported for *Tilapia zillii* (Lall and Kaushik, 2021). However, significantly lower concentrations, such as 10 mg Co kg^{-1} have been shown to be sufficient in *Malabar grouper* to support adequate gastrointestinal synthesis of vitamin B_{12}, thereby fulfilling the species' dietary need for this vitamin (Lin et al., 2010). In freshwater fish, cobalt uptake occurs mainly through the gills and gastrointestinal tract, which serve as the principal absorption routes (Baudin et al., 2000; Wood et al., 2012). The uptake pathways, homeostatic regulation, and mechanisms underlying cobalt toxicity have also been comprehensively reviewed by Wood et al. (2012). Cobalt is present in most common feed ingredients, including those used in animal and aquafeeds at typically lower levels and do not pose toxicity risks (NRC, 2005; Suttle, 2010). Research into the role of trace minerals in aquaculture has demonstrated that dietary cobalt can positively influence growth performance in species such as carp and rainbow trout, while also enhancing survival in gold spot mullet (*Liza parsia*) (Paul and Mukhopadhyay, 2001). Pati and Mondal (2009) observed that the optimal cobalt levels for fish generally range from 0.05 to 5 mg kg^{-1} of diet. Cobalt supplementation has been found to improve growth in *Asian sea bass* and Asian catfish (Sapkale and Singh, 2011). A recent study by Huang et al. (2024) also confirmed that optimal dietary cobalt levels enhanced growth performance and feed utilization in largemouth bass.

Chromium

Chromium (Cr) is a transition metal that exists in Cr^{3+} (trivalent) and Cr^{6+} (hexavalent) forms in food and the environment. Its bioavailability and toxicity vary greatly depending on the oxidation states. Although pharmacological doses of chromium have been investigated for their potential benefits in improving insulin sensitivity and lipid metabolism, chromium is not regarded as an essential mineral (EFSA, 2014; Vincent, 2017). Research on the specific effects of Cr in fish relates to its role in metabolism, growth, and toxicity (Giri et al., 2014; Vincent, 2017). Chromium is absorbed across the gills and transferred to tissues via blood, but the processes of absorption from the gills and the gastrointestinal tract, as well as excretion. Cr^{6+} quickly crosses cellular membranes and converts to the trivalent form (Reid, 2012). Increased Cr levels in feed and water have been associated with histological abnormalities in the intestine, gills, liver, and kidney, although the mechanism of intoxication is not fully understood (Reid, 2012; Bakshi and Panigrahi, 2018).

CONCLUSION

The importance of minerals in fish nutrition and the need for trace elements in small amounts to support normal metabolism and biological functionshas been discussed in detail in this review. It also highlights the potential risks of excessive supplementation leading to toxicity. Fish can absorb some necessary elements directly from the water through their gills or body surface, but these sources may not fully meet their requirements, necessitating the consumption of supplemental feed or natural food. Detecting ultra-trace elements at the tissue level requires precise analytical methods. The passage also points out the lack of sufficient research on how trace elements affect the fatty acid metabolism, especially that of polyunsaturated fatty acids. To meet the demand for trace minerals, specific diets with added trace minerals should be formulated. It emphasizes the need of research to understand the role and requirements of trace mineral nutrition in fish.

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