doi:10.20944/preprints202108.0088.v1

Review

Nutrition and Metabolism of Minerals in Fish

Santosh P. Lall [1], Sadasivam J. Kaushik[2]

[1] Retired from National Research Council of Canada, Halifax, NS, Canada; santosh.lall13@gmail.com
[2] Retd. INRA, France; Former ERA Chair, Ecoaqua, Univ Las Palmas de Gran Canarias, Spain ; kjsachi@gmail.com
Correspondence: santosh.lall13@gmail.com

Simple Summary: Our aim is to introduce the mineral nutrition of fish and explain the complexity of determining requirements as these elements, which are absorbed and excreted by the fish into the surrounding water. To date, only the requirement of nine minerals have been investigated. The review is focused on the absorption and the dietary factors that reduce their absorption from feed ingredients of plant and animal origin. Some of diseases such as cataracts, anaemia and bone deformity have been linked to dietary deficiency of minerals.

Abstract: Aquatic animals have unique physiological mechanisms to absorb and retain minerals from their diets and water. Research and development in the area of mineral nutrition of farmed fish and crustaceans have been relatively slow and major gaps exist in the knowledge of trace element requirements, physiological functions and bioavailability from feed ingredients. Quantitative dietary requirements have been reported for three macroelements (calcium, phosphorus and magnesium) and six trace minerals (zinc, iron, copper, manganese, iodine and selenium) for selected fish species. Mineral deficiency signs in fish include reduced bone mineralization, anorexia, lens cataracts (zinc), skeletal deformities (phosphorus, magnesium, zinc), fin erosion (copper, zinc), nephrocalcinosis (magnesium deficiency, selenium toxicity), thyroid hyperplasia (iodine), muscular dystrophy (selenium) and hypochromic microcytic anaemia (iron). An excessive intake of minerals from either diet or gill uptake causes toxicity and therefore a fine balance between mineral deficiency and toxicity is vital for aquatic organisms to maintain their homeostasis either through increased absorption or excretion. Release of minerals from uneaten or undigested feed and from urinary excretion can cause eutrophication of natural waters, which requires additional consideration in feed formulation. The current knowledge in mineral nutrition of fish is briefly reviewed.

Keywords: Minerals, Trace elements, Fish, Copper, Iron, Selenium, Manganese, Zinc, Calcium, Phosphous, Magnesium

---

1. Introduction

All aquatic animals require minerals for their vital physiological and biochemical functions and to maintain their normal life processes. Fish live in a wide range of salinity (0-35 0/00) in freshwater (FW), seawater (SW) and brackish water (BW) environments, and unlike other vertebrates absorb minerals from the diet as well as surrounding water. Most of the essential minerals required for animals and other vertebrates (Suttle, 2010) have been detected in fish tissues. The essentiality of macrominerals (calcium, phosphorus, magnesium, sodium, potassium and chloride) and certain trace elements (cobalt, copper, iodine, iron, manganese selenium and zinc) have been confirmed in fish (NRC, 1993; 2011). Other trace elements (arsenic, boron, chromium, fluorine, nickel, lithium, lead, molybdenum, silicon, and vanadium) considered essential for humans and animals based on the impairment of specific physiological functions have not been reported in fish. Mineral nutrition of fish has received limited attention as compared to other nutrients. The main focus of the current review is trace element nutrition and metabolism of fish with a brief discussion on major macrominerals. A significant amount of research has been directed towards the physiological aspects of waterborne mineral toxicity and is the subject of comprehensive reviews (Wood et al., 2012a,b).

The biochemical mechanisms of mineral metabolism in fish are generally considered similar to those of terrestrial animals at the cellular level. The exchange of ions from across the gills and skin of fish in surrounding water complicates the determination of the quantitative dietary requirement (Lall, 2002). Gills comprise over 50% of the surface area of the fish and are considered the major route of uptake of waterborne minerals in FW. In SW fish exhibit obligatory drinking as part of their overall physiological osmoregulatory mechanism to maintain internal body fluids substantially hypotonic to the external salinity of seawater (Evans and Claiborne, 2009). Therefore, absorption of dietary minerals from the gastrointestinal tract is important in FW fish, whereas in SW fish, both dietary and waterborne minerals are absorbed. The life cycle of anadromous fish like salmonids consists of FW and SW, where they gradually adapt to a marine environment and acquire inorganic elements by drinking SW similar to marine fish.

In the past two decades, the number of crustaceans, FW and marine fish species have increased considerably (Tacon et al., 2021). Often generalization is made estimating their mineral requirements based on salmonids and certain freshwater species with proper consideration for the determination made on different types of diets (purified, semi-purified and practical diet) and use of inorganic supplements with high bioavailability. In addition, fish feeds have become increasingly comprised of alternate sources of plant-based feed ingredients as compare to widely used fish meal before due to the increase in global aquaculture production and its limited supply. Obviously there is a need to reassess the mineral requirements as well as their bioavailability from a wide range of plant feed ingredients as well as new alternate sources of feed ingredients to fish meal. The absorption of minerals may vary among fishes because of differences in gastric acid secretion in fish with stomach and agastric or stomachless fish (Lall, 2002) as well as uptake of minerals from water. There are also differences in the methodology used to measure the mineral requirements and response criteria (e.g., growth, feed utilization, whole body and/or vertebrae, plasma/serum and tissue mineral concentration, hematology and changes in specific enzyme activities).

Minerals are known to interact with other nutrients due to their lability and tendency to form chemical bonds. The term “interaction” for minerals was defined by O’Dell (1997) as “interrelationships among mineral elements as revealed by physiological or biochemical consequences”. Such interactions are broadly classified as positive or synergistic, or negative or antagonistic. Direct positive interactions between elements in structural processes such as the requirement of copper (Cu) and iron (Fe) for hemoglobin formation, calcium (Ca), phoshorus (P) and magnesium (Mg) for formation of bone hydroxyapatite and an interaction of Mn with Zn for proper conformational shape of RNA molecules in the liver have been widely recognized. Antagonistic relationships occur when elements with a similar electronic configuration and ionic radius compete for binding sites, e.g., Zinc (Zn) and cadmium (Cd) in metallothionein, and Mg/manganese (Mn) substi¬tutions at enzyme active sites. In the gastrointestinal tract, antagonistic relationships may occur by a simple mechanism, which involves a chemical reaction forming an insoluble complex between minerals such as Cu and sulphur (S) to form copper sulfide or a mineral and another dietary component such as Zn combined with phytic acid to form phytate (Erdman, 1979). A wide range of potential mineral-mineral and mineral-vitamin interactions in fish have also been reported (Hilton, 1989). Specific trace element interactions are discussed in appropriate individual sections.

Extensive research conducted on animals have clearly shown that mineral requirements are significantly affected by their bioavailability from different forms of feed supplements and feed ingredients. Bioavailability has been defined as the proportion of element consumed that is utilized for biochemical or physiological functions (O’Dell, 1997). Generally, the bioavailability reflects the absorption of the nutrient. From a practical standpoint, measurement of biochemical and physiological functions may not always be possible. Ammerman et al. (1995) suggested that more emphasis should be on the degree to which an ingested element could be utilized for metabolism. Limited information exists on the utilization and metabolism of trace elements in fish. The following methods have been used to determine the bioavailability of trace minerals in animals (Ammerman, 1995; O'Dell, 1997, Spears and Hansen, 2008): a), growth, b) apparent absorption or digestibility, c) plasma or tissue mineral concentration, d) mineral retention or balance, e) specific enzyme activity (e.g., superoxide dismutase, glutathione peroxidase) or blood parameter (e.g., hemoglobin level), f), prevention of deficiency signs. Some of these methods have also been used in fish to estimate the bioavailability of Zn, Fe and selenium (Se) from chemically defined or practical diets based on fish meal and plant protein and are discussed later in individual sections.

Aquatic animals accumulate excessive minerals from water which can interact with as well as inhibit proteins that facilitate essential ion transport (Bury et al., 2003; Wood, 2012). Metal binding reactions include competition at the biotic ligand with other cations (e.g., Na+, H+, Ca2+) and competing complexation reactions for the metal by other ligands in solution including inorganic anions (e.g., chloride, hydroxide, sulfide) as well as organic ligands such as dissolved organic carbon (Brix et al., 2017). For example, accumulation of Cu or silver (Ag) at the fish gill interferes with Na+ uptake, thereby disrupting ionic balance in the organism leading to toxicity (Grosell, 2012). Similarly, Cd and Zn interfere with Ca uptake at the fish gill, leading to hypocalcaemia and toxicity (Hogstrand, 2012). The ability of fish to regulate high concentrations of trace elements originating from water varies among different fish species. The major route of uptake for some metals, such as Se, mercury (Hg), and arsenic (As) is trophic transfer through the food chain. Certain fish are able to excrete high proportions of excessive metal intake and consequently regulate the concentration in their body at relatively normal levels (Handy, 1996). The soluble trace elements in water are considered more toxic than higher dietary intake of minerals such as Cu, Fe and Zn. The subject of aquatic toxicology to fish is beyond the scope of this review.

Minerals discharged from uneaten feeds, excretion of undigested material in feces and urine from hatcheries and aquaculture operations directly influence the aquatic environment (Lall and Milley, 2008a). These minerals excreted in soluble and particulate forms affect the water quality. The particulate form can settle to the bottom of the tank or accumulate in the sediment under fish cages. The breakdown of organically-bound minerals from feed and feces varies considerably due to differences in the chemical characteristics of feed ingredients and type of mineral supplements used, the environmental conditions (e.g., temperature, oxygen, pH and salinity, water current) and the type of micro-organisms in natural waters. Elevated levels of Zn and Cu have been found in sediments under the sea cages of salmon farms (Dean et al., 2007). Experimental studies have demonstrated that the concentration of these trace elements in sediments decrease to background levels after chemical remediation (Brooks et al., 2003). These studies indicate that metals complexed with free sulphides, particularly Cu and Zn are released to the water column during the chemical remediation process.

Copper, zinc and cadmium may be incorporated into the sediment from accumulated feed and faeces; however, these trace elements can also be associated with naturally occurring organic debris. The decomposition of organic material during early stages of diagenesis in the oxidized surface layers influences the pore water concentration of Cu, Zn and Cd, and results in elevated pore water levels. Organic particles associated with metals are remobilized into the dissolved phase, and soluble Cu, Zn and Cd form complexes with organic ligands in pore waters (Petersen et al., 1995; Ponce et al., 2000). Generally fish feeds are not supplemented with Cd, however, fishery by-products and other ingredients may contribute to a minor amount of Cd in the finished feed. Cadmium is relatively less soluble in reducing pore waters than toxic overlying waters (Sundby et al., 2004). Cadmium can be scavenged from the water column and ultimately deposited with organic particles (McGeer et al., 2012). Several countries have developed regulations to regulate the maximum limit of mineral supplementation in aquatic animal feeds to reduce their impact on the environment.

The main purpose of this review is to update current knowledge of mineral nutrition of fish and to identify areas that require future research particularly trace elements.

2. Microminerals

Optimum levels of essential macro-and microminerals are required for growth and maintenance of normal health of fish. Four broad biochemical functions of micro or trace elements are widely recognized: a) catalytic, b) structural, c) physiological and d) regulatory (Mertz, 1998). Trace minerals can act as catalysts in enzyme and endocrine systems, as integral and specific components of the structure of metalloenzymes and hormones or as activators (coenzymes) within those systems. More than one-third of all proteins require a trace element cofactor for normal function (Maret, 2010; Andreini et al., 2009). Numerous metalloenzymes are required for a wide range of metabolic activities such as energy production, protein digestion, cell replication and antioxidant activity, which are discussed in later sections. Deficiencies or suboptimum levels of the trace element may cause a decrease or loss of enzyme activities (Lall, 2010). Increased attention has been focused on certain micronutrients and immunostimulants to reduce susceptibility to various stressors and diseases, as well as enhance the overall health of humans, animals and fish (Lehmann et al., 2011; Richards et al., 2010; Mohan et al., 2019). The concept is based on understanding the contribution of minerals in reducing the detrimental effects of free radicals and toxic metabolites on immune processes in the animal's body. The knowledge in this area on the role of minerals in fish or shrimp as compared to animals and humans is scant.

2.1. Copper

It is widely accepted that Cu is an essential trace element required for cellular functioning of all living organisms. Copper ions have a unique chemistry due to their ability to adopt distinct redox states, either oxidized Cu2+ or the reduced state Cu3+. Because of the high avidity of biological ligands, free ionic Cu2+ is present in physiological fluids at extremely low concentrations. Copper metalloenzymes are involved in Fe metabolism, cellular energy production (cytochrome c oxidase), protection of cells from free radical damage (superoxide dismutase), collagen synthesis (lysyl oxidase) in brain neurotransmitters (dopamine hydroxylase and peptidyl alpha amidating monoxygenase), and melanin production (tyro-sinase) (Linder, 2002). Four Cu-containing enzymes, known as multi-copper oxidases (MCO) or ferroxidases oxidize Fe2+ to Fe3+ ion, the form of iron that can be incorporated onto the protein transferrin for transport to the site of red blood cell formation. The MCO family comprises the circulating and membrane bound ceruloplasmin and two other proteins (Prohaska, 2011). Metabolic changes in Cu requiring proteins or alterations in enzyme activities may cause pathophysiological conditions (Harris, 2003).

Fish absorb Cu via the gills and digestive tract; however, the diet is considered a major source of Cu for growth, development and essential physiological functions (Kamunde et al., 2002; Bury et al., 2003). The gill may contribute to a significant amount of Cu uptake depending upon the Cu concentration of the water (Taylor et al., 2003), particularly when dietary Cu intake is low (Miller, 1993). In rainbow trout fed Cu-deficient diet, waterborne Cu uptake contributed the major proportion (60 %) of the body's Cu; however, feeding high levels of Cu contributed to nearly 99 % of body Cu (Kamunde et al., 2002). Uptake of Cu from water and its toxicity has been extensively studied and reviewed (McDonald and Wood 1993; Grosell, 2012). Copper uptake is facilitated via two distinctive mechanisms: a) by a transmembrane protein (Cu transporter 1) and b)the apical Na+-uptake pathways located at branchial epithelial cells. The former pathway is insensitive to external Cu concentrations, and the latter pathway involving Na+-uptake is sensitive to Cu (Grosell and Wood, 2002). In gastrointestinal Cu transport, apical Cu uptake appears to be passive while basolateral transport is active and rate limiting (Clearwater et al., 2000; Handy et al., 2000). Copper is known to induce oxidative stress, olfactory impairment, increased plasma ammonia and disturbed acid-base balance (Eyckmans et al., 2011; Grosell, 2012).

Maintaining Cu homeostasis demands a critical physiological orchestration between Cu uptake and distribution within cells, and detoxification and removal. In fish and terrestrial vertebrates, the liver is the main organ involved in Cu homeostasis and metabolism (Cousins, 1985; Grosell and Wood., 2002). Most studies on Cu homeostasis in fish have been conducted in FW fish. After gill uptake and absorption from the gut, Cu is cleared from blood by the liver and incorporated into ceruloplasmin for transport to extrahepatic organs, stored in Cu-protein complexes or excreted via the bile (Handy , 1996; Grosell et al., 1996).

2.1.1. Requirement

The dietary Cu requirement has been reported for several freshwater and marine fish (Table 1). These requirements are relatively low as compared to other trace elements. It is necessary to know the concentration of Cu in water, feed ingredients and tissue levels prior to requirement studies, in order to properly estimate the quantitative Cu requirement (Suttle, 2010). Copper in the water alone cannot meet the requirements so oral administration of Cu is essential for aquatic animals (NRC, 2011). Dietary Cu requirement would also depend on the physiological state of the animal, Cu concentration in the water, and probably the level of elements that are metabolic antagonists of copper, such as Fe, Zn, Cd, and Mo (NRC, 2005; Suttle, 2010). A meta-analysis of published information on Cu requirement of several fish species showed relatively close estimates for the Cu requirement (mg kg-1 diet) based on the following parameters: weight gain, 5; liver Cu concentration, 6; liver CuZn SOD activity, 4 (Antony Jesu Prabhu et al., 2016). In rainbow trout, the antagonistic effects of Zn and Cu have not been observed (Knox et al., 1982). An interaction between dietary Cu and Se was observed in Atlantic salmon, where liver Se was inversely related to dietary Cu concentration (Lorentzen et al., 1998).

As regards shrimp, Davis et al. (1993b) found that Pacific white shrimp (*P. vannamei*) would require no more than 34 mg total Cu/kg-1 diet and that high levels of dietary Cu levels did not have any adverse effects on growth or survival. In black tiger shrimp, P. monodon, Lee and Shiau (2002) established the dietary Cu requirement to be 15–21 mg Cu kg-1 diet. Based on immune response indicators, a dietary Cu requirement of about 10– 30 mg Cu kg-1 diet was established to elicit non-specific immune responses. When fed very high dietary Cu levels, an increase in dietary vitamin C improved growth, haemocyte respiratory burst response and prevented tissue Cu accumulation (Lee and Shiau, 2003).

TABLE 1 near here

2.1.2 Deficiency

Copper deficiency is well recognized in domestic animals (Suttle, 2010); however, gross deficiency signs of Cu have not yet been reported for fish. Unlike terrestrial vertebrates, low amounts of Cu are supplied from water as well as feeds. Therefore, overt deficiency signs would only occur during a long period of Cu deprivation. To date, the response criteria used to detect the Cu deficiency and adequacy of this element are not consistent in studies conducted on 14 FW and marine fish species (Table 1). A decrease in growth, body and liver Cu concentration and ceruloplasmin and enzyme activities (liver CuZn SOD, heart cytochrome c oxidase) have been reported. In a long term study, carp fed diets containing white fish meal without Cu supplement showed reduced growth and cataract formation (Satoh et al., 1983a).

2.1.3 Toxicity

Generally dietary Cu toxicity rarely occurs under practical feeding conditions except when there is an error in feed mixing or the use of Cu contaminated feed ingredients. Toxicity of Cu has been experimentally produced in rainbow trout, Atlantic salmon, rockfish (Sebastes schlegeli), Nile tilapia and African walking catfish (Clarias gariepinus), however, the tolerance of Cu varies among fish species (Lanno et al., 1985; Baker, 1998; Berntssen et al., 1999a,b; Clearwater et al., 2002; Hansen et al., 2004; Kim and Kang, 2004; Kang et al., 2005; Shaw and Handy, 2006; Hoyle et al., 2007; Damasceno et al., 2016). Signs of oral Cu toxicity include reduced growth and feed utilization, changes in hematological parameters and tissue lipid peroxidation. Dietary copper toxicity measured as growth inhibition in rainbow trout was approximately 664-730 mg Cu kg-1 feed corresponding to 44 mg Cu kg-1 body weight per day (Lanno et al., 1985; Clearwater et al., 2002). Much lower concentrations of Cu (34 mg kg-1) in Atlantic salmon diet caused tissue lipid peroxidation (Berntssen et al., 2000). The estimated threshold of diet borne Cu toxicity for Atlantic salmon parr and fry, based on organ copper burden and reduced growth ranged from 15 to 17 mg Cu/kg body weight per day (Clearwater et al., 2002). EU commission authorized maximum content of Cu in complete feed for salmonid and other fish species is 25 mg kg-1 (EFSA, 2016c).

Aquatic Cu toxicity in fish and other organisms has been the subject of extensive research for five decades (Grosell, 2012) and is briefly mentioned in this section. The mechanism of Cu toxicity differs in FW and SW. In FW, Cu toxicity varies with water hardness, pH, anions and dissolved organic carbon. Copper toxicity is more lethal in soft compared to hard waters rich in cations (e.g. Ca 2+ and Mg2+) as cations reduce bioavailability of Cu and thus accentuate toxic effects (Pagenkopf 1983). Copper is more toxic under acidic conditions ($pH < 6$). Anions and dissolved organic carbon bind to Cu and form compounds thus reducing the toxic effects (Niyogi and Wood 2004). In SW, waterborne Cu toxicity affects not only gills but also the intestine because marine fish drink to compensate for water loss into the surrounding water. The cause of reduced oxidative metabolism appears to be gill damage, manifested as either disruption of branchial structure, secretion of mucus that binds metals and impedes the rates of diffusion, inhibition of respiratory enzymes, and damage to gill oxygen receptors (Grosell, 2012). In addition to gill, Cu toxicity also affects liver, kidney, heart, brain and reproductive organs. In summary, an exposure to higher levels of Cu in water affects several physiological and biochemical functions affecting the performance of the whole organism by decreasing metabolic rate and causing oxidative stress (Beaumont et al., 2000; McDonald and Wood, 1993). Oxidative damage from Cu exposure has been observed as changes in biomarkers (e.g. protein carbonyls, lipid peroxidation, and DNA damage products) in the gill, liver and intestine of numerous fish species (McDonald and Wood, 1993). Low concentrations of waterborne Cu affected the hatching of fish eggs by inactivating chorionase activity that causes osmotic disturbances and also affects the muscular movements necessary to break the eggshell (Johnson et al., 2007; (Jezierska et al., 2009). Other effects may include low pigmentation of the embryo, spinal cord deformation, cranial malformations, jaw underdevelopment, decreased length, increased time for complete yolk absorption, oedema and opaque yolk sacs (Jezierska et al., 2009).

2.1.4 Bioavailability

Limited information exists on the availability of Cu from feed ingredients or Cu feed additives. Feed ingredients of plant and animal sources show a variable Cu content resulting from either contaminant originating from soil or during the processing of plant and animal products. Common Cu feed additives commercially available to supplement fish and animal feeds are, copper sulphate, cupric chloride; cupric carbonate; cupric acetate; cupric methionate; cupric oxide; cupric chelate of amino acid hydrate; copper lysine sulphate, cupric chelate of glycine hydrate, copper chelate of hydroxy analogue of methionine, dicopper chloride trihydroxide and copper bislysinate. In most fish studies, copper sulphate has been used as a dietary supplement or a standard for the evaluation of Cu bioavailability. To date, limited research effort has been made to measure the bioavailability of Cu from inorganic and organic forms or the residual Cu present in feed ingredients. A wide range of methods (e.g., plasma/liver Cu, erythrocyte SOD activity, plasma ceruloplasmin and bile Cu have been used to estimate Cu bioavailability in animals (Spears and Hansen, 2008).

Studies conducted on bioavailability from different organic Cu sources in animal feeds show similar bioavailability while others show higher bioavailability relative to copper sulphate NRC (2005). Some of the differences have been attributed to species differences, age of animals, response criteria and the method used. In rainbow trout fed semi-purified diets, cupric sulphate Cu-proteinate, and Cu-lysine showed similar bioavailability (Kjoss et al., 2006). Recently, Cu-Met and nano-copper oxide were shown to be more bioavailable than copper sulphate in Russian sturgeon (Wang et al., 2016). Metal ion interactions with Cu-Zn have been observed in animal studies (Baker and Ammerman, 1995); however, no significant antagonism between Cu and Zn was observed in rainbow trout fed plant-based diets (Read et al., 2014).

2.2 Iron

Iron is one the most investigated essential trace elements, which is present in all body cells of vertebrates. It is essential for the functioning of several biochemical processes, which include the electron transfer reaction, gene regulation, binding and transport of oxygen and regulation of cell growth and differentiation. The most important Fe-containing compounds are the heme proteins, hemoglobin, myoglobin and cytochromes. Enzymes containing non-heme Fe such as iron-sulphur cluster proteins (e.g., NADH dehydrogenase, succinate dehydrogenase, xanthine oxidase) are involved in energy metabolism. Another group of Fe-containing enzymes (e.g., hydrogen peroxidases) are well known to act on reactive molecules originating as the by products of oxygen metabolism. The formation of the reduced form of iron, Fe2+ can produce highly reactive hydroxyl and lipid radicals, which can damage lipid membranes, nucleic acids and proteins. In mammals, iron homeostasis involves the regulation of its absorption into the body, regulation of iron entry into cells, the incorporation of iron into proteins, the storage of iron in ferritin, and the regulation of iron released for transport to other cells and organs.

Although there is relatively little information on absorption and metabolism of iron in fish, some studies suggest that mechanisms of iron absorption from the digestive tract, and storage and excretion may be similar to those in other vertebrates (Glover and Hogstrand, 2002; Bury et al., 2003). The uptake of Fe from natural waters is considered low. Fish gills play an important role in Fe acquisition (Bury and Grosell, 2003), particularly in developing fish when the digestive tract is not fully functional (Andersen, 1997). The gastrointestinal tract is considered the major site of Fe absorption (Cooper and Bury, 2007). In the acidic environment of the stomach, ferric ion is released from the ingested food materials and binds to mucin which may facilitate metal solubility in the small intestine of fish (Whitehead et al., 1996). It is proposed that epithelial mucus secretion may play an important role in maintaining metal solubility in fish (Bury et al., 2012; Glover and Hogstrand, 2003). The mechanism of Fe absorption in marine fish is not clear. They ingest significant amounts of Ca and Mg from SW and also secrete large quantities of bicarbonate (Wilson et al., 2002) that could potentially cause problems for intestinal iron uptake. It has been suggested that metal-mucus chelates that retain the metal in solution in the intestinal tract, reducing agents in foods (e.g. ascorbic acid) and other physiological factors in the gut may modify Fe solubility and enhance its absorption (Andersen et al., 1997; Bury et al., 2003). Food is regarded as the main source of Fe for metabolic purposes (Bury et al., 2003; Andersen et al., 1997). It is widely accepted that the control of body Fe status is mainly dependent on tight regulation of Fe uptake from the diet and water. A small amount of Fe is eliminated via the liver (i.e., bile) and to some extent by the kidney (Bury et al., 2012).

2.2.1 Requirement

The Fe requirement reported for certain fish species (Table 1) ranges from 30-170 mg kg-1 diet with the exception to gibel carp which has an optimum requirement value of 202 mg kg-1 diet. Response criteria used to estimate Fe requirement were weight gain, whole body, liver and plasma iron concentration, and hematological parameters (hemoglobin, hematocrit, mean corpuscular volume, mean corpuscular hemoglobin). A meta-analysis of published information on Fe requirement of several fish species showed estimates for Fe requirement ranging from 58.8-166.4 mg kg-1 with a wide variation for all parameters tested (Antony Jesu Prabhu et al., 2016). It should be emphasized that weight gain alone may not provide a good estimate of Fe requirement. Most of the Fe body pool is in the form of hemoglobin in red blood cells. At later stages of growth and maturity, the Fe requirement is likely to change as the blood volume declines and a lower rate of iron deposition occurs in tissues (Suttle, 2010).

Even a dietary level of around 12 mg Fe kg-1 was found to be sufficient in P. vannamei fed practical diets and with diets containing processed land animal proteins, which are rich in iron, there was no need for iron supplementation. High levels of dietary Fe did not appear to induce any adverse effects in P. vannamei (Davis et al. 1992; Morgan, 2013).

2.2.2 Deficiency and toxicity

Generally Fe deficiency causes anemia and tissue Fe depletion in fish and other vertebrates (Lall, 2010). A characteristic microcytic anemia has been detected in brook trout (Kawatsu, 1972), rainbow trout (Desjardins et al., 1987), Atlantic salmon (Bjornvic and Maage, 1993; Andersen et al, 1996), red sea bream (Sakamoto and Yone, 1976), yellowtail (Ikeda et al., 1973), eels (Nose and Arai, 1979) and carp (Sakamoto and Yone, 1978b) fed low iron diets. In most cases, semi-purified diet without Fe supplementation did not affect the growth of fish, except cobia, where fish fed a basal diet without Fe supplement (45.8 mg kg-1) showed a decrease in weight gain and feed efficiency (Qiao et al., 2013). In addition, a decrease in Hb and serum catalase activity was also observed. In catfish, Fe deficiency suppressed hematocrit, hemoglobin, and plasma iron levels and caused transferrin saturation (Gatlin and Wilson, 1986b).

Effects of Fe toxicity in fish and animals have been comprehensively reviewed (NRC, 2005: Bury et al., 2012) and are briefly mentioned in this section. Dietary Fe toxicity was experimentally produced in rainbow trout fed levels higher than 1380 mg Fe kg-1 (Desjardins et al., 1987), a concentration far above the level found in ingredients used to formulate either practical or purified diets. The major effects of Fe toxicity were reduced growth, poor feed utilization, feed refusal, increased mortality, diarrhea and histopathological damage to liver cells. Iron toxicity occurs from excessive Fe exposure of fish in water, which interferes with Fe homeostatic regulation by causing Fe overload in tissues (Bury et al., 2012). Iron naturally exists as soluble ferrous (Fe2+) and insoluble ferric particulate iron (Fe3+). In oxygenated waters, soluble Fe2+ oxidizes to Fe3+ and in circumneutral waters (pH > 6.5), Fe3+ions are insoluble and rapidly precipitate as hydroxides and oxyhydroxides. Iron toxicity in water is closely related to Fe speciation and the interaction of Fe with body and gill surfaces. Excess Fe in the water is known to cause respiratory disruption due to physical clogging of the gills (Dalzell and MacFarlane, 1999).

2.2.3 Bioavailability

Iron in feeds is in two forms, heme iron and non-heme iron. Feed ingredients of animal origin (e.g., fish meal, animal meat and blood meal) are the major sources of heme iron. None heme iron refers to other sources of iron within feeds or inorganic contaminants from ingredient and/or feed processing. In cereal grains, a small proportion of Fe may be present as an iron phytin complex. Several factors are known to affect Fe absorption including, amount and chemical form of Fe, Fe status and age of animal, physiological conditions of gastrointestinal tract (e.g., pH) and other dietary components (e.g., phytic acid, ascorbic acid, citrate) (Henry and Miller, 1995). In juvenile animals, growth, hemoglobin concentration, plasma Fe and its retention may respond linearly to Fe supplementation; however, Fe repletion in deficient animals is considered the preferred method to estimate iron bioavailability (Spears and Hansen, 2010).

Little is known about the bioavailability of Fe from feed ingredients and inorganic /organic iron feed supplements for fish. Bioavailability of ferrous sulfate and ferric chloride are considered essentially the same (Lall, 2002). In red sea bream, ferrous and ferric chloride were more efficiently utilized than ferric citrate (Sakamoto and Yone, 1979a).

Biological availability of Fe measured by a hemoglobin regeneration assay in Atlantic salmon showed that the relative availability of Fe from ferric chloride, ferric oxide, blood meal and herring meal was 98.8, 17.8, 52.3 and 47.1%, respectively (Naser, 2000). However, higher bioavailability of iron from blood meal (Andersen et al., 1997), Fe-hydroxy methionine analogue (Huang et al., 2018) and Fe-methionine (Qiao et al., 2013) have been reported for Atlantic salmon, grouper and cobia respectively. The quality of blood meal varies widely in terms of protein quality. Whether the wide range of temperature and processing conditions used to produce blood meal affects the bioavailability of Fe remains to be investigated. There is also a need to standardize the method to predict the bioavailability of Fe in fish diets.

2.3 Manganese

Manganese plays an important role in protein and energy metabolism, bone mineralization, glycosaminoglycans synthesis, cellular defence against free radicals and metabolic regulation (Aschner and Aschner, 2005). The essentiality of Mn in the above biochemical processes is based on its function as an enzyme activator (e.g., oxidoreductases, lyases, ligases, hydrolases, kinases, decarboxylases) and constituent of several metalloenzymes (Leach and Harris, 1997). Many enzymes activated by Mn can be also activated by other metals particularly Mg with the exception of glutamine synthetase, glycosyltransferases, farnesyl pyrophosphate synthetase, phosphoenolpyruvate carboxykinase, which show specific Mn activation. Manganese metalloenzymes include arginase, pyruvate carboxylase, and Mn superoxide dismutase (MnSOD). Limited information exists on the physiological aspects of Mn uptake from both gills and intestine and its metabolism in fish. In mammals, gastrointestinal absorption and biliary elimination of Mn, are the two main regulatory sites of Mn homeostasis, which are influenced by the dietary Mn intake (Keen et al., 1999; Aschner and Aschner, 2005). Excretion of Mn in bile and feces has also been observed in Atlantic salmon (Antony Jesu Prabhu et al., 2019a). Manganese and Fe compete for absorption sites. A small fraction of biliary Mn excreted into the intestine may be reabsorbed. Manganese is efficiently absorbed from diet but the absorption may be reduced by high levels of Ca and P, fiber and phytate (Lall, 2002). Divalent Mn entering the circulation system is removed rapidly by the liver. Reduced intestinal absorption, enhanced liver metabolism, and increased biliary excretion are considered adaptive mechanisms during high dietary intake of Mn (Aschner and Aschner, 2005).

Manganese uptake from FW has been demonstrated from gills and gastrointestinal tract (Miller et al., 1980; Rouleau et al, 1995). Unlike other trace metals, the mechanisms of Mn uptake from gills, gut, skin and other tissues and toxicity are poorly understood. Brown trout (exposed to low concentration of Mn readily accumulated this metal in blood and other tissues (gills, epidermal mucus, liver, kidney, viscera, skeleton and brain) (Rouleau et al, 1995). The Mn toxicity was affected by water hardness and low pH and a higher risk of Mn toxicity to fish has been observed in acidic and Ca-deficient water (Rouleau et al, 1995; Peters et al, 2011). These conditions can markedly enhance the uptake and toxicity of Mn and other metals. High concentrations of Mn caused Na imbalance, reduced the absorption of Ca and P, affected carbohydrate metabolism and impaired the immune functions of fish (Partridge and Lymbery, 2008; Ye et al., 2009). It also caused oxidative stress, tissue damage, inflammation, neurodegeneration and disruption of other metals homeostasis in fish (Rouleau et al, 1995; Vieira et al. 2012;).

2.3.1 Requirement

Manganese requirements of fish range from 2.5 to 25 mg kg-1 diet (Table 2). Some of these differences are likely due to differences in Mn uptake in water and bioavailability of Mn in experimental diets. Different requirement values were found using three different forms of Mn additives for cobia, manganese sulphate, 15.4; Mn-glycine, 11.2; Mn-2-hydroxy-4-(methylthio) butyrate, 10.5 mg Mn kg-1 (Nie et al., 2016). In addition to growth, several studies have shown that body and vertebrae Zn provide a good estimate of Mn requirement. Meta-analysis of Mn requirement on several fish species estimated 10.7, 13.4

and 18.4 mg Mn kg-1 for weight gain, whole body Mn and vertebrae Mn content respectively (Antony Jesu Prabhu et al., 2016). It appears that broodstock fish require higher amounts of Mn than juvenile fish (Takeuchi et al., 1981). Other dietary (e.g., Ca, P, phytate) and physiological factors, particularly changes occurring in bone mineralization at various stages of development should also be taken into account for the estimation of Mn requirement of fish (Lall, 2002).

TABLE 2 near here

In shrimp, Kanazawa et al. (1984) suggested that a dietary supply of Mn was not required. Similar observations were also made by Fa-Yi and Lawrence (1997) who found that there was no need for dietary supplementation with Mn.

2.3.2 Deficiency

The deficiency signs of Mn have been experimentally produced in several fish species. In addition to reduced growth, Mn deficiency causes skeletal abnormalities in rainbow trout, carp and tilapia (Ishak and Dollar, 1968; Ogino and Yang, 1980; Yamamoto et al., 1983). In studies designed to determine Mn requirement of certain fish species (Table 2), low intake of Mn caused reduced body and/or vertebrae Mn concentration, a sign of poor bone mineralization. Although Mn deficiencies have shown a decrease in the activity of several enzymes in mammals (Aschner and Aschner, 2005), to date decreases in the activity of liver Mn SOD activity have been reported in Atlantic salmon (Maage et al., 2000), tilapia (Lin et al., 2008b), cobia (Nie et al., 2016), gibel carp (Pan et al., 2008) and yellow catfish (Tan et al., 2012). Low levels of dietary Mn (2.4 mg kg-1) did not affect Mn SOD activity in catfish (Gatlin et al.,1984a). A decrease in cardiac muscle Cu-Zn SOD was also observed in rainbow trout fed Mn deficient diet (Knox et al., 1981). Mn deficiency in broodstock rainbow trout diets affected reproductive performance and poor hatchability of eggs (Takeuchi et al, 1981). Manganese is considered to be one of the least toxic of the essential elements (NRC, 2005). However, high concentrations of dietary Mn supplementation (1g kg-1) affected changes in feeding behavior, decrease in body Fe concentration and elevation of Zn concentration in body and vertebrae of grouper (Ye et al., 2009). Freshwater borne Mn toxicity in brown trout caused histological changes in their olfactory nerve and brain (Rouleau et al., 1995). The effects of dietary Mn toxicity on olfactory system and brain function of human and animals are well documented (Horning et al., 2015).

2.3.3 Bioavailability

Dietary Mn absorbed from the gastrointestinal tract is generally low in monogastric animals (Spears and Hansen, 2010). Several manganese compounds are available for use in animal/fish feeds: manganous chloride ($MnCl_2.4H_2O$), manganous oxide (MnO), manganous sulphate ($MnSO_4.4H_2O$ or $MnSO_4.H_2O$, manganese carbonate ($MnCO_3$), manganese acetate, manganous hydrogen phosphate ($MnHPO_4.3H_2O$), manganese amino acid complex, manganese methionine complex, manganese amino acid chelate and manganese proteinate. However, the availability of only a few compounds have been tested and their availability may differ in various inorganic Mn salt supple¬ments. Manganese in manganous oxide is poorly utilized by rainbow trout and Atlantic salmon (Watanabe et al., 1997; Lall, 2002). The most commonly used source of Mn in fish feeds is manganous sulphate, monohydrate. The availability of Mn is low in manganous carbonate for carp (Satoh et al., 1987b). Mn-glycine was effectively utilized by cobia, turbot and Atlantic salmon reared in SW (Ma et al., 2015; Nie et al., 2016; Antony Jesu Prabhu et al., 2019b). Mn-glycine was better utilized by cobia and turbot than manganous sulphate (Ma et al., 2015; Nie et al., 2016). Availability of Mn-methionine and Mn-2-hydroxy-4-(methylthio) butyrate were relatively high for turbot (Ma et al., 2015) and cobia (Nie et al., 2016) respectively. Phytic acid like other divalent ions (Zn^{2+}, Cu^{2+}, and Fe^{2+}) binds inorganic Mn and reduces their bioavailability (Lall and Milley, 2008b). Recently, Antony Jesu Prabhu et al. (2019a,b) found that dietary supplementation of 15 mg kg−1 of Mn-Gly lowered the digestibility of

Zn and Cu. The environmental impact of undigested Mn excretion in natural water is widely recognized so the upper limit has been set for Mn in complete feeds in certain countries. In Europe the maximum limit for fish feed is 100 mg kg-1 (EFSA, 2016b).

2.4 Selenium

Selenium as an essential micronutrient for salmonids as well as a toxicant in diets and water is widely recognized (Poston et al., 1976; Hilton et al., 1980; Hodgson and Hilton, 1983). Essentiality of Se for several farmed fish species grown in FW and SW is now widely recognized (Lall. 2002; NRC, 2011; Antony Jesu Prabhu et al., 2016). In nature, inorganic Se is present in four oxidation states: selenate, selenite, elemental Se and selenide. These forms are converted by all biological systems into more bioavailable organic forms, mainly as the two seleno-amino acids selenocysteine (SeC) and selenomethionine (SeMet). Selenoproteins are responsible for diverse biological functions and they all contain at least one SeC (Labunsky et al., 2014; Roman et al., 2014). A comprehensive study of the identification and comparative analysis of vertebrate selenoproteomes have shown more than 45 selenoproteins in mammals and among bony fishes as well as 38 selenoproteins in zebrafish (Mariotti et al., 2012).

SeC is present in vertebrates at the active sites of glutathione peroxidases, thioredoxin reductases, iodothyronine deiodinases, and selenophosphate synthetases, as well as an essential component of other selenoproteins, (Hesketh, 2008; Labunskyy et al., 2014). The biochemical functions of many of these selenoproteins are poorly understood in fish. In several organisms, there are eight glutathione peroxidases (GPXs), five of them are selenocysteine enzymes (GPX1, GPX2, GPX3, GPX4 and GPX6), whereas the other three (GPX5, GPX7 and GPX8) have a cysteine at their catalytic site (Papp et al., 2007; Labunskyy et al., 2014). Three best characterized groups of selenoproteins in fish include glutathione peroxidases, thioredoxin reductases and iodothyronine deiodinases. The GPXs are involved in the hydrogen peroxide (H2O2) signalling, detoxification of hydroperoxides, and maintaining cellular redox homeostasis. GPX1 is the most abundant selenoprotein, which is considered a potent antioxidant in the cell scavenging of toxic H2O2. This protection of cells from oxidative damage by degrading toxic H2O2 has been closely linked to health and disease prevention in animals, humans and fish (Arthur et al., 2003; Fairweather-Tait, 2011; Choi et al., 2013; Roman et al., 2014; Khan et al., 2017; Dalgaard et al., 2018). Thioredoxin reductases are also important antioxidant enzymes that maintain cellular redox status. Selenium as an integral part of GPx and thioredoxin reductase interacts with certain micronutrients (e.g., a-tocopherol) that affect redox status (i.e. pro-oxidant and antioxidant balance). The third group of selenoproteins are iodothyronine deiodinases, which activate the prohormone thyroxine (T4) to the active thyroid hormone triiodothyronine (T3), and catalyze the inactivation of T4 to reverse T3 and T3 to diiodothyronine (T2) (Labunsky et al., 2014).

Fish absorb limited amounts of Se from the environment via the gills and skin under certain conditions; however, the gastrointestinal tract is the primary site for Se absorption (Janz, 2012). Low concentrations of selenium are found extensively in aquatic ecosystems (Janz et al, 2019). The uptake of Se as selenite across gills is very efficient at low waterborne concentrations (Hodgson et al., 1983). Selenocysteine and selenomethionine are likely to be absorbed by an active amino acid transport mechanism, whereas selenite is absorbed by simple diffusion and selenate by a sodium-mediated carrier shared with sulfate (Burk and Hill, 2015). Absorbed Se is associated with proteins in the plasma and transported to tissues. After absorption from the diet Se is transported to the liver and metabolized to selenide and incorporated into selenocysteine for selenoprotein synthesis or converted to selenosugars or methylated metabolites for excretion. Fish and other vertebrates excrete Se via feces, but urine is the primary excretion route and likely plays a quantitatively important role in Se homeostasis (Janz, 2012; Burk and Hill, 2015).

Beneficial effects and toxicity of dietary Se supplementation in fish and animals are well documented (NRC, 2005, 2011; 2012; Suttle, 2010; Hosnedlova et al., 2017). The effects of dietary Se also show an increase in expression of selenoprotein P in rainbow trout and zebrafish (Fontagné-Dicharry et al., 2015; Pacitti et al., 2015; Penglase et al., 2015; Wang et al.,2018). In Se-adequate animals, the kidney and liver have the highest Se content. Muscle has moderate levels of Se content but accounts for the largest pool of body Se. Retention and distribution of Se in tissues are affected by the body Se status and chemical form of Se (Berntssen et al., 2017). Selenium deficient animals retain Se more efficiently than Se-adequate animals. Dietary Se supplementation showed an increase in expression of selenoprotein P in rainbow trout and zebrafish (Fontagné-Dicharry et al., 2015; Pacitti et al., 2015; Penglase et al., 2015; Wang et al.,2018).

2.4.1 Requirement

Selenium requirements (mg Se kg-1 diet) of several fish species have been determined on the basis of different response criteria (growth, liver and plasma/serum GPx activities, and Se concentration of total body and tissues e.g., liver, muscle) and are summarized in Table 3. The lack of standard methodology and form of Se used makes it difficult to compare the results of different species or within species. The minimum Se requirement of fish varies with the form of Se (inorganic or organic) ingested, Se availability from different feed ingredients from the diet, vitamin E content of the diet, and concentrations of waterborne selenium. The estimated Se requirement based on weight gain, whole-body Se retention and of liver GSH-Px activities have shown different values for some fish species. Some studies have used a single or limited number (<3) to test the requirements, which have limited value in assessing the Se requirement properly. Published data on the Se requirement of farmed animals have demonstrated that growth alone does not reflect their Se requirement. A meta-analysis of published information on Se requirements of several fish species showed different estimates for the Se requirement (mg/kg-1) based on different parameters: weight gain, 0.35 ; enzyme activities of liver GPx, 0.78; serum GPx, 0.43; liver GR activity, 0.41 (Antony Jesu Prabhu et al., 2016). In a recent study, the estimated requirement of Atlantic salmon smolts based on available Se in a plant ingredient based-diet was much lower (0.27 mg/kg-1). Supplementation of SeMet as compared to sodium selenite showed lower Se requirements for Atlantic salmon smolts (Antony Jesu Prabhu et al., 2020) and gibel carp (Zhu et al., 2016). In addition to differences between the bioavailability of Se from the experimental diets, Se uptake from water, age, dietary vitamin E levels and Se bioavailability, and differences among fish species in the utilization of Se must be considered when published requirement values are applied in feed formulation.

Table 3 near here

Quantitative data on Se requirement for maximum growth was established to be about 0.6-0.7 mg Se kg-1 diet (Kong et al. 2017) who also showed that higher dietary Se levels (>1.1 mg kg-1) were required to maximise body Se concentrations. A dietary supply of 0.45 mg kg-1 was found sufficient for improving growth (Yu et al. 2021) and higher levels (0.8 mg kg-1 diet) led to increased antioxidant enzyme activities but also led to stress and tissue damage in the same species. A supply of 0.43 to 0.45 mg kg-1 of Se in the form of hydroxyl methionine selenium (HMSe) was likewise found to be effective (Wang et al. 2021) for maintaining high growth and an antioxidant response.

2.4.2 Deficiency

Unlike other micronutrients, gross deficiency of Se alone has not been characterized due to its interaction with vitamin E, polyunsaturated fatty acids, and other dietary factors. Early clinical signs of deficiency caused by low dietary intake of Se have been detected in low enzyme activities in plasma and liver glutathione peroxidase of several fish species (Poston et al., 1976; Hilton et al., 1980; Gatlin and Wilson,1984b; Bell et al., 1985; Wang and Lovell, 1997; Liu et al., 2010a; Han et al., 2011; Zhu et al., 2011; Zhu et al., 2016; Dominquez et al., 2019; Ning et al., 2020; Wang et al., 2019). Selenium deficiency caused growth depression in rainbow trout (Hilton et al., 1980), carp (Satoh et al., 1983b), and catfish (Gatlin and Wilson, 1984b), but Se deprivation alone did not produce any patho¬logical signs in these fish. Both Se and vitamin E were required to prevent muscular dystrophy in Atlantic salmon (Poston et al., 1976) and exudative diathesis in rainbow trout (Bell et al., 1985). Extensive research conducted on animals show that it is very difficult to produce or distinguish symptoms of Se deficiency alone from that of a Se-vitamin E deficiency (Suttle, 2010).

Although effects of selenium deficiency on reproduction of animals is well documented (Suttle, 2010; Hosnedlova et al., 2017), effects of Se on reproductive performance of fish are not clear. Recently, Wischhusen et al. (2019) found that Se-supplementation of diets based on a major proportion of plant ingredients enhanced the total number of spawning fish and higher levels of hydroxymethionine supplementation led to earlier spawning. There was no evidence of transfer of maternal Se to progeny and supplementation of organic Se increased activity of GPx activity and mRNA expression of other proteins involved in antioxidant protection at the cellular levels as well as elevated tissue vitamin C and E concentrations.

2.4.3 Toxicity

Dietary Se toxicity has been extensively studied in farm animals and the following three possible mechanisms of toxicity have been proposed : a) substitution of Se for sulfur in important biochemical reactions and structures (e. g. disulfide bonds may disrupt normal function and cell integrity); b) reaction between selenite and glutathione depletes cellular free and protein-bound thiol levels thus affecting the activities of certain enzymes; c) free radicals such as superoxide anions produced by the reactions of certain forms of Se with tissue thiols may cause oxidative injuries to tissues (NRC, 2005; Suttle, 2010). In fish, both dietary and water borne Se toxicities have been experimentally produced (Hodgson and Hilton, 1983). The physiological mechanisms involved in the uptake of Se from water and its toxicity to fish and other aquatic organisms have been extensively investigated and are the subject of comprehensive reviews (Hamilton, 2004; Janz, 2012 Janz et al., 2019). Dissolved inorganic forms of Se (selenate and selenite) in water are oxyanions that are not absorbed appreciably through gill membranes (Pedersen et al., 1998) and ingestion of natural food organisms that accumulate Se from the aquatic environment appear to be more toxic (Janz et al., 2019). The susceptibility to Se toxicity and the mode of action of Se toxicity may differ among fish due to their diverse chemical properties, uptake and metabolism from diet and water. Coho salmon are more sensitive than chinook salmon to inorganic Se (Hamilton and Buhl, 1990). As in the case of trace element bioavailability, the relative toxicity of a given Se compound is affected by its chemical form and solubility. Highly insoluble elemental Se is much less toxic to many species than other more soluble forms such as selenite and selenate (NRC, 2005; Janz, 2012). Dietary Se-Meth was less toxic to chinook salmon, coho salmon and Atlantic salmon than selenite or selenate (Hamilton and Buhl, 1990; Berntssen et al., 2018). However, the Se-Meth caused Se toxicity in white sturgeon fed levels above 20.5 mg Se kg-1diet (Tashjian et al., 2006).

A relatively narrow range between dietary requirement and toxicity exists in fish and other vertebrates (Hilton et al., 1980; Janz, 2012; Hosnedlova et al., 2017). Selenium toxicity in rainbow trout and catfish occurs when dietary Se exceeds 13 and 15 mg kg-1 dry feed, respectively (Hilton et al., 1980; Gatlin and Wilson, 1984b). Reduced growth, poor feed efficiency, and high mortality were observed as the major adverse effects of Se when concentration exceeded the dietary requirements of juvenile fish. In addition to reduced growth, several other adverse effects of feeding higher levels of selenite and SeMet in diets include decreased energy retention (De Riu et al. 2014; Zee et al. 2016), lower egg viability (Schultz and Hermanutz, 1990), decrease in swimming activity (Tashjian et al., 2006), reduced immunological functions (Choi et al. 2013), pathological changes in liver, kidney and ovaries (Hicks et al. 1984; Hamilton, 2004) and skeletal deformities (Kupsco and Schlenk, 2016; Berntssen et al., 2018).

For the assessment of early sublethal adverse effects of selenite and SeMet toxicity, several biomarkers such as tissue lipid peroxidation, reduced glutathione (oxidative stress marker) and changes in lipid composition have also been proposed (Berntssen et al., 2017). Elevated Se levels for rainbow trout, chinook salmon, fathead minnow, striped bass, bluegill, and razorback sucker ranged from 2.4 to 70 mg Se kg-1 in feed and 47 to 472 ◎g L-1 of water (Hamilton, 2004). In most cases, reduced growth or survival occurred at dietary Se levels close to 3 mg Se kg-1. Atlantic salmon tolerated either 1–2 or 3 mg Se kg-1 of selenite and SeMet supplementation respectively in a feed based on a high proportion of plant ingredients that contained 0.45mg Se kg-1 (Berntssen et al., 2018). Relative toxicity of different Se supplements may be largely related to their solubility in water and nutrient bioavailability, and can be modulated by dietary factors such as protein, sulfate, vitamin E, and a number of trace elements including As, Cu, and Hg. The maximum limit for total Se in animal feeds, including fish, has been set at 0.5 mg Se kg−1 feed by the U.S. Food and Drug Administration and the European Union (EFSA,2016a), which is considered low to meet the Se requirement of Atlantic salmon fed diets based on plant ingredients and low in fish meal (Anthony Jesu Prabhu et al., 2020).

The primary biochemical mechanism for chronic Se toxicity was initially considered to be linked to the substitution of Se for sulfur in cysteine and methionine, which affected the tertiary structure of protein and its function by altering disulfide linkages (Maier and Knight, 1994). More recently, oxidative stress has been proposed as a main cause for excess dietary Se intake or exposures in fish (Berntssen et al., 2017). In Atlantic salmon fed high levels of selenite and SeMet yeast, oxidative stress was a main driver for Se toxicity (Berntssen et al., 2017); however, white sturgeon and brown trout fed high levels of organic Se did not show oxidative stress (Knight et al., 2016; Zee et al., 2016). Altered liver lipid synthesis and metabolism have been shown to be the central mechanism in dietary organic Se toxicity in rainbow trout (Knight et al., 2016; Pacitti et al., 2016). Recent wide-scope pathway assessments by the application of metabolomics techniques show that disturbance in lipid metabolism is an important factor in inorganic and organic Se toxicity (Berntssen et al., 2017).

2.4.4 Bioavailability

Feed sources of Se used in feeds are either in inorganic (selenite, SeO32-or selenate, SeO42-) or organic (selenized yeast, SeMet and analogues) forms and they differ significantly in bioavailability, metabolism and toxicity. The major proportion of Se in common feed ingredients occurs as seleno-amino acids with SeMet being the most predominant form (Suttle, 2010). In addition, other minor organic forms derived from plants or yeast metabolism such as Se-adenosylselenohomocysteine, methylselenocysteine, selenocystathionine and γ-glutaminyl-Se-methylselenocysteine have been reported (Rayman et al., 2004; Schrauzer, 2006). The Se content of feed ingredients of plant origin varies in various geographical locations to a great extent, depending on the Se concentration of the soil and its uptake. In cereal grains, it may range from <0.1 to >0.8 mg kg-1 (Scott and Thomson, 1972; NRC, 2011). Fish meals represent the best natural source of Se among the common feedstuffs with concentrations ranging from 1-2.4 mg kg-1 with the exception of tuna and mackerel meals where concentrations may exceed 5 mg kg-1 (Scott and Thomson, 1971; NRC, 2011). High concentrations of Se have also been reported in shrimp meal and crab meal (Scott and Thomson, 1972). Selenium is widely distributed in small concentrations in FW (0.1 0.3 ug L−1) and SW (0.05- 0.2 ug L−1) (NRC, 2005). In certain regions of the USA with highly seleniferous exposed shale deposits, as high as 5-50 ug Se L− in water have been reported (Canton and Van Derveer, 1997). Limited amounts of dissolved inorganic forms of Se as selenate and selenite in water is absorbed through gill membranes (Pedersen et al., 1998).

Several factors affect the bioavailability of Se including, form of Se, other dietary components, physiological status of Se in animals and species differences (Henry and Ammerman, 1995; Fairweather et al, 2010). The effects of the chemical form of Se in feeds and feed ingredients on the bioavailability and metabolism of this element have been extensively studied in animals (Henry and Ammerman, 1995) and humans (Thiry et al., 2012). Different criteria have been used to determine the bioavailability of Se including GSH-Px activity, tissue Se concentration and prevention of Se deficiency. Activity of GSH-Px in plasma, red blood cells and a number of tissues respond to dietary Se concentration. Organic sources of Se supplements have shown a higher bioavailability as compared to inorganic forms for fish (Wang and Lovell, 1997; Rider et al., 2010; Sele et al., 2018; Le and Fotedar, 2014; Fontagné Dicharry et al., 2015; Mechlaoui et al. 2019; Antony Jesu Prabhu et al. 2020). Selenium enriched yeast showed higher bioavailability than sodium selenite (Godin et al., 2015). Nanoforms of Se also show high bioavailability in vertebrates (Hosnedlova et al., 2017); however, their bioavailability, metabolism and safety remain to be fully evaluated in fish (Khan et al., 2017).

The early work of Bell and Cowey (1989) showed higher bioavailability in Atlantic salmon and it follows the order from highest to lowest: selenomethionine > selenite >selenocysteine > fish meal (Bell and Cowey, 1989). Certain fish meals, e.g. tuna, may have poor biological availability because of heavy metal com¬plexing of Se. A wide variation in Se availability (38.5-60%) of different batches of capelin meal measured using GSH-Px activity in a chick bioassay was observed (Gabrielsen and Opstvedt, 1980). Until the initiatives to reduce the amount of fish meal with plant ingredients , Se supplementation of farmed fish diets was not considered necessary. An increase in plant protein sources and reduction in fish meal in feeds has reduced the Se and bioavailability of Se (Sissener et al., 2013; Antony Jesu Prabhu et al., 2020; Godin et al., 2015; Fontagne-Dicharry et al., 2015; Betancor et al., 2016; Sele et al., 2018; Silva et al., 2019). Selenium supplementation of fish diets appears to be the most effective method to meet its requirement.

2.5 Zinc

Zinc is the second most abundant trace element, after Fe, essential to all cells in most living organisms (Vallee and Falchuk 1993). It has many diverse biochemical functions and is the subject of extensive studies to define the role of Zn at the subcellular level in nutrition and health of human and animals. Most knowledge related to the biochemical function of Zn has emerged from research on other vertebrates and this area is wide open for research from fish perspectives. The ubiquitous distribution of Zn among cells, coupled it being the most abundant intracellular trace element, have resulted in identification of three specific functions in biology of vertebrates and plants: a) catalytic, b) structural and c) regulatory. The catalytic role of Zn is essential for the biological function of all six classes of more than 300 enzymes (McCall et al., 2000). Some examples are RNA nucleotide transferases (RNA polymerase I, II and III), alkaline phosphatase, carbonic anhydrases. In the structural role of metalloenzyme, Zn ion stabilizes the tertiary structure of enzymes (e.g., CU-Zn superoxide dismutase). For this enzyme Cu serves at the catalytic site and Zn serves a role in structure. Zn fingers (where some histidine replaces cysteine) motif in protein represent an important structural role. The single Zn atom at the base of motif influences the binding of protein to DNA. The linking of these Zn fingers to the corresponding sites on DNA initiates the transcription factor and initiates gene expression. Approximately 3000 Zn proteins in human genome and fish genome carry the annotation Zn binding. (Passerini et al., 2007). Zinc is required for the structural and functional integrity of over 2000 transcription factors and almost every signalling and metabolic pathway is dependent on one or more zinc-requiring proteins (Maret, 2013). Also, Zn as an intracellular regulatory ion activates or inhibits transcription factors responsible for regulating gene expression. An example of this role is metallothionein (MT) or MT-like proteins.

The homeostasis of Zn is tightly controlled at the whole body, tissue, cellular, and subcellular levels by a number of proteins with zinc transporters playing key roles. Two Zn transporter families, Zn transporters (ZnT) and Zrt-, Irt-related proteins (ZIP) function in zinc mobilization of influx, efflux, and compartmentalization and sequestration across biological membranes (Kambe et al., 2015). ZnT and ZIP contribute to a wide range of physiological and cellular functions (e.g., immune, endocrine, reproductive, skeletal, and neuronal) by tightly controlling zinc homeostasis (Fukada and Kambe, 2011; Kambe et al., 2015). Biochemical roles for Zn transporters and regulation of specific genes have been studied in zebrafish (Feeney et al. 2005; Zhao et al, 2014) and are beyond the scope of this review.

The two main routes of zinc uptake from water are through the gills and gastrointestinal tract in fish (Spry et al., 1988). However, the major absorption of Zn occurs primarily through the gut. Waterborne and dietary Zn is also a source of this mineral for salmonids and marine fish because they drink SW (Pentreath, 1973; Lall and Bishop, 1977). In FW fish, uptake across the gill can contribute significantly (~50%) to total Zn absorption if the Zn concentration in the water is high or that in the diet low. Zn may interfere with calcium homeostasis by competitive inhibition of Ca2+ transfer across the apical membrane of the gill epithelial cells by Zn2+ (Hogstrand et al., 1996). The accumulation of Zn in gills is also regulated through alteration in Zn uptake mechanisms limiting its excessive uptake (Bury et al., 2003). Zinc chelation with certain amino acids, such as histidine and cysteine that have a high affinity for this element, may enhance Zn distribution in various tissues of fish (Glover and Hogstrand, 2002). The gills in rainbow trout also play a major role in excretion of dietary Zn (Hardy et al., 1987).

Calcium may have an inhibitory or a stimulatory effect on Zn uptake from water depending on the concentration (Glover and Hogstrand, 2003; Ojo and Wood, 2007). Waterborne Ca is a competitive inhibitor of branchial Zn influx. Zinc inhibits the influx of Ca across gills thus Ca in water protects fish against Zn toxicity. The accumulation of Zn in gills is also regulated through alteration in Zn uptake mechanisms limiting its excessive uptake (Bury et al., 2003). The excretory mech¬anisms and control of gastrointestinal tract uptake may play impor¬tant roles in maintaining Zn homeostasis. The Zn status of fish is tightly controlled and surplus Zn is excreted via bile, the sloughing of intestinal mucosa in feces and through gills (Handy, 1996). Information on the absorption of Zn from gut is limited. In the intestine, dietary Zn binds to the mucus of the intestinal epithelium, and is transported into the epithelial cells either as Zn ions or as ions bound to amino acids (Bury et al., 2003; Hogstrand, 2012). It is well known that high intakes of phytate and iron reduce the absorption of zinc (Lall. 2002). Development of enterocyte models show potential to investigate specific mechanisms involved in absorption of Zn from fish diets, which contain different forms of organic and inorganic Zn (Antony Jesu Prabhu et al., 2018b).

2.5.1 Requirement

A dietary requirement for Zn (mg kg-1) has been reported for several juvenile fish species (Table 4). The minimum Zn requirement varies with age, sexual maturity, composition of diet, water temperature and water quality (NRC, 2011). The response criteria used to determine Zn requirement of fish in various studies include growth, feed efficiency, deficiency signs, whole body Zn concentration and retention, serum or plasma levels and enzyme activities. Most of the above criteria show responses to increasing dietary concentration, the major proportion of dietary Zn is retained in skeletal tissues particularly vertebrae. A meta-analysis of published information on Zn requirement of several fish species showed estimates ranging from 33.5-64.6 mg kg-1 on the basis of different parameters tested (weight gain, 36; whole body Zn, 33.5; vertebrae Zn, 64.6; serum Zn, 53.4; serum ALP activity, 47) (Antony Jesu Prabhu et al., 2016).

Table 4 near here

Studies by Shiau and Jiang (2006) with tiger shrimp, Penaeus monodon, showed that for improved growth, a dietary level of 32-34 mg Zn kg-1 diet was sufficient but an increased supply (35-48 mg Zn kg-1 diet) led to beneficial effects in terms of non-specific immune responses. Shi et al (2021) showed that dietary organic zinc promoted growth, immune response and antioxidant capacity and the optimal dietary zinc level required was estimated to be 104.8 mg kg-1 for juvenile Pacific white shrimp (P. vannamei) and that a higher dietary level (130.6 mg kg−1) led to increased tissue zinc concentrations. Davis et al. (1993a) showed that a dietary supplementation of 200 mg Zn/kg diet was required to overcome the depressed bioavailability of zinc and to maintain normal zinc levels in the hepatopancreas.

2.5.2 Deficiency

Overt signs of Zn deficiency are difficult to produce in short term experiments due the ubiquity of this trace element in water and feed ingredients. Early work of Ogino and Yang (1978) showed lens cataracts, erosion of fins, skin as well as growth depression and high mortality in juvenile rainbow trout fed semi-purified diet containing a low level of Zn. Later, Satoh et al. (1983b) observed short body dwarfism due to poor mineralization of trout vertebrae. In several fish species, low dietary Zn intake caused reduced growth, low serum, liver, scale, body and vertebrae Zn concentrations. Widespread occurrence of cataracts in salmonids fed diets based on high amounts of white fish meal in United States hatcheries were attributed to Zn deficiency (Ketola, 1979). Zinc is considered essential for normal eye development in juvenile fish and high levels of dietary Ca, P in fish meal and phytic acid in plant ingredients reduces Zn bioavailability resulting in lens cataracts (Ketola et al., 1979; Richardson et al., 1985; Satoh et al., 1983b; Welker et al., 2016). Dietary histidine has also been found to prevent development of cataracts in Atlantic salmon smolts (Waagbø et al, 2010). Zinc and multiple dietary, genetic and environmental factors may be involved in the pathogenesis of cataracts (Bjeerkäas and Sveier,2004; Lall, 2010). Broodstock diets low in Zn reduced egg production and hatchability of eggs (Takeuchi et al., 1981). Caudal fin Zn concentration is considered a good indicator of Zn status in rainbow trout (Wekell et al., 1986).

2.5.3 Toxicity

Excessive dietary zinc levels may become toxic to fish and compete for similar binding sites with other bivalent minerals such as Cu, Fe, Ca and Cd in the digestive tract during absorption (Clearwater et al., 2002; Luo et al., 2011; Moazenzadeh et al., 2017). Rainbow trout and carp can tolerate 1700 to 1900 mg zinc kg-1 in diet without any apparent signs of toxicity (Wekell et al., 1983). Common carp accumulate higher concentrations of Zn in their tissues, particularly in the viscera than other fish studied, without any overt toxicity signs (Jeng and Sun, 1981). In rainbow trout, high concentrations of dietary Zn (500 to 1,000 mg Zn kg1) caused reduced hemoglobin, hematocrit, and hepatic Cu concentrations in rainbow trout (Knox et al., 1982).

Effects of environmental pollution and heavy metal contamination of aquatic organisms have been the subject of intensive research particularly their accumulation in fish (Alsop and Wood, 1999). Uptake and toxicity of zinc and other metals from water are known to vary, depending on an organism’s physiology and osmoregulatory mechanisms (Alsop and Wood,1999; Bielmyer et al., 2012). The physiological toxic effects of Zn have been conducted mainly in FW, which show that hypocalcemia caused by Zn interferes with active Zn uptake at the gills (Hoagstrand, 2012). Sublethal Zn exposure of killfish in FW and SW caused pathological changes in both Ca and Na homeostasis and an increase in salinity exerted protective effects against sublethal and lethal Zn toxicities (Loro et al., 2014). Mineral sensitivity is highest during the larval stage, compared to other times in the life history of a fish. Zinc content of scales reflect environmental metal concentrations (Hoagstrand, 2012)

2.5.4 Bioavailability

Dietary factors (e.g., form of Zn, protein source, phytic acid, and dietary Ca and P levels) are known to affect absorption and retention of Zn in fish (Gatlin and Wilson, 1983; Richardson et al., 1985; Wekell et al., 1986; Hardy et al., 1987; Satoh et al., 1987a; McClain and Gatlin, 1988; Satoh et al., 1989; Apines -Amar et al, 2004; Welker et al., 2016; Silva et al., 2019). In most Zn requirement studies (Table 4), zinc sulfate ($ZnSO4.7H2O$) has been used due its high bioavailability. Both zinc sulfate and zinc nitrate (40 mg kg-1) alleviated dwarfism and cataract problems in rainbow trout (Satoh et al., 1987a). The bioavailability of Zn oxide is low in Atlantic salmon and other fish species probably due to the lower solubility of this compound (Lall, 2002). Recent studies on monogastric animals show high variability of zinc oxide feed supplements in color, texture and Zn content and manufacturing techniques, which affects their bioavailability (EFSA, 2016a). Organically complexed minerals (amino acid chelate, yeast complexes, etc.), including zinc, appear to be more readily available to rainbow trout compared with inorganic sources (Apines et al. 2003a,b; Apines-Amar et al. 2004; Rider et al. 2009, 2010). No apparent differences in the bioavailability of zinc sulphate and zinc methionine were observed in catfish (Li and Robinson, 1996).

Although fish meal produced from whole fish (e.g., herring and capelin meal) is considered a good source of Zn (80 to 130 mg Zn kg-1) and other minerals, the concentration of Zn varies in meals produced from processing discards containing partial fish parts. Feed ingredients of animal origin (meat and bone meal, poultry feather meal) contain high zinc levels (90−140 mg Zn kg-1). High levels of Ca and P in high ash fish meal and meat and bone meal affects the bioavailability of Zn (Hardy and Shearer 1985; Hilton, 1989; Watanabe et al. 1997; Lall 2002). Phytate in plant products, especially cereals and legumes, irreversibly binds zinc in the intestinal lumen and reduces their bioavailability. Furthermore, there are copper–zinc and calcium–phytate–zinc antagonistic interactions, which can decrease bioavailability of zinc to rainbow trout (Hilton 1989; Watanabe et al. 1997; Lall 2002). Fiber may interfere with Zn absorption but this may be attributed to the phytate content of high fiber plant feedstuffs. Amino acids, such as histidine and methionine, and other low-molecular-weight ions, such as EDTA and organic acids (e.g., citrate), are known to have a positive effect on zinc absorption (Lönnerdal, 2000). The removal or reduction of phytate by enzyme (phytase) treatment, fermentation or plant breeding/ genetic engineering markedly improves zinc absorption (Kumar et al., 2011). Increasing levels of Cd in foods associated with environmental contaminants and other factors have also been shown to reduce zinc absorption (Lönnerdal, 2000). A higher limit in fish feed has been set for salmonid (150 mg kg-1 of diet) and other fish (100 mg kg-1 of diet) in Europe (EFSA, 2015).

2.6 Iodine

Iodine is an essential constituent of the thyroid hormones, T3 (3,5,3′-triiodo-L-thyronine) and T4 (L-thyroxine; 3,5,3′,5′-tetraiodo-L-thyronine) that regulate cell activity and growth in all tissues. The metabolism of thyroid hormones (TH) and iodine which mainly exists as inorganic iodide are closely linked, TH play a critical role in cellular oxidation, hematopoiesis, circulation, reproduction, neuromuscular functioning, and metabolism of major nutrients (Hetzel and Welby, 1997). T3 is the predominant hor¬mone secreted by the thyroid gland and is regarded as an active precursor for T4. T3 is more biologically active than T4 in several fish species (Higgs et al., 1982; Cyr and Eales, 1996). The inhibition of extrathyroidal T4 -to-T3 conversion reduces the potency of thyroid hormone (Cyr et al., 1988; Lebel and Leloup, 1992); however, the mode of action of the less active T4 is not fully established. Thyroid has an established role in development and metamorphosis (Blanton and Specker, 2007; Power et al., 2008), and where TH metabolism could differ. Major differences exist between fish and mammals in the physiology of iodine and extrathyroidal metabolism of T4 and T3 and recently reviewed (Eales, 2019).

The branchial uptake of iodide by fish is widely recognized. Marine fish drink SW ensuring an adequate intestinal I absorption, which is supplemented by I in food and possible I uptake through body surfaces (Moren et al., 2008). FW fish drink negligibly, hence, dietary and gill uptake are both considered important sources of I (Geven et al., 2007; Higgs et al., 1982). Most research on I metabolism in fish has been focused on salmonids in the FW phase of their lifecycle. In rainbow trout, approximately 19% iodine is derived from diet, 80% from water, and less than 1% from recycling iodide originating from thyroid hormone degradation (Hunt and Eales, 1979). Salmonids undergo parr-smolt transformation, with established thyroid involvement (Specker et al., 2000). After the growth phase during sexual maturation and reproduction, some changes in thyroidal status occurs as well as interaction of TH with sex-related hormones (Cyr and Eales, 1996; Habibi et al., 2012). Female fish transfer significant amounts of thyroid hormones to developing ova (Blanton and Specker, 2007; Brown et al., 2014) and the offspring may rely on parental iodine storage to complete their early development. Some of these physiological changes may affect the iodine metabolism and requirement at different stages of the life cycle of fish (Higgs et al,1982).

Iodine enrichment of live food organisms such rotifers, copepod and Artemia to increase their I concentration has been tested with cod, halibut and Senegal sole larvae (Einarsdottir, et al., 2006; Ribeiro et al., 2012; Penglase et al, 2013); however, its retention was low in some species, probably due to differences in the bioavailability of I from water or the form of I compounds used to increase the I concentration (Hamre et al., 2013). Recent work of Penglase et al. (2013) has clearly demonstrated that rotifers could be successfully enriched with I. Feeding cod larvae, a high concentration of I enriched rotifers (129 mg I kg−1 DW) caused I toxicity. Ozone treatment of sea water in recirculation systems oxidizes I to an unavailable IO3 form, which has low bioavailability for fish (Sherrill et al., 2004). Nitrate (NO3−) is considered goitrogenic for fish and as its build up in water may block iodide uptake by the sodium iodide symporter (Tonacchera et al., 2004), which causes goiter in sharks (Morris et al., 2011).

The relation of Iodine deficiency to enlargement of the thyroid gland or goiter in salmonid fish was first shown by Marine (1914). Senegalese sole larvae developed thyroid hyperplasia and hypertrophy (goiter) fed Artemia and grown in recirculation system (Ribeiro et al., 2012). In vertebrates, other deficiency signs of I includes goiter, cognitive and neuromuscular retardation, embryonal and postnatal mortality and impaired fertility (Delange, 1994). Excessive I intake can also negatively affect thyroid hormone production and produce goiter, termed I or colloid goiter in humans (Vanderpas, 2006). In most fish species, I requirement and deficiency remain to be investigated. Woodall and LaRoche (1964) found a higher iodine requirement for advanced parr compared to fingerlings due to increased thyroid activity during smoltification. Lall et al. (1985) observed that 4.5 mg I kg-1 of diet was essential to protect Atlantic salmon from bacterial kidney disease infections. It is likely that I requirement is influenced by growth, sex, age, physiological status, environmental stress, disease, and iodine content of the water.

Few definitive studies on iodine bioavailability have been conducted due to high uptake of I from water and the problem with distinguishing absorption from water and dietary sources. Iodine concentration of marine fishes is relatively high (Julshamn et al., 2001; Lall, 1995); however, substantial amounts of iodine are lost during fish meal processing (Lall, 2002). Ingested inorganic iodine and iodate are reduced to iodide and absorbed almost completely from the gastrointestinal tract (Hetzel and Welby, 1997). Certain seaweeds also contain high levels of iodine (Teas et al., 2004). Goitrogenic substances in feed may increase iodine requirement depending on the amount and type of this natural toxicant (Bell, 1984). Glucosinolates (GLS) in rapeseed meal are known to impair thyroid function causing goiter in vertebrates (Mawson et al., 1994) and fish (Leatherland et al., 1987; Higgs et al., 1982). This effect is caused by their hydrolytic products (e.g., thiocyanate anions, visnyloxazolidinethiones, and isothiocyanates). The thiocyanate anions are competitors of iodine for active transport across the cell membrane and for binding to tyrosine residues of thyroglobulin. Burel et al. (2001) showed that dietary supplementation with T3 or iodine induced an increase in plasma T3 levels, as compared to fish fed rapeseed meal diets, and reduced the deleterious effect of rapeseed meal (RM) on growth. Processing methods have been developed to overcome these antinutritional factors in rapeseed products (Francis et al., 2001).

2.7 Chromium

Chromium is a transition metal that exists in food and the environment as Cr3+(trivalent) and Cr6+ (hexavalent) forms. These naturally occurring oxidation states differ significantly in their bioavailability and toxicity. Trivalent Cr has been postulated to be involved in regulating carbohydrate and lipid metabolism by enhancing insulin's efficacy (Vincent 2000). No Cr-dependent enzymes have been identified. The precise biochemical mechanism of Cr as an essential trace element is not clearly known; however, it has been shown that Cr binds to an oligopeptide to form chromodulin, a low-molecular-weight, chromium-binding substance that binds to and activates the insulin receptor to promote insulin action (Vincent, 2017). It may also have antioxidant effects. Recent research has suggested that although pharmacologic amounts Cr as a therapeutic agent might increase insulin sensitivity and affect lipid metabolism, it is not an essential mineral (Vincent, 2017; EFSA, 2014). Because, according to the definition of an "essential, trace element", its absence or deficiency from the diet does not produce abnormalities that can be reversed with the addition of Cr. Molecular mechanisms have been proposed for the beneficial effects of Cr but have not been definitively shown to occur consistently in animals.

Several studies on the effect of Cr in fish have been related to its role in metabolism (Hertz et al., 1989; Shiau and Lin, 1993; Ng and Wilson, 1997; Shiau and Shy, 1998; Fernandez et al., 1999; Liu et al., 2010b; Giri et al., 2014; Wang et al., 2014; 2019), growth (Tacon and Beveridge, 1982; Jain et al., 1994) and toxicity (Calamari and Solbé, 1994). To date, many of these studies have provided some evidence that Cr has an effect on the metabolism of fish; however, Cr forms tested and their level as well as experimental conditions have been different in these reports. Chromium yeast appears to modulate the immune response of rainbow trout, and this effect was both dose- and time-dependent (Gatta et al., 2001). Information on the need for supplemental chromium in practical diets of certain animals including fish was too sparse to allow any conclusions (NRC, 2005). A need for research designed to create reproducible signs of chromium deficiency in animals, which would facilitate the establishment of dietary chromium requirements, was identified.

Chromium is absorbed across the gills and transported via blood to tissues but mechanisms of absorption from gills and the gastrointestinal tract, and excretion is not known. Studies on the uptake of Cr from water as it relates to physiology and toxicology have been reviewed (Reid, 2012). The toxic Cr6+ readily passes cellular membranes and is then reduced to the trivalent form. This Cr3+combines with several macromolecules including genetic material inside the cytosol, and ultimately exposes the toxic and mutagenic alterations of Cr toxicity. Higher levels of Cr in diet and water caused histological changes in intestine, gills, liver and kidney but the mechanism of toxicity remains to be established (Reid, 2012; Bakshi and Panigrahi, 2018).

2.8 Cobalt

Cobalt is a component of vitamin Bl2 , which is collectively called "cobalamins". Methylcobalamin and 5-deoxyadenosylcobalamin are the metabolically active forms of this vitamin: however, two others form, hydroxycobalamin and cyanocobalamin are converted to the active forms methylcobalamin and 5-deoxyadenosylcobalamin. Microbiota in the digestive tract of ruminants and algae are known to synthesize vitamin Bl2 from inorganic cobalt sources. Monogastric animals and fish require vitamin B12 because they lack the ability to synthesize this vitamin from dietary Co in sufficient amounts by microbiota in their digestive tract. In certain warmwater fish, intestinal synthesis of vitamin B12 by microorganisms appears to satisfy the requirements of this vitamin for Nile tilapia (Lovell and Limsuwan, 1982) and hybrid tilapia (Shiau and Lung, 1993), but not for channel catfish (Limsuwan and Lovell, 1981). The estimated dietary Co requirement reported for Tilapia zillii, was about 100 mg Co kg-1 of diet (Anadu et al., 1990). A lower concentration of Co (10 mg Co kg-1) in the diet promoted gastrointestinal bacterial synthesis of vitamin B12 in Malabar grouper and met the dietary requirement of this vitamin (Lin et al., 2010b).

Cobalt is absorbed by FW fish via the gills and gut as main routes of uptake (Baudin et al., 2000; Blust, 2012). Some uptake of cobalt occurred in rain¬bow trout eggs during embryonic development (Kuenze et al., 1978). The uptake routes, homeostasis and mechanism of Co toxicity has been reviewed (Blust,2012). Cobalt normally present in common feed ingredients, and animal and fish diets are relatively low to cause toxicity (Suttle, 2010; NRC, 2005).

2.9 Boron

Boron is an essential nutrient for plants including algae, but biological functions required to establish its essentiality for humans and animals are not clearly identified. To date, boron has been found to be essential for only zebrafish to complete their life cycle (Eckhert and Rowe, 1999). It also stimulates embryonic growth in trout (Eckhert, 1998) and zebrafish (Row and Eckhert, 1998). Boron has beneficial effects on such functions as reproduction and development, calcium metabolism, bone formation, brain function, insulin and energy substrate metabolism, immunity, and the function of vitamin D and steroid hormones (Nielsen, 2014; Hunt, 2012). As compared to FW, the concentration of boron in the marine environment is relatively high (0.4 mM), which is efficiently taken up by algae (Miller et al., 2016). Acute toxicity of B to fry of Chinook salmon and Coho salmon has been reported (Hamilton and Buhl, 1990).

2.10 Cadmium

Cadmium is a heavy metal that does not have a clear physiological function as a nutrient and is considered a toxicant for fish by its uptake from the aquatic environment. The toxicity of Cd causes the disruption of Ca ion homeostasis and to some extent Na and Mg (McGeer et al., 2012). Cadmium enters the gill epithelium via the same pathway as Ca2+(apical Ca2+ channel of the chloride cells) and inhibits basolateral Ca2+ ATPase, thereby blocking active Ca2+ uptake (Verbost et al. 1989). Atlantic salmon fed 25 mg Cd kg-1 showed inhibition of ATP dependent Ca uptake measured as Ca2+and Na+/K+-ATPase in the intestine (Berntssen et al., 2003). Generally, the concentration of Cd in most feed ingredients is relatively low (Adamse et al., 2017).

2.11 Other trace elements

Biochemical functions of other trace elements (As, F, Li, Ni, Pb, Si and V) have been shown in animals and humans, but their essentiality based on the defined criteria of physiological impairment has not been widely accepted. These minerals in fish have been studied mostly from physiological aspects of their uptake from water and toxicity. Arsenic is naturally abundant in aquatic environments and is considered moderately toxic (McIntyre and Linton, 2012). Supplementation of rainbow trout diet with As, reduced growth and resulted in As accumulation in several tissues (Cockell et al., 1991; Erickson et al., 2011). A maximum tolerable limit for fish may be in the range of 5 mg As kg-1 diet (NRC, 2005). Arsenic levels in algae and crustaceans are particularly high due to their uptake from water or consumption of aquatic organisms through the food web, but are relatively low in fish (Borak and Hosgood, 2007; Taylor et al., 2017). Marine fish accumulate higher levels of As than FW fish, presumably because of the higher levels of arsenobetaine in their prey. Approximately 90% of As in fish is organic As, with arsenobetaine being the dominant form in marine fish; which is virtually non-toxic (NRC, 2005). Some fish meals may contain high levels of total As, but their inorganic As concentration is low (Sloth et al., 2005). Arsenic is far less toxic to fish than are most metals (Spehar and Fiandt, 1986; Buhl and Hamilton, 1991).

3. Macrominerals

3.1 Calcium and phosphorus

Calcium and phosphorus play a major role in the development and maintenance of the skeletal system and perform many other physiological functions including the mainte¬nance of acid base equilibrium. In skeletal tissue, Ca and P are deposited as tricalcium phosphate [Ca3(PO4)2], which then undergoes further crystalline changes to form hydroxyapatite, Ca10(PO4)6(OH)2, which is deposited in the organic matrix during mineralization. The ratio of Ca to P in bone may show some changes during development, however, their ratio reported in several fish species ranges from 1.6:1 to 2:1. Fish scale is also a calcified tissue and serves as an internal Ca reservoir during periods of increased Ca demand, such as sexual maturation and starvation (Persson et al., 1998). During the reproductive period, the plasma Ca level increases in females, which is bound to vitellogenin, a major component of egg protein and a calcium-binding protein (Kwon et al., 1993).

Fish absorb Ca and P from the surrounding aquatic environment via gills, gastrointestinal tract and integument; however, the gills represent the major site of Ca uptake (Evans and Claiborne, 2009). The physiological aspect of Ca uptake at the gills is well established and is the subject of several reviews (Flik et al., 1995; Marshall 2002; Lin and Hwang 2016). The absorption and metabolism of Ca depends not only on its concentration in the surrounding water, but it is affected by species differences and their homeostasis by the endocrine system, biological availability from diet and P level (Lall, 2021). Osmoregulation allows them to control their Ca levels predominantly via the hypocalcemic hormones, stanniocalcin and calcitonin. Certain minerals (e.g., Cd, Cu, Mg, Sr, Zn) may reduce Ca absorption from gills or gastrointestinal tract (Berntssen et al., 2003; Baldisserotto et al., 2006; Zimmer et al., 2019). In vertebrates, vitamin D is known to play an essential role in Ca metabolism. Although, limited research has been conducted on fish, the function of the endocrine system and metabolites identified appears similar in fish and terrestrial vertebrates (Sundell et al., 1992; Graff et al., 1999; Fraser, 2018).

In addition to skeletal tissue metabolism. P as phosphate (HPO42-) plays a major role in the function of all cells. It is a major signaling molecule, and structural component of cell walls, essential for nucleic acid helical structure (i.e., RNA and DNA), and a component of high-energy compounds (i.e., AMP, ADP, and ATP). Food is the main source of P for fish because FW and SW are low in phosphate. Thus regulation of phosphate is considered more critical than that of Ca because fish must effectively absorb, and conserve phosphate in both FW and SW environments. Dietary P concentration is a major regulator of P metabolism in fish (Coloso et al. 2003). The amount of phosphate absorbed from the food is affected by the level of phosphate in the blood (Lall, 2002). The serum concentration of phosphate and the total body content of phosphate are highly regulated and movement into cells is mediated by sodium-phosphate co-transporters (Hernando and Wagner et al., 2018).

Information on the endocrine regulation of P homeostasis in fish is limited. The hormones involved in phosphate regulation include ST, prolactin and parathyroid like hormones (Pth1h). With the rise in serum Ca, stanniocalcin is secreted by the corpuscles of stannius to inhibit gill and intestinal Ca transport and to promote P reabsorption in the kidney to maintain normal physiological serum Ca and P levels (Wagner, 1993; Wagner et al., 1998). Parathyroid hormone-like hormone, Pth3 and Pth4 play an important role in functions related to P and bone mineral homeostasis (Potts 2005; Guerreiro et al. 2007). It is also not clear whether the effect is mediated by the vitamin D metabolites as happens in terrestrial vertebrates (Wendelaar Bonga and Flick, 1995). Although intraperitoneal injection of vitamin D metabolites influence P homeostasis (Fenwick and Vermette, 1989), dietary intake of cholecalciferol had no clear effect on P absorption and retention in rainbow trout (Vielma et al., 1999).

3.1.2 Requirement

The Ca requirement of fish is affected by dietary factors (e.g. bioavailability, P level), uptake from water and species differences (NRC, 2011; Hossain and Yoshimatsu, 2014). Generally, a large part of Ca requirement of most fish is met by its absorption through gills in FW and by drinking SW. A low concentration of calcium (0.34 % or less) is required in the diet of carp, red sea bream, striped bass, tilapia, catfish and chum salmon (Sakamoto and Yone, 1973; Ogino and Takeda, 1976; Lovell, 1978; Nakamura, 1980; Robinson et al.,1984; Dougall et al, 1996). Catfish and tilapia reared in water with a low calcium concentration (< 1 mg Ca/L) required 0.45 % and 0.7 % calcium in the diet, respectively (Robinson et al., 1986, 1987). Atlantic salmon absorb Ca from SW, thus making dietary supplementation unnecessary (Lall and Bishop, 1977). There is a relatively low requirement (0.1-0.25 %) of Ca for farmed marine fish (NRC, 2011). Other details related to Ca utilization

doi:10.20944/preprints202108.0088.v1

and requirements of certain fish species have been reviewed (Hossain and Yoshimatsu, 2014; Lall, 2021).

The P requirement (g/100g) of a wide range of fish species reared in fresh, brackish and SW have been reported. Requirement in FW: Atlantic salmon, 0.6-1.0 (Ketola, 1975; Vielma and Lall, 1998; Åsgård and Shearer, 1997), rainbow trout, 0.34-0.8 (Ogino and Takeda, 1976; Rodehutscord, 1996; Ketola and Richmond, 1994); chum salmon, 0.5-0.6 (Watanabe et al., 1980); channel catfish, 0.33-0.8 (Andrews et al., 1973; Lovell et al., 1978; Wilson et al., 1988) milkfish, 0.85 (Borlongan and Satoh, 2001); blue tilapia, 0.5 (Robinson et al., 1987); Nile tilapia, 0.65-0.86 (Yao et al., 2014; Carvalho et al., 2017); common carp, 0.6-0.7 (Ogino and Takeda, 1976); gibel carp, 0.67-1.07 (Xie et al., 2017); grass carp, 0.85 (Liang et al., 2012); crucian carp, 0.78-0.83 (Sun et al., 2018); stinging catfish, 0.9-1.1 (Zafar and Khan, 2018); African giant catfish, 1.23 (Nwanna et al., 2009); walking catfish, 0.58-0.73 (Yu et al., 2012); Chinese sucker, 0.83-0.86 (Yuan et al., 2011); hybrid striped bass, 0.5 (Brown et al., 1993); snakehead, 0.96 (Shen et al., 2016); tambaqui, 0.7 (Araujo et al., 2016); Japanese eel, 0.29 (Nose and Arai, 1979). Requirement in brackish water (salinity, 5-6 0/00): red drum, 0.86 (Davis and Robinson, 1987). Requirement in SW: Atlantic salmon, 0.6 (Lall and Bishop, 1977); red sea bream, 0.68 (Sakamoto and Yone, 1978a); gilthead seabream, 0.75 (Pimental-Rodrigues and Olivia-Teles, 2001); black seabream, 0.55 (Shao et al., 2008); haddock, 0.96 (Roy and Lall, 2003); Japanese seabass, 0.86-0.90 (Zhang et al., 2006); European seabass, 0.65 (Olivia-Telesand Pimental-Rodrigues, 2004); orange spotted grouper, 1.09 (Ye et al., 2006); Yellow croaker, 0.89-0.91 (Mai et al., 2006); Japanese flounder, 0.6-1.5 (Choi et al., 2005; Wang et al., 2005; Uyan et al., 2007).

The requirement estimates above are mainly based on juvenile fish studies and there were differences in dietary sources of P and their bioavailability, fish size and response criteria selected. Anthony Jesu Prabhu et al. (2013) used a meta-analysis approach to estimate the P requirements based on published information on P utilization for 40 different fish species where requirement values were determined using differences in the response criteria. They found that requirement based on weight gain, and P concentration of whole-body and vertebrae were 0.35, 0.47 and 0.52 g available P/100 g diet (dry matter basis) respectively. Some of these estimates differed from NRC recommendation on P requirement (g/100g) for major farmed fish species: Atlantic salmon, 0.8; rainbow trout, 0.7; Pacific salmon, 0.6; channel catfish, 0.33; common carp. 0.7; tilapia sp., 0.4; hybrid striped bass, 0.5 ; red drum, 0.8; European seabass, 0.65; Japanese flounder, 0.6 P/100 g diet. Obviously, there is a need to better define the P requirement of fish taking into account the stage of development, bioavailability of P from the test diet and feed supplement used to fortify the experimental diets. Studies conducted on other animals show that the maximum growth rates are not necessarily adequate for maximum bone mineralization and they may need higher levels of P in their diet (NRC, 2012).

3.1.3. Deficiency

Calcium deficiency has not been detected in carp and catfish in FW (Andrews et al., 1973; Ogino and Takeda, 1976) or in Atlantic salmon in SW (Lall and Bishop, 1977) fed low Ca diets. Generally, uptake of Ca from water and absorption from dietary feed ingredients supplies sufficient calcium to meet the requirements of most finfish. Studies conducted on the P requirement of several fish species have shown reduced weight gain, feed utilization and bone mineralization when the P content of the diets were low, with certain exceptions, gibel carp (Xie et al., 2015), red drum (Davis and Robinson, 1987), gilthead bream (Pimental-Rodrigues and Olivia-Teles, 2001) and European seabass (Olivia-Teles and Pimental-Rodrigues, 2004). Other P deficiency signs experimentally produced in fish included increases in liver or body fat, reduced blood phosphate levels and poor mineralization of scales. Fish fed diet containing either mineral deficient or low P diet mobilize minerals including Ca and P to maintain normal physiological functions (Lall, 2021) and fish scales appear to be the most sensitive indicator of P deficiency in young fish (Skonberg et al., 1997; Vielma and Lall, 1998a). The cause of low dietary P-induced skeletal deformities in salmonids and certain marine fish have been the subject of intensive research and several reviews have been published in this area (Sugiura et al., 2004; Lall and Lewis-McCrea. 2007; Lall, 2010; Baeverfjord et al., 2019). Common skeletal deformities with low intake of P include curved spines and soft bones in Atlantic salmon (Baeverfjord et al., 2019), cephalic deformities in the frontal bones of common carp (Ogino and Takeda, 1976), and compressed vertebral bodies resulting in scoliosis in haddock (Roy and Lall, 2003) and halibut (Lall and Lewis-McCrea,2007). Recent, studies of bone tissues have revealed that mobilization of minerals during low intake of dietary P does not fully explain the biochemical mechanism involved in the demineralization process (Witten et al., 2016, 2019; Drabiková et al., 2021). A decrease in dietary P content in a practical diet of Atlantic salmon smolts showed vertebrae without any significant changes in organic matrix and demineralization of bone (Fjelldal, et al. 2007; Witten et al., 2019). Several nutrients support skeletal growth including bone and scale matrix mineralization, and interactions between P and other nutrients in skeletal tissue biomineralization are poorly understood (Lall, 2010).

3.1.4 Bioavailability

The bioavailability of P by fish differs markedly among feed ingredients and inorganic P supplements as well as among other dietary factors (e.g., chemical form, digestibility of diet, particle size, interaction with other nutrients, feed processing and water chemistry) (Lall, 1991; NRC, 2011). Most of the P in cereal grains and oilseed meals present in the form of an organic complex, phytic acid or phytate (myo-inositol 1, 2, 3, 4, 5, 6-hexakis dihydrogen phosphate) is not available to fish because their intestinal tract does not have sufficient extracellular phytase like other nonruminant vertebrates. Phytate depresses protein and amino acid digestibility and utilization efficiency in fish and other higher animals. Phytate interactions with proteins are also pH-dependent (Cheryan, 1980). Several reviews have considered various aspects of phytates in fish nutrition and potential strategies to improve the bioavailability of phytates in feed ingredients of plant origin (Cao et al., 2007; Kumar et al., 2012; Dersjant-Li et al., 2015; Lemos and Tacon, 2015). The hydrolysis of phytic acid can be achieved by enzymatic and nonenzymatic degradation. Development of phytases and optimization of their catalytic features has been a promising strategy for efficient reduction of phytate in animal feeds. Phytate also forms complexes with lipid and derivatives along with other nutrients (Vohra and Satanarayana, 2003) but this aspect of chelate formation has not been investigated in fish. The preferable method of phytase application in feeds is coating a liquid form of the enzyme after extrusion and drying which prevents loss of enzyme activity during processing (Verlhac-Trichet et al., 2014).

Phosphorus in fish meal is mainly in the form of an insoluble Ca-P complex, hydroxyapatite which varies with the source of fish used and its bioavailability varies among fish species (NRC, 1993; 2011) Acid hydrolysis of fish bone by-products appears to increase P availability of the hydroxyapatite in bone (Albrektsen et al, 2017). There are significant differences in the availability of P from a variety of inorganic salts: the more soluble the salt, the higher the availability of P, thus P is more readily available from mono- or di-calcium phosphates than from tri-calcium phosphate (NRC, 1993; 2011). Salmonids utilize P present in fish meal more efficiently than carp, tilapia and channel catfish (Lovell, 1978; Ogino et al., 1979; Watanabe et al., 1988; Köprücü and Özdemir, 2005).

3.2 Magnesium

Magnesium is a critical intracellular divalent cation that plays an essential physiological role in many functions in the body. It forms a key complex with ATP and plays a key role in many important biological processes such as protein synthesis, cell replication, and energy metabolism. Magnesium is a regulator of ion channels, an important intracellular signaling molecule, involved in nerve conduction, muscle contraction, potassium transport and a modulator of oxidative phosphorylation. Extracellular Mg is vital to normal nerve conduction, muscle function, and skeletal tissue metabolism. It plays an important role in the respiratory adaptation of FW fish (Houston, 1985). The major

doi:10.20944/preprints202108.0088.v1

proportion (50-70%) of Mg in the body of fish is located in skeletal tissues and scales (Bijwelds et al., 1998). The remainder is found within the cells of soft tissues. In muscle, it comprises approximately 20% of the total body Mg pool (Knox et al., 1981).

Dietary Mg is considered the main source for growth and development of fish (Cowey et al., 1977; Lall, 2002). When dietary Mg concentration was low in FW, part of its requirement was met by uptake from water via gills (Shearer and Asgard, 1992; Dabrowska et al., 1991). However, in most fish species studied, Mg uptake from FW was insufficient to meet their dietary Mg requirement (Lall, 2002; NRC, 2011). There is some evidence that excess Mg is excreted renally by fish in FW (Oikari and Rankin, 1985). In SW, fish absorb Mg by drinking (Hickman and Trump, 1969) and the major part of the Mg requirement of Atlantic salmon and other marine fish could be met by absorption of SW (Lall and Bishop, 1977).

3.2.1 Requirement

Magnesium requirements of most farmed fish species have ranged from 0.4 to 0.6 g kg-1 diet (NRC, 2011; Lall, 2021). Hybrid tilapia showed the Mg requirements of 0.2 and 0.02 % in FW and SW respectively. No requirement of Mg for yellow croaker and red mullet has been reported (El-Zibdeh et al., 1996). A meta-analysis of Mg requirement reported for several fish species showed relatively close estimates for the Mg requirement (g kg-1 diet) based on the following parameters: weight gain, 0.34; whole body Mg, 0.49; vertebrae Mg, 0.42; plasma Mg, 0.5 (Antony Jesu Prabhu et al., 2016). In SW, Mg requirement for Atlantic salmon and red seabream was not observed (Lall and Bishop, 1977; Sakamoto and Yone, 1979b). Unlike terrestrial animals, Mg requirement of rainbow trout was not influenced by an increase in dietary Ca and P levels (Knox et al., 1981).

3.2.2. Deficiency

Magnesium is mobilized from bones and scales when dietary Mg intake is low (Cowey et al., 1977). Deficiency signs of Mg in carp, catfish, hybrid tilapia, eel, and rainbow trout may include one or more of the following deficiency signs: anorexia, reduced growth, sluggishness, high mortality, and reduced magnesium content (NRC, 2011; Lall, 2010). In rainbow trout, Mg deficiency also causes calcinosis of kidney, vertebrae deformity, and degeneration of muscle fibers and epithelial cells of the pyloric cecum and gill filaments (Cowey et al., 1977; Ogino et al., 1978). A low concentration of Mg in water reduced the Mn concentration of eggs in carp, which reduced the hatchability of egg and survival of offspring and also caused deformities and tissue necrosis (Van der Valden et al., 1991).

3.2.3 Bioavailability

Information on Mg bioavailability from feed ingredients and inorganic supplements for fish is scarce. Generally , Mg concentration in natural feed ingredients of plant and animal origin contain moderate levels of Mg. Inorganic Mg feed supplements include magnesium sulfate, magnesium chloride, magnesium oxide and magnesium acetate. Magnesium sulfate is more water soluble than magnesium oxide and therefore more available for absorption. Magnesium present as Mg acetate was more efficiently used by tilapia than either Mg oxide or sulfate (Dabrowska et al., 1989).

4. Concluding remarks

Many gaps exist in the knowledge of mineral nutrition of fish and shrimp related to their dietary requirements, physiological functions, absorption from gastrointestinal tract and bioavailability from feed ingredients. Information on animal and human nutrition has been useful to confirm the biochemical functions of certain inorganic elements including skeletal tissue metabolism, cellular respiration, oxygen transport, regulation of acid-base equilibrium as well as important components of hormones, enzymes and enzyme activators. Extensive research on farm animals has demonstrated that mineral requirements differ at various stages of their production cycle, certain trace elements play important role

doi:10.20944/preprints202108.0088.v1

in immune functions and disease prevention and application of specific methodologies are useful to predict the bioavailability of minerals from feed ingredients; however, the research in these areas on fish is limited. Another issue specific to aquatic animals is that there is a need to consider the impact of water-borne minerals from both the nutritional and environmental points of view.

Aquaculture is now the fastest growing food production system globally with many new challenges to address the nutritional problems of more than 40 major farmed fish species. Early studies on mineral nutrition were conducted on salmonids and some warm water fishes using semi-purified diets and trace element supplements of high bioavailability. Most known mineral requirements (Ca, P, Mg, Cu, Zn, Mn, Se) were determined for young fish. NRC (1993, 2011) requirement values for certain minerals for about 10 fish species have been used as guidelines and as a starting point to establish recommendation allowances for new fish species. Many studies were short term and gave little consideration to the dietary intake or mineral status prior to the experimental period and to the effect of the previous diet may have on body stores at the commencement of the study. Some minerals take longer period, depending on the water temperature to reach a steady state following a change in their dietary intake. A shift from the use of fish meal as a major source of protein and minerals in feeds to proteins of plant origin and land animal products, now requires better assessment of mineral bioavailability for improving feed formulation more precisely. There are also new trace element supplements available which require proper assessment of their rate of absorption and potential impact on fish performance.

Because an animal's requirement for any nutrient is affected by many factors, limited data on nutrient requirement values (e.g., NRC, 2011) should not be regarded as fixed quantities. Instead of solely relying on these values, changes in animal performance with alterations in nutrient intake should be determined as dynamic responses, to derive requirement estimates that are appropriate to the particular fish species under different culture conditions and dietary regimes. This should start with the units of expression of data on mineral requirements. Meta analyses of existing data on requirements provide some general guidelines on recommendations. Factorial models are now being applied to estimate nutrient requirements and metabolism of farmed animals and fish; however, additional reliable new data on mineral requirements of major farmed fish species is needed to generate reliable information for use in feed formulation.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Title 1	**Title 2**	**Title 3**
entry 1	data	data
entry 2	data	data [1]

[1] Tables may have a footer.

The text continues here (Figure 2 and Table 2).

(**a**) (**b**)

Figure 2. This is a figure. Schemes follow another format. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

Table 2. This is a table. Tables should be placed in the main text near to the first time they are cited.

Title 1	**Title 2**	**Title 3**	**Title 4**
entry 1	data	data	data
	data	data	data
	data	data	data
entry 2	data	data	data
	data	data	data
entry 3	data	data	data
	data	data	data
	data	data	data
	data	data	data
entry 4	data	data	data
	data	data	data

Author Contributions: Conceptualization, S.P.L., S.J.K.; original draft preparation S,P.L., S.J.K.; visualization, S. P.L., S.J.K. Both authors have read and agreed to the published version of the manuscript..

Funding: Please add: “This research received no external funding”

Institutional Review Board Statement: Not applicable.

Data Availability Statement. Not applicable

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: “The authors declare no conflict of interest.”.

References

Adamse, P.; Van der Fels-Klerx , H.J.; de Jong. J. Cadmium, lead, mercury and arsenic in animal feed and feed materials – trend analysis of monitoring results, *Food Add. Contam. Part A*, **2017**, *34*, 1298-1311.

Albrektsen, S.; Lock, E.-J.; Baeverfjord, G.; Pedersen, M.; Krasnov, A.; Takle, H.; Veiseth-Kent, E.; Veiseth- Kent, E.; Waagbø, R.; Ytteborg, E. Utilization of H_2SO_4- hydrolysed phosphorus from herring bone byproducts in feed for Atlantic salmon (*Salmo salar*) 0+ postsmolt. *Aquac. Nutr*. **2017**, *24*, 348-365..

Alsop, D.H.; Wood, C.M. Influence of waterborne cations on zinc uptake and toxicity in rainbow trout, *Oncorhynchus mykiss*. *Can. J. Fish. Aquat. Sci.* **1999**, *56*, 2112–2119.

Ammerman, C.B. Methods for estimation of mineral bioavailability. In *Bioavailability of Nutrients for Animals: Amino acids, Minerals and Vitamins*; Ammerman, C. B., Baker, D. J., Lewis, A. J., Eds.; Academic Press: San Diego, USA, 1995; pp. 83-94.

Ammerman, C.B., Baker, D. J., Lewis, A .J. *Bioavailability of Nutrients for Animals: Amino acids, Minerals and Vitamins;* Academic Press: San Diego, USA, 1995.

Anadu, D.I.; Anozie, O.C.; Anthony, A.D. Growth responses of *Tilapia zillii* fed diets containing various levels of ascorbic acid and cobalt chloride. *Aquaculture* **1990**, *88*, 329-336.

Andersen, F.; Maage, A.; Julshamn, K. An estimation of iron requirement of Atlantic salmon *Salmo salar L.*, parr. *Aquac. Nutr*. **1996**, *2*, 41–47.

Andersen, F.; Lorentzen, M.; Waagbø, R.; Maage, A. Bioavailability and interactions with other micronutrients of three dietary iron sources in Atlantic salmon, *Salmo salar*, smolts. *Aquac. Nutr*. **1997**, 3, 239-246.

Andreini, C.; Bertini, I.; Rosato, A. Metalloproteomes: A bioinformatic approach. Accounts Chem. Res. **2009,** *42*, 1471–1479.

Andrews, J.W.; Murai, T.; Campbell, C. Effects of dietary calcium and phosphorus on growth, food conversion, bone ash and hematocrit levels of catfish. *J. Nutr.* **1973**, *103*, 766-771.

Antony Jesu Prabhu, P.; Schrama, J.W.; Kaushik, S.J. Quantifying the dietary phosphorus requirement of fish – a meta-analytic approach. *Aquac. Nutr.* **2013**, *19*, 243-249.

Antony Jesu Prabhu, P.; Schrama, J.W.; Kaushik, S.J. Mineral requirements of fish: a systematic review. *Rev. Aquac.* , **2016**, *8*, 172–219.

Antony Jesu Prabhu, P.; Stewart, T.; Silva, M.; Amlund, H.; Ørnsrud, R.; Lock, E-J.; Waagbo, R.; Hogstrand, C. Zinc uptake in fish intestinal epithelial model RTgutGC: impact of media ion composition and methionine chelation. *J. Trace Elem. Med. Biol.* **2018b**, *50*, 377-383.

Antony Jesu Prabhu, P.; Silva; M.S.; Kröeckel, S.; Holme, M.; Ørnsrud, R.; Amlund, H.; Erik-Jan Lock, E.-J.; Waagbø, R. Effect of levels and sources of dietary manganese on growth and mineral composition of post-smolt Atlantic salmon fed low fish meal, plant-based ingredients. *Aquaculture*, **2019a**, *512*, 734287.

Antony Jesu Prabhu, P.; Fountoulaki, E.; Maas, R.; Heinsbroek, L.T.N.; Eding, E.H.; Kaushik, S.J.; Schrama, J.W. Dietary ingredient composition alters faecal characteristics and waste production in common carp reared in recirculation system. *Aquaculture* **2019**b, *512*, 734357.

Antony Jesu Prabhu, P.; Holen, E.; Espe, M.; Silva, M.S.; Holme, M.-H.; Hamre, K.; Lock, E.; Waagbø, R. Dietary selenium required to achieve body homeostasis and attenuate pro-inflammatory responses in Atlantic salmon post-smolt exceeds the present EU legal limit. *Aquaculture* **2020**, *526*, 735413. doi:10.1016/j.aquaculture.2020.735413.

Apines. M.J.S.; Satoh, S.; Kiron, V.; Watanabe, T.; Aoki, T. Availability of supplemental amino acid-chelated trace elements in diets containing tricalcium phosphate and phytate to rainbow trout, *Oncorhynchus mykiss*. *Aquaculture* **2003a**, *225*, 431-444.

Apines. M.J.S.; Satoh, S.; Kiron, V.; Watanabe, T.; Fujita, S. Bioavailability and tissue distribution of amino acid chelated trace elements in rainbow trout *Oncorhynchus mykiss*. *Fisher. Sci*. **2003b**, *69*, 722-730.

Apines-Amar, M.J.S; Satoh, S.; Caipang, C.M.A.; Kiron, V.; Watanabe, T.; Aoki, T. Amino acid-chelate: a better source of Zn, Mn and Cu for rainbow trout, *Oncorhynchus mykiss*. *Aquaculture* **2004,** *240*, 345-358.

Araújo, J.G.; Guimarães, I.G.; Mota, C.S.; de Paula, F.G.; Café, M.B.; Pádua, D.M.C. Dietary available phosphorus requirement for tambaqui, *Colossoma macropomum* , juveniles based on growth, haematology and bone mineralization. *Aquac. Nutr*. **2016**, 23, 822-832.

Arthur, J. R.; McKenzie, R. C.; Beckett, G. J. Selenium in the immune system. *J Nutr*. **2003**, *133*, 1457S–1459S.

Aschner, J.L.; Aschner, M. Nutritional aspects of manganese homeostasis, *Mol. Aspects Med.* **2005**, *26*, 353-362.

Åsgård, T.; Shearer, K.D. Dietary phosphorus requirement of juvenile Atlantic salmon, *Salmo salar* L. *Aquac. Nutr.* **1997**, *3*, 17-23.

Baeverfjord, G.; Antony Jesu Prabhu, P.; Fjelldal, P.G.; Albrektsen, S.; Hatlen, B.; Denstadli, V.; Waagbø, R. Mineral nutrition and bone health in salmonids. Rev. Aquac. **2019**, *11*, 740-765.

Baker, R.T.M. Chronic dietary exposure to copper affects growth, tissue lipid peroxidation, and metal composition of the grey mullet, *Chelon labrosus*. *Mar. Environ. Res*. **1998**, *45*, 357–365.

Baker, D.J., Ammerman, C.B. Copper bioavailability. In *Bioavailability of Nutrients for Animals: Amino acids, Minerals and Vitamins*; Ammerman, C. B., Baker, D. J., Lewis, A. J., Eds.; Academic Press: San Diego, USA, 1995; pp. 127-156.

Bakshi, A.; Panigrahi, A.K. A comprehensive review on chromium induced alterations in fresh water fishes. *Tox. Rep*. **2018**, *5*, 440-447.

Baldisserotto, B.; Chowdhury, M.J.; Wood, C.M. *In vitro* analysis of intestinal absorption of cadmium and calcium in rainbow trout fed with calcium- and cadmium-supplemented diets. *J. Fish Biol*. **2006**, *69*, 658-667.

Baudin, J.P.; Veran, M.P.; Adam, C.; Garnier-LaPlace, J. Dietary uptake, retention and tissue distribution of ^{54}Mn, ^{60}Co and ^{137}Cs in rainbow trout (*Oncorhynchus mykiss* Walbaum). *Water Res*. **2000**, *34*, 2869-2878.

Beaumont, M. Exposure of brown trout, *Salmo trutta*, to a sub-lethal concentration of copper in soft acidic water: effects upon muscle metabolism and membrane potential. *Aquat. Toxicol*. **2000**, 51, 259-272.

Bell, J.M. Nutrients and toxicants in rapeseed meal: a review. *J. Animal Sci*. **1984**, *58*, 996-1010.

Bell, J.G.; Cowey, C.B. Digestibility and bioavailability of dietary selenium from fishmeal, selenite, selenomethionine and selenocystine in Atlantic salmon (*Salmo salar*). *Aquaculture* **1989**, *81*, 61-68.

Bell J.G.; Cowey C.B.; Adron J.W.; Shanks, A.M. Some effects of vitamin E and selenium deprivation on tissue enzyme levels and indices of tissue peroxidation in rainbow trout (*Salmo gairdneri*). *Br. J. Nutr*. **1985**, *53*, 149-157.

Berntssen, M.H.G.; Lundebye, A.K.; Maage, A. Effects of elevated dietary copper concentrations on growth, feed utilisation and nutritional status of Atlantic salmon (*Salmo salar* L.) fry. *Aquaculture* **1999a**, *174*, 167-181.

Berntssen, M.H.G.; Waagbø, R.; Toften, H.; Lundebye, A.K. Effects of dietary cadmium on calcium homeostasis, Ca mobilization and bone deformities in Atlantic salmon (*Salmo salar* L.) parr. *Aquac. Nutr*. **1999b**, *9*, 175-183.

Berntssen, M.H.G.; Lundebye, A.-K.; Hamre, K. Tissue lipid peroxidative responses in Atlantic salmon (*Salmo salar* L.) parr fed high levels of dietary copper and cadmium. *Fish Physiol. Biochem*. **2000**, 21, 35-48.

Berntssen, M.H.G.; Waagbo, R.; Toften, H.; Lundebye, A.-K. Effects of dietary cadmium on calcium homeostasis, Ca mobilization and bone deformities in Atlantic salmon (*Salmo salar* L.) parr. *Aquac. Nutr*., **2003**, *9*, 175-183.

Berntssen, M.H.G.; Sundal, T.K.; Olsvik, P.A.; Amlund, H.; Rasinger, J.D.; Sele, V.; Hamre, K.; Hillsted, M.; Buttle, L.; Ørnsrud, R. Sensitivity and toxic mode of action of dietary organic and inorganic selenium in Atlantic salmon (*Salmo salar*). *Aquat. Toxicol*. **2017**, *192*, 116–126.

Berntssen, M.H.G.; Betancor, M.; Caballero, M.J.; Hillestad, M.; Rasinger, J.; Hamre, K.; Sele, V.; Amlund, H.; Ørnsrud, R. Safe limits of selenomethionine and selenite supplementation to plant-based Atlantic salmon feeds. *Aquaculture* **2018**, *495*, 617-630.

Betancor, M.; Dam, T.; Walton, J.; Morken, T.; Campbell, P.; Tocher, D. Modulation of selenium tissue distribution and selenoprotein expression in Atlantic salmon (*Salmo salar* L.) fed diets with graded levels of plant ingredients. *Br. J. Nutr*. **2016**, *115*, 1325-1338.

Bielmyer,G.K.; Bullington, J.B.; DeCarlo, C.A.; Chalk, S.J.; Smith, K. The effects of salinity on acute toxicity of zinc to two euryhaline species of fish, *Fundulus heteroclitus* and *Kryptolebias marmoratus*, *Integ. Comp. Biol*. **2012**, *52*, 753-760.

Bijvelds, M.; Velden, J.; Kolar, Z.I.; Flik, G. Magnesium transport in freshwater teleosts. *J. Exp. Biol.* **1998**, *201*, 1981-1990.

Bjeerkäas, E.; Sveier, H. The influence of nutritional and environmental factors on osmoregulation and cataracts in Atlantic salmon (*Salmo salar* L.). *Aquaculture* **2004**, *235*, 101–122.

Bjørnevik, M.; Maage, A. Effects of dietary iron supplementation on tissue iron concentration and haematology in Atlantic salmon (*Salmo salar*). *Fisk. Dir. Skr. Ser. Ernaering*. **1993**, *6*, 35–45.

Blanton, M.L.; Specker, J.L. The hypothalamic-pituitary-thyroid (HPT) axis in fish and its role in fish development and reproduction. Crit. Rev. Toxicol. **2007,** *37*, 97-115.

Borak, J.; Hosgood, H.D. Seafood arsenic: implications for human risk assessment. *Regul. Toxicol. Pharmacol.* **2007**, *47*, 204-212.

Borlongan, I.; Satoh, S. Dietary phosphorus requirement of juvenile milkfish, *Chanos chanos* (Forsskal). *Aquacult. Res*. **2001**, *32*, 26-32.

Blust, R. Cobalt. *Fish Physiol.* **2012**, 31A, 291-326.

Brix, K.V.; Tellis, M.S.; Crémazy, A.; Wood, C.M. Characterization of the effects of binary metal mixtures on short-term uptake of Cd, Pb, and Zn by rainbow trout (*Oncorhynchus mykiss*). *Aquat. Toxicol*. **2017**, *193*, 217–227.

Brooks, K.M.; Stierns, A.R.; Mahnken, C.V.W.; Blackburn, D.B. Chemical and biological remediation of the benthos near Atlantic salmon farms. *Aquaculture* **2003**, *219*, 355-377.

Brown, M.L.; Jaramillo, F.; Jr., Gatlin, D.M., III. Dietary phosphorus requirement of juvenile sunshine bass, *Morone chrysops* × *M. saxatilis*. *Aquaculture* **1993**, *113*, 355–363.

Brown, C.L.; Urbinati, E.C.; Zhang, W.; Brown, S.B.; McComb-Kobza, M. Maternal thyroid and glucocorticoid hormone interactions in larval fish development, and their applications in aquaculture. *Rev. Fish. Sci. Aquac*. **2014**, *22*, 207-220.

Buhl, K.J.; Hamilton, S.J. Relative sensitivity of early life stages of Arctic grayling, coho salmon, and rainbow trout to nine inorganics. *Ecotoxicol. Environ. Safety*. **1991**, *22*, 184–197.

Burk, R.F.; Hill, K.E. Regulation of selenium metabolism and transport. *Ann.Rev. Nutr*. **2015**, *35*, 109-134

Bury, N.; Grosell, M. 2003. Iron acquisition by teleost fish. *Comp. Biochem. Physiol. Part C* **2003**, *135*, 97-105.

Bury, N.R.; Walker, P.A.; Glover, C.N. Nutritive metal uptake in teleost fish. *J. Exp. Biol*. **2003**, *206*, 11-23.

Bury, N.R.; Boyle, D.; Cooper, C.A. Iron. *Fish Physiol.* **2012**, 31A, 201-251.

Calamari, D.; Solbé, J.F. Report on chromium and freshwater fish. In *Water Quality for Freshwater Fish*; Howells, G., Ed.; Gordon and Breach Science Publisher: Yverdon, Switzerland, 1994, pp. 1–30.

Canton, S.P.; Van Derveer, W.D. Selenium toxicity to aquatic life: an argument for sediment-based water quality criteria. *Environ. Toxicol. Chem*. **1997**, *16*, 1255-1259.

Cao, L.; Wang, W.; Yang, C.; Yang, Y.; Diana, J.; Yakupitiyage, A.; Luo, Z.; Li, D. Review: application of microbial phytase in fish feed. *Enzym. Microb. Technol*. **2007**, *40*, 497-507.

Cao, J.; Miao, X.; Xu, W.; Li, J.; Zhang, W.; Mai, K. Dietary copper requirements of juvenile large yellow croaker *Larimichthys croceus*. *Aquaculture* **2014**, *432*, 346-350.

Carvalho, P.L.P.F.; Koch, J.F.A.; Cintra, F.T.; Fernandes, A.C., Jr.; Sartori, M.M.P.; Barros, M.; Padihla, P.D.; Pezzato, L.L. Available phosphorus as a reproductive performance enhancer for female Nile tilapia. *Aquaculture* **2018**, *486*, 202-209.

Cheryan, M.; Rackis, J.J. Phytic acid interactions in food systems. *Crit. Rev. Food Sci*. **1980**, Nutr. *13*, 297-335.

Choi, Y.J.; Kim, N.N.; Shin, H.S.; Park, M.S.; Kil, G.-S.; Choi., Y.C. Effects of waterborne selenium exposure on the antioxidant and immunological activity in the goldfish, *Carassius auratus* . *Mol. Cell. Toxicol*. **2013**, *9*, 365–373.

Choi, S.M.; Kim, K.W.; Kang, Y.J.; Wang, X.J.; Kim, J.W.; Yoo, G.Y.; Bai, S.C. Re-evaluation of the phosphorus requirement of juvenile olive flounder *Paralichthys olivaceus* and the bioavailability of various inorganic phosphorus sources. *J. World Aquacult. Soc.* **2005**, *36*, 217-222

Clearwater, S.J.; Baskin, S.J.; Wood, C.M.; McDonald, D.G. Gastrointestinal uptake and distribution of copper in rainbow trout. *J. Exp. Biol*. **2000**, *203*, 2433–2466.

Clearwater, S. J.; Farag, A.; Meyer, J. Bioavailability and toxicity of diet borne copper and zinc to fish. *Comp. Biochem. Physiol. C* **2002**, *132*, 269-313.

Cockell, K.A.; Hilton, J.W.; Bettger, W.J. Chronic toxicity of dietary disodium arsenate heptahydrate to juvenile rainbow trout (*Oncorhynchus mykiss*). *Arch. Environ. Contam. Toxicol*. **1991**, *21*, 518-527.

Coloso, R.; King, K.; Fletcher, J.W.; Hendrix, H.A.; Subrmanyam, M.; Weiss, P.; Ferraris, R.A. Phosphorus utilization in rainbow trout (*Oncorhynchus mykiss*) fed practical diets and its consequences on effluent phosphorus levels. *Aquaculture* **2003**, *220*, 801-820.

Cooper, C.A.; Bury, N.R. The gills as an important uptake route for the essential nutrient iron in freshwater rainbow trout *Oncorhynchus mykiss*. *J. Fish Biol*. **2007**, *71*, 115–128.

Cousins, R.J. Absorption, transport, and hepatic metabolism of copper and zinc: special reference to metallothionein and ceruloplasmin. *Physiol. Rev*. **1985**, *65*, 238-309.

Cowey, C.B.; Knox, D.; Adron, J.W.; George, S.; Pirie, B. The production of renal calcinosis by magnesium deficiency in rainbow trout (*Salmo gairdneri*). *Br. J. Nutr*. **1977**, *38*, 127-135.

Cyr, D.G.; Bromage, N.R.; Dustin, J.; Eales, J.G. Seasonal patterns in serum levels of thyroid hormones and sex steroids in relation to photoperiod-induced changes in spawning time in rainbow trout, *Salmo gairdneri*. *Gen. Comp. Endocrinol*. **1988**, *69*, 217-25.

Cyr, D.G.; Eales, J.G. Interrelationships between thyroidal and reproductive systems in Fish. *Rev. Fish Biol. Fish*. **1996**, 6, 165-200.

Dabrowska, H.; Meyer-Burgdorff, K.; Gunther, K.D. Interaction between dietary protein and magnesium level in tilapia (*Oreochromis niloticus*). *Aquaculture*, **1989**, *76*, 277-291.

Dabrowska, H.; Meyer-Burgdorff, K.; Gunther, K.D. Magnesium status in freshwater fish, common carp (*Cyprinus carpio*, L.) and the dietary protein-magnesium interaction. *Fish Physiol. Biochem*. **1991**, *9*, 165-172.

Dalgaard, T.S.; Briens, M.; Engberg, R.M.; Lauridsen, C. The influence of selenium and selenoproteins on immune responses of poultry and pigs. *Anim. Feed Sci. Tech*. **2018**, *258*, 73-83.

Dalzell, D.J.B.; MacFarlane, N.A.A. The toxicity of iron to brown trout and effects on the gills: a comparison of two grades of iron sulphate. *J. Fish Biol*. **1999**, *55*, 301–315.

Damasceno, F.M.; Fleuri, .L.F.; Sartori, M.M.P.; Amorim, R.L.; Pezzato, L.E.; da Silva, R.L.; Carvalho, P.L.P.F.; Barros, M.M. Effect of dietary inorganic copper on growth performance and hematological profile of Nile tilapia subjected to heat-induced stress. *Aquaculture* **2016**, *454*, 257-264.

Davis, D.A.; Robinson, E.H. Dietary phosphorus requirement of juvenile red drum *Sciaenops ocellatus*. *J. World Aquacult. Soc*. **1987**, *18*, 129-136.

Davis, D.A.; Lawrence, A.L.; Gatlin, III, D.M. Evaluation of the dietary iron requirement of *Penaeus vannamei*. *J. World Aquac. Soc*. **1992**, 23, 15-22.

Davis, D.A.; Lawrence, A.L.; Gatlin, III, D.M.,. Evaluation of the dietary zinc requirement *of Penaeus vannamei* and effects of phytic acid on zinc and phosphorus bioavailability. *J. World Aquac. Soc*. **1993a**, 24, 40-47.

Davis, D.A.; Lawrence, A.L.; Gatlin, III, D.M. Dietary copper requirement of *Penaeus vannamei*. *Bull. Jpn. Soc. Sci. Fish.* **1993b**. 59. 117-122.

De Riu, N.; Lee, J.-W.; Huang, S.S.Y.; Moniello, G.; Hung, S.S.O. Effect of dietary selenomethionine on growth performance, tissue burden, and histopathology in green and white sturgeon. *Aquat. Toxicol*. **2014**,*148*, 65-73.

Dean, R.J.; Shimmield, T.M.; K.D. Black. Copper, zinc and cadmium in marine cage fish farm sediments: An extensive survey. *Environ. Pollut*. **2007**, 145, 84-95

Dersjant-Li, Y.; Awati, A.; Schulze, H.; Partridge, G. Phytase in non-ruminant animal nutrition: a critical review on phytase activities in the gastrointestinal tract and influencing factors. *J. Sci. Food Agric*. **2015**, *95*, 878-896.

Desjardins, L.M.; Hicks, B.D.; Hilton, J.W. Iron catalysed oxidation of trout diets and its effect on growth and physiological response of rainbow trout. *Fish Physiol. Biochem*. **1987**, *3*, 173-182.

Domínguez, D.; Sehnine, Z.; Castro, P.; Robaina, L.; Fontanillas, R.; Prabhu, P.A.J.; Izquierdo, M. Optimum selenium levels in diets high in plant-based feedstuffs for gilthead sea bream (*Sparus aurata*) fingerlings. *Aquac. Nutr*. **2019**, *26*, 579-589.

Dougall, D.S.; Woods, L.C.; Douglass, L.W.; Soares, J.H. Dietary phosphorus requirement of juvenile striped bass *Morone saxatilis*. *J. World Aquacult. Soc*. **1996**, *27*, 82-91.

Drábiková, L.; Fjelldal, P.G.; De Clercq, A.M.N.; Morken,T.; McGurk, C.; Witten, P.E. Vertebral column adaptations in juvenile Atlantic salmon *Salmo salar*, L. as a response to dietary phosphorus, *Aquaculture* **2021**, *541*, 736776. https://doi.org/10.1016/j.aquaculture.2021.736776

Eales, J. G. The relationship between ingested thyroid hormones, thyroid homeostasis and iodine metabolism in humans and teleost fish. *Gen. Comp. Endoc*. **2019**, *280*, 62-72.

Eckhert, C.D. Boron stimulates embryonic trout growth. *J. Nutr*. **1998**, 128, 2488-2493.

Eckhert, C.D.; Rowe. R.I. Embryonic dysplasia and adult retinal dystrophy in boron-deficient zebrafish. *J. Trace Elem. Exp. Med*. **1999**, *12*:213-219.

Eid, A.E.; Ghonim, S.I. Dietary zinc requirement of fingerling *Oreochromis niloticus*. *Aquaculture* **1994**, *119*, 259-264.

Einarsdottir, I.E.; Silva, N.; Power, D.M.; Smaradottir, H.; Bjornsson, B.T. Thyroid and pituitary gland development from hatching through metamorphosis of a teleost flatfish, the Atlantic halibut. *Anat. Embryol.* **2006**, *211*,47-60.

El-Zibdeh, M.; Ide, K.; Furuichi, M. Effects of the Deletion of Mg or Fe from Semi Purified Diets on Growth and Efficiency of Feed Utilization of Yellow Croaker *Nibea albiflora*. *J. Facult. Agr. Kyushu Univ*. **1996**, *40*, 391-397.

EFSA NDA Panel (EFSA panel on dietetic products, nutrition and allergies); Scientific opinion on Dietary Reference Values for chromium. *EFSA Journal* **2014**, NNNN, 27 pp. doi:10.2903/j.efsa.2014.NNNN.

EFSA FEEDAP Panel (EFSA panel on additives and products or substances used in animal feed). Scientific opinion on the safety and efficacy of zinc compounds (E6) as feed additives for all animal species (zinc acetate, dihydrate; zinc chloride, anhydrous; zinc oxide; zinc sulphate, heptahydrate; zinc sulphate, monohydrate; zinc chelate of amino acids, hydrate; zinc chelate of glycine, hydrate), based on a dossier submitted by FEFANA asbl. *EFSA Journal* **2015**, 13(4), 4058, 46 pp. doi:10.2903/j.efsa.2015.4058

EFSA FEEDAP Panel (EFSA panel on additives and products or substances used in animal feed). Scientific opinion on the safety and efficacy of selenium compounds (E8) as feed additives for all animal species: sodium selenite, based on a dossier submitted by Retorte GmbH Selenium Chemicals and Metals. *EFSA Journal* **2016a**,14(2), 4398, 26 pp. doi:10.2903/j.efsa.2016.4398.

EFSA FEEDAP Panel (EFSA panel on additives and products or substances used in animal feed). Scientific opinion on the safety and efficacy of manganese hydroxychloride as feed additive for all animal species. *EFSA Journa*l **2016b**,14(5), 4474, 15 pp. doi:10.2903/j.efsa.2016.4474

EFSA FEEDAP Panel (EFSA panel on additives and products or substances used in animal feed). Scientific opinion on the revision of the currently authorised maximum copper content in complete feed. *EFSA Journa*l **2016c**, 14(8),4563, 100 pp. doi:10.2903/j.efsa.2016.4563

Erdman, J.W., Jr. Oilseeds phytates: Nutritional implications. *J. Amer. Oil Chem. Soc.* **1979**, 66, 736-741

Erickson, R.J.; Mount, D.R.; Highland, T.L.; Russell Hockett, J.; Jenson, C.T. The relative importance of waterborne and dietborne arsenic exposure on survival and growth of juvenile rainbow trout. *Aquat. Toxicol*. **2011**, *104*, 108-115.

Evans, D.H.; Claiborne, J.B. Osmotic and ionic regulation in fishes. In: *Osmotic and Ionic regulation: Cells and Animals*, Evans, D.H. Ed.; Taylor and Francis Group: Boca Raton, USA, 2009; pp. 295-366.

Eyckmans M.; Celis N.; Horemans N.; Blust R.; De Boeck G. Exposure to waterborne copper reveals differences in oxidative stress response in three freshwater fish species. *Aquatic Toxicol*. **2011**, *103*, 112–120.

Fa-Yi, L.; Lawrence, A. Dietary manganese requirement of *P. vannamei*. *Chinese J. of Ocean. Limn*. **1997**, 15, 163-167.

Fairweather-Tait, S.J.; Collings, R.; Hurst, R. Selenium bioavailability: current knowledge and future research requirements. *Amer. J. Clin. Nutr*. **2010**, *91*, 1484S-1491S.

Fairweather-Tait, S.J.; Bao, Y.; Broadley, M.R.; Collings, R.; Ford, D.; Hesketh, J.E.; Hurst, R. Selenium in Human Health and Disease. *Antioxid. Redox Signaling* **2011**, *14*, 1337-1383.

Feeney, G.P.; Zheng, D.; Kille, P.; Hogstrand, C. The phylogeny of teleost ZIP and ZnT zinc transporters and their tissue specific expression and response to zinc in zebrafish. *Biochim. Biophy. Acta (BBA) - Gene Struct. Express*. **2005**, *1732*, 88-95

Fenwick, J.C.; Vermette, M.G. Vitamin D_3 and the renal handling of phosphate in American eels. *Fish Physiol. Biochem.* **1989**, *177*, 351-358

Fernandez, F.; Miquel, A.G.; Martinez, R.; Serra, E.; Guinea, J.; Narbaiza, F.J.; Caseras, A.; Baanante, I.V. Dietary chromium oxide does not affect the utilization of organic compounds but can alter the utilization of mineral salts in gilthead sea bream *Sparus aurata*. *J. Nutr.* **1999**, *129*, 1053-1059

Fjelldal, P.G.; Nordgarden, U.; Hansen, T. The mineral content affects vertebral morphology in underyearling smolt of Atlantic salmon (*Salmo salar* L.). *Aquaculture* **2007**, *270*, 231-239.

Flik, G.; Verbost, P.M.; Bonga, S.E.W. Calcium transport processes in fishes. *Fish Physiol*. **1995**, *12*, 317-342.

Fontegné-Dicharry, S.; Godin, S.; Liu, H.; Antony Jesu Prabhu, P.; Bouyssière, B.; Bueno, M.; Tacon, P.; Médale, F.; Kaushik, S.J. Influence of the forms and levels of dietary selenium on antioxidant status and oxidative stress-related parameters in rainbow trout (*Oncorhynchus mykiss*) fry. *Brit. J. Nutr*. **2015**, *113*, 1876-1887.

Francis, G.; Makkar, H.P.S.; Becker, K. Antinutritional factors present in plant-derived alternate feed ingredients and their effects in fish. *Aquaculture* **2001**, *199*,197-227.

Fraser, D.R. Evolutionary biology: mysteries of vitamin D in fish. In: *Vitamin D : Biochemistry, Physiology and Diagnostics*, Feldman, D., Pike, J.W., Bouillon, R., Giovannucci, E., Goizman, D., Hewison, M. Eds.; Academic Press: San Diego, USA, 2018; Volume 1, pp. 13–27.

Fukada T; Kambe T. Molecular and genetic features of zinc transporters in physiology and pathogenesis. *Metallomics* **2011**, *3*, 662-674.

Gabrielsen, B.J.; Opstvedt, J. Availability of selenium in fish meal in comparison with soybean meal, corn gluten meal and selenomethionine relative to selenium in sodium selenite for restoring glutathione peroxidase activity in selenium-depleted chicks. *J. Nutr*. **1980**, *110*, 1096-1100.

Gatlin,III, D.M.; Robinson, E.H.; Poe, W.E.; Wilson, R.P. Magnesium requirement of fingerling channel catfish and signs of magnesium deficiency. *J. Nutr*. **1982**, *112*, 1182-1187.

Gatlin,III, D.M.; Wilson, R.P. Dietary zinc requirement of fingerling channel catfish. *J. Nutr.*, **1983**, *113*, 630-635.

Gatlin,III, D.M.; Wilson, R.P. Studies on the manganese requirement of fingerling channel catfish. *Aquaculture* **1984a**, *41*, 85-92.

Gatlin,III, D.M.; Wilson, R.P. Dietary selenium requirement of fingerling channel catfish. *J. Nutr.* **1984b**, *114*, 627-633.

Gatlin,III, D.M.; Wilson, R.P. Characterization of iron deficiency and the dietary iron requirement of fingerling channel catfish. *Aquaculture,* **1986a**, *52*, 191-198.

Gatlin,III, D.M.; Wilson, R.P. Dietary copper requirement of fingerling channel catfish. *Aquaculture,* **1986b**, 54, 277-285.

Gatlin,III, D.M.; O'Connell, J.P.; Scarpa, J. Dietary zinc requirement of the red drum, *Sciaenops ocellatus*. *Aquaculture* **1991**, *92*, 259-265.

Gatta, P.P.; Thomson, K. D.; Smullen, R.; Piva, A.; Testi, S.; Adams, A. Dietary organic chromium supplementation and its effect on the immune response of rainbow trout (*Oncorhynchus mykiss*). *Fish Shellfish Immun*. **2001**, *11*, 371-382.

Geven, E.J.W.; Nguyen N-K.; van den Boogaart, M.; Spanings, F.A.T.; Flik, G.; Klaren, P.H.M. Comparative thyroidology: thyroid gland location and iodothyronine dynamics in Mozambique tilapia (*Oreochromis mossambicus* Peters) and common carp (*Cyprinus carpio* L.). *J Exp. Biol*. **2007**, *210*, 4005-4015

Giri, A.F.; Sahu, N.P.; Saharan, N.; Dash, G. Effect of dietary supplementation of chromium on growth and biochemical parameters of *Labeo rohita* (Hamilton) fingerlings, *Ind. J. Fish.* **2014**, 61, 73-81.

Glover, C.N.; Hogstrand, C. Amino acid modulation of *in vivo* intestinal zinc uptake in freshwater rainbow trout. *J. Exp. Biol*. **2002**, *205*:151-158

Glover, C.N.; Hogstrand, C. Effects of dissolved metals and other hydrominerals on in vivo intestinal zinc uptake in freshwater rainbow trout. Aquat. Toxicol. 2003, 62, 281-293.

Godin, S.; Fontagné-Dicharry, S.; Bueno, M.; Tacon, P.; Antony Jesu Prabhu, P.; Kaushik, S.; Médale, F.; Bouyssiere, B. Influence of dietary selenium species on selenoamino acid levels in rainbow trout. J. Agric. Food Chem. 2015, 63, 6484-6492.

Graff, I.E.; Aksnes, L.; Lie, O. In vitro hydroxylation of vitamin D3 and 25-hydroxy vitamin D3 in tissues of Atlantic salmon *Salmo salar*, Atlantic mackerel *Scomber scombrus*, Atlantic halibut *Hippoglossus hippoglossus* and Atlantic cod *Gadus morhua*. *Aquac. Nutr*. **1999**, 5, 23-32.

Grosell, M. Copper. *Fish Physiol.* **2012**, 31A, 53-133.

Grosell, M.; Wood, C.M. Copper uptake across rainbow trout gills: mechanisms of apical entry. *J. Exp. Biol.* **2002**, *205*, 1179-1188.

Guerreiro, P.M.; Renfro, J.L.; Power, D.M.; Canario, A.V. The parathyroid hormone family of peptides: structure, tissue distribution, regulation, and potential functional roles in calcium and phosphate balance in fish. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **2007**, *292*, R679–R696

Habibi, H.R.; Nelson, E.R.; Allan, E.R.O. New insights into thyroid hormone function and modulation of reproduction in goldfish, *Gen. Comp. Endoc*. **2012**, *175*, 19-26.

Hamilton S.J. Review of selenium toxicity in the aquatic food chain. *Sci. Total Env*. **2004**, *326*, 1-31.

Hamilton, S.J.; Buhl, K.J. Acute toxicity of boron molybdenum and selenium to fry of Chinook salmon and coho salmon. *Arch. Environ. Contam. Toxicol*. **1990**, *19*, 366-373

Hamre, K.; Yúfera, M.; Rønnestad, I.; Boglione, C.; Conceição, L.E.C.; Izquierdo, M. Fish larval nutrition and feed formulation: knowledge gaps and bottlenecks for advances in larval rearing. *Rev. Aquacult*. **2013**, *5*, S26–S58.

Han, D.; Xie, S.; Liu, M.; Xiao, X.; Liu, H.; Zhu, X.; Yang, Y. The effects of dietary selenium on growth performances, oxidative stress and tissue selenium concentration of gibel carp (Carassius auratus gibelio). *Aquac. Nutr*. **2011**, 17, e741–e749.

Handy, R.D. Dietary exposure to trace metals in fish. In *Toxicology of Aquatic Pollution*, E.W. Taylor Ed.; Cambridge University Press: Cambridge, USA, 1996; pp. 29-60.

Handy, R.D.; Musonda, M.M.; Phillips, C.; Falla, S.J. Mechanisms of gastrointestinal copper absorption in the African walking catfish: copper dose-effects and a novel anion dependent pathway in the intestine. *J Exp Biol* **2000**, *203*, 2365-2377.

Hansen, J.A.; Lipton, J.; Welsh, P.G.; Cacela, D.; MacConnell, B. Reduced growth of rainbow trout (*Oncorhynchus mykiss*) fed a live invertebrate diet pre-exposed to metal-contaminated sediments. *Environ. Toxicol. Chem*. **2004**, *23*, 1902–1911.

Hardy, R.W.; Shearer, K. Effect of dietary calcium phosphate and zinc supplementation on whole body zinc concentration of rainbow trout *(Salmo gairdneri*). *Can J. Fish. Aquat. Sci*. **1985**, *42*, 181-184.

Hardy, R.W.; Sullivan, C.V.; Koziol, A.M. Absorption, body distribution, and excretion of dietary zinc by rainbow trout *(Salmo gairdneri*), *Fish Physiol. Biochem.* **1987**, *3*, 133-143.

Harris, E.D. Basic and clinical aspects of copper. *Crit Rev Clin Lab Sci.* **2003**, *40*, 547-86.

Henry, P.R., Ammerman, C. B. Selenium bioavailability. In *Bioavailability of Nutrients for Animal.: Amino Acids, Minerals, and Vitamins*, Ammerman, C.B., Baker, D.H., Lewis, A.J. Eds.; Academic Press: San Diego, USA, 1995; pp. 303-336.

Henry, P.R., Miller E. R. Iron bioavailability. In *Bioavailability of Nutrients for Animal.: Amino Acids, Minerals, and Vitamins*, Ammerman, C.B., Baker, D.H., Lewis, A.J. Eds.; Academic Press: San Diego, USA, 1995; pp. 169-199.

Hernando, N.; Wagner, C.A. Mechanisms and regulation of intestinal phosphate absorption. *Compreh. Physiol*. **2018**, *8*, 1065-1090.

Hertz, Y.; Madar, Z.; Hepher, B.; Gertler, A. Glucose metabolism in the common carp (*Cyprinus carpio* L.): the effects of cobalt and chromium. *Aquaculture* **1989**, *76*, 255-267

Hesketh, J. Nutrigenomics and selenium: gene expression patterns, physiological targets, and genetics. *Ann. Rev. Nutr*. **2008**, *28*, 157-77

Hetzel B. S.; M. C. Welby. Iodine. In *Handbook of Nutritionally Essential Mineral Elements*, O'Dell, B. L., Sunde, R. A., Eds.; Marcel Dekker: New York, USA, 1997; pp. 557–582

Hickman, C.P.; Trump, B.F. The kidney. In: *Fish Physiology;* Hoar, W.S., Randall, D.J. Eds.; Academic Press, New York, USA, 1969; Vol. 1, pp. 91–239.

Hicks, B.D.; Hilton, J.W.; Ferguson, H.W. Influence of dietary selenium on the occurrence of nephrocalcinosis in the rainbow trout, *Salmo gairdneri* Richardson. *J. Fish Dis*. **1984**, *7*, 379-389.

Higgs, D.A.; Fagerlund, U.H.M.; Eales, J.G.; McBride, J.R. Application of thyroid and steroid hormones as anabolic agents in fish culture. *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry*, **1982**, *73*, 143–176.

Hilton, J.W. The interaction of vitamins, minerals and diet composition in the diet of fish. *Aquaculture* **1989**, *79*, 223-244.

Hilton, J.W.; Hodson, P.V.; Slinger, S.J. The requirement and toxicity of selenium in rainbow trout (*Salmo gairdneri*). *J. Nutr*. **1980**, *110*, 2527-2535.

Hodson, P.V.; Hilton, J.W. The nutritional requirements and toxicity to fish of dietary and waterborne selenium. *Ecol. Bull*. **1983**, 35, 335-340.

Hogstrand, C. Zinc. *Fish Physiol.* **2012**, 31A, 135-200.

Hogstrand, C.; Verbost, P.M.; Bonga, S.E.; Wood, C.M. Mechanisms of zinc uptake in gills of freshwater rainbow trout: interplay with calcium transport. *Am. J. Physiol*. **1996**, *270*, R1141–R1147.

Horning, K.J.; Caito, S.W.; Tipps, K.G.; Bowman, A.B.; Aschner, M. Manganese Is Essential for Neuronal Health. *Ann. Rev. Nutr*. **2015**, *35*, 71–108.

Hosnedlova, B.; Kepinska, M.; Skalickova, S.; Fernandez, C.; Ruttkay-Nedecky, B.; Malevu, T.D.; Sochor , J.S.; Baron, M.; Melcova, M.; Zidkova, J.; Kizek, R. A summary of new findings on the biological effects of selenium in selected animal species—A critical review. *Int'l. J. Mol. Sci.* **2017**, *18*, 2209.

Hossain, M.A.; Yoshimatsu, T. Dietary calcium requirements of fishes. *Aquac. Nutr*. **2014**, *20*, 1-11.

Houng-Yung, C.; Yu-Chun, C.; Li-Chi, H.; Meng-Hsien, C. Dietary zinc requirements of juvenile grouper, *Epinephelus malabaricus*. *Aquaculture*, **2014**, *432*, 360–364.

Hoyle, I.; Shaw, B.J.; Handy, R.D. Dietary copper exposure in the African walking catfish, *Clarias gariepinu*s: transient osmoregulatory disturbances and oxidative stress. *Aquat. Toxicol*. , **2007**, *83*, 62–72

Huang, F.; Jiang, M.; Wen, H.; Wu, F.; Liu, W.; Tian, J.; Yang, C. Dietary zinc requirement of adult Nile tilapia (*Oreochromis niloticus*) fed semi-purified diets, and effects on tissue mineral composition and antioxidant responses. *Aquaculture*, **2015**, *439*, 53–59.

Huang, Q.-C.; Kwaku, A.; Wang, E.-L.; Dong, X.H. Iron bioavailability of different sources in juvenile grouper *Epinephelus coioides. Aquac. Res*. **2018**, *49*, 2799-2807.

Hunt, C.D. Dietary boron: Progress in establishing essential roles in human physiology. *J. Trace Elem. Med. Biol*., **2012** , *26*, 157-160.

Hunt D. W.C.; Eales J.G. Iodine balance in rainbow trout *(Salmo gairdneri*) and effects of testosterone propionate. *J. Fish. Res. Board Can*. **1979**, *36*, 282-285.Houston, A.;. Erythrocytic magnesium in freshwater fishes. *Magnesium* **1985**, *4*, 106-128.

Ikeda, Y.; Ozaki, H.; Vematsu, K. Effect of enriched diet with iron in culture of yellow-tail. *J. Tokyo Univ. Fish* **1973**, *59*, 91-99.

Ishak, I. M.; Dollar, A.M. Studies on manganese uptake in *Tilapia mossambica* and Salmo gairdneri. I. Growth and survival of *Tilapia mossambica* in response to manganese. *Hydrobiologia* **1968**, *31*, 572-584.

Jain, K.K.; Sinha, A.; Srivastava, P.P.; Berendra, D.K. Chromium: an efficient growth enhancer in Indian major carp, *Labeo rohita*. *J. Aquacul. Tropics* **1994**, *9*, 49-54

Janz, D.M. Selenium. *Fish Physiol.* **2012**, 31A, 329-375.

Janz, D.M.; DeForest, D.K., Brooks, M., Chapman, P.M., Gilron,G.; Hoff, D.; Hopkins W.A.; Mcintyre, D.O; Mebane, C.A.; Palace, V.P.; Skorupa, J.P.; Wayland, M. Selenium Toxicity to Aquatic Organisms. In *Ecological Assessment of Selenium in the Aquatic Environment*, Chapman, P.M., Adams, Brooks, M., Delos, C., Luoma, Mahr, W.A., Ohlendorf, H.M., Presser, T.S., Shaw. P. Eds.; CRC Press: Boca Raton, USA, 2019; pp. 141-231.

Jezierska, B.; Ługowska, K.; Witeska, M. The effects of heavy metals on embryonic development of fish (a review). *Fish Physiology and Biochemistry*, **2009**, *35*, 625-640.

Jeng, S.S.; Sun, L.T. Effects of dietary zinc levels on zinc concentrations in tissues of common carp. *J. Nutr.* **1981**, *111*, 134-140.

Jiang, M.; Wu, F.; Huang, F.; Wen, H.; Liu, W.; Tian, J.; Changgeng, Y.; Wang, W. Effects of dietary Zn on growth performance, antioxidant responses, and sperm motility of adult blunt snout bream, *Megalobrama amblycephala*. *Aquaculture* **2016**, *464*, 121–128.

Johnson, A.; Carew, E.; Sloman, K.A. The effects of copper on the morphological and functional development of zebrafish embryos, *Aquat. Toxicol*. **2007**, *84*, 431-438.

Julshamn, K.; Dahl, L.; Eckhoff, K. Determination of iodine in seafood by inductively coupled plasma/mass spectrometry. *J. Assoc. Off. Anal. Chem*. **2001**, *84*, 1976-1983

Kambe, T.; Tsuji, T.; Hashimoto, A.; Itsumura, N. The physiological, biochemical, and molecular roles of zinc transporters in zinc homeostasis and metabolism. *Physiol. Rev*. **2015**, *95*, 749-784.

Kamunde, C.; Grosell, M.; Higgs, D.; Wood, C.M. Copper metabolism in actively growing rainbow trout (*Oncorhynchus mykiss*): interactions between dietary and waterborne copper uptake. *J. Exp. Biol*. **2002**, *205*, 279–290.

Kanazawa, A.; Teshima, S.; Sasaki, M. Requirements of the juvenile prawn for calcium, phosphorus, magnesium, potassium, copper, manganese, and iron. *Mem. Fac. Fish. Kagoshima Univ.* **1984**, 33, 63-71.

Kang, J.-C.; Kim, S.-G.; and Jang, S.-W. Growth and hematological changes of rockfish, *Sebastes schlegeli* (Hilgendorf) exposed to dietary Cu and Cd. *J. World Aquacul. Soc*. **2005**, *36*, 188–195.

Kim, S.G.; Kang, J.C. Effect of dietary copper exposure on accumulation, growth and hematological parameters of the juvenile rockfish, *Sebastes schlegeli*. *Mar. Environ. Res*. **2004**, *58*, 65–82.

Kawatsu, H. Studies on the anemia of fish. 5. Dietary iron deficient anemia in brook trout (*Salvelinus fontinalis*). *Bull. Freshwater Fish. Res. Lab* **1972**, *22*, 59-67.

Keen, C.L.; Ensunsa, J.L.; Clegg, M.S. Manganese metabolism in animals and humans including the toxicity of manganese. *Met Ions Biol Syst*. **1999**, *37*, 89-121

Ketola, H.G. Requirement of Atlantic salmon for dietary phosphorus. *Trans. Am. Fish. Soc*. **1975**, *104*, 548-551.

Ketola H.G. Influence of dietary zinc on cataracts in rainbow trout (*Salmo gairdneri*). *J. Nutr*. **1979**, *105*, 965-969.

Ketola, H.G.; Richmond, M.E. Requirement of rainbow trout for dietary phosphorus and its relationship to the amount discharged in hatchery effluents. *Trans. Am. Fish. Soc*. **1994**, *123*, 587-594.

Khan, K.U.; Zuberi, A.; Fernandes, J.B.K.; Ullah, I.; Sarwar, H. An overview of the ongoing insights in selenium research and its role in fish nutrition and fish health. *Fish Physiol. Biochem*. **2017**, *43*, 1689-1705.

Kim, S.G.; Kang, J.C. Effect of dietary copper exposure on accumulation, growth and hematological parameters of the juvenile rockfish, *Sebastes schlegeli*. *Mar. Envir. Res*., **2004**, *58*, 65–82

Knight, R.; Marlatt, V.L.; Baker, J.A.; Lo, B.P.; Debruyn, A.M.H.; Elphick, J.R.; Martyniuk, C.J. Dietary selenium disrupts hepatic triglyceride stores and transcriptional networks associated with growth and Notch signaling in juvenile rainbow trout. *Aquat. Toxicol*. **2016**, *180*, 103-114.

Kjoss, V.A.; Wood, C.M.; McDonald, D.G. Effects of different ligands on the bioaccumulation and subsequent depuration of Cu and Zn in juvenile rainbow trout *Oncorhynchus mykiss*. *Can. J. Fish. Aquat. Sci.* **2006**, *63*, 412–422.

Knox, D.; Cowey, C.B.; Adron, J.W. Studies on the nutrition of salmonid fish. The magnesium requirement of rainbow trout (*Salmo gairdneri*). *Br. J. Nutr*. **1981**, *45*, 137-148.

Knox, D.; Cowey, C.B.; Adron, J.W. Effects of dietary copper and copper: zinc ratio on rainbow trout (*Salmo gairdneri*). *Aquaculture* **1982**, *27*, 111-119.

Kong, Y.; Ding, Z.; Zhang, Y.; Ye, J.; Du, Z. Dietary selenium requirement of juvenile oriental river prawn *Macrobrachium nipponense*. *Aquaculture*. **2017**, 476, 72-78.

Köprücü, K.; Özdemir,Y. Apparent digestibility of selected feed ingredients for Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, **2005**, *250*, 308-316.

Kupsco, A.; Schlenk, D. Molecular mechanisms of selenium-Induced spinal deformities in fish. *Aquat. Toxicol*., **2016**, *179*, 143-150.

Kuenze, J.; Buhringer, H.; Harms, V. Accumulation of cobalt during embryonic development of rainbow trout (*Salmo gairdneri* Rich.). *Aquaculture* **1978**, *13*, 61-66.

Kumar. V.; Sinha, A.K.; Makkar, H.P.S.; De Boeck, G.; Becker, K. Phytate and phytase in fish nutrition. *J. Anim. Physiol. Anim. Nutr*. **2012**, *96*, 335-364.

Labunsky, V.M.; Hatfield, D.L.; Gladyshev, V.N. Selenoproteins: molecular pathways and physiological roles. *Physiol. Rev*. **2014**, *94*, 739-777.

Lall, S.P. Digestibility, metabolism and excretion of dietary phosphorous in fish. In: *Nutritional Strategies and Aquaculture Waste;* Cowey, C.B., Cho, C.Y., Eds; University of Guelph, Guelph, ON, CA, 1991; pp. 21–36.

Lall, S.P. Macro and trace elements in fish and shellfish. In *Fish and Fishery Products*, Ruiter, A., Ed.; CAB International: Wallingford, UK, 1995; pp. 187-213.

Lall, S.P. The minerals. In *Fish Nutrition*, 3rd ed.; Halver, J.E., Hardy, R.W. Eds.; Academic Press: San Diego, USA, 2002; pp. 259–308.

Lall, S.P., 2021.The minerals. In *Fish Nutrition*, 4th ed.; Halver, J.E., Hardy, R.W. Eds.; Academic Press: San Diego, USA, Elsevier (In press).

Lall, S.P. Disorders of nutrition and metabolism. In *Fish Diseases and Disorders*, Leatherland, J. F., Woo, P.T.K., Eds.; CABI: Wallingford, UK, 2010, Vol 2: Non-infectious disorders, pp. 202-237.

Lall, S.P. and Bishop, F.J. Studies on mineral and protein utilization by Atlantic salmon (*Salmo salar*) grown in sea water. *Fish. Mar. Serv. Tech. Rep*. **1977**, *688*, 1-16.

Lall, S.P.; Lewis-McCrea, L.M. Role of nutrients in skeletal metabolism and pathology in fish-An overview. *Aquaculture* **2007**, *267*, 3-19.

Lall, S.P.; Milley, J.E. Impact of aquaculture on aquatic environment: trace minerals discharge. In *Trace Elements in Animal Production Systems*, Schlegel, P., Durosoy, S., Jongbloed, A.W. Eds.; Wageningen Academic Publishers: The Netherlands, 2008a; pp. 77-87.

Lall, S.P., Milley, J.E. Trace mineral requirements of fish and crustaceans. In *Trace Elements in Animal Production Systems*, Schlegel, P., Durosoy, S., Jongbloed, A.W. Eds.; Wageningen Academic Publishers: The Netherlands, 2008b; pp.203-214.

Lall, S.P.; Paterson, W.D.; Hines, J.A.; Adams, N J. Control of bacterial kidney disease in Atlantic salmon *Salmo salar* L. by dietary modification. *J. Fish. Dis*. **1985**, *8*, 113-124.

Lanno, R.P.; Slinger, S.J.; Hilton J.W. Maximum tolerable and toxicity levels of dietary copper in rainbow trout (*Salmo gairdneri* R.). *Aquaculture* **1985**, *49*, 257-268.

Le, K.T.; Fotedar, R. Bioavailability of selenium from different dietary sources in yellowtail kingfish (*Seriola lalandi*). *Aquaculture* **2014**, *420-421*, 57–62.

Leach, R.M.; Harris, E.D. Manganese, In *Handbook of Nutritionally Essential Minerals*, O'Dell, B.L.,Sunde, R.A. Eds.; Marcel Dekker: New York, USA, 1997; pp. 335-355.

Leatherland, J.F.; Hilton, J.W.; and Slinger, S.J. Effects of thyroid hormone supplementation of canola meal-based diets on growth, and interrenal and thyroid gland physiology of rainbow trout (*Salmo gairdneri*). *Fish Physiol. Biochem*. **1987**, *3*, 73–82

Lebel, J.M.; Leloup, J. La triiodothyronine est necessaire á l'acclimation á l'eau de mer de la truite fario (*Salmo trutta*) ou arc en ciel (*Oncorhynchus mykiss*) *C.r. Acad. Sci. Paris* **1992**, *314*, 461-468

Lee, M.-H.; Shiau, S.-Y. Dietary copper requirement of juvenile grass shrimp, *Penaeus monodon*, and effects on non-specific immune responses. *Fish Shellfish Imm*. **2002**, 13, 259-270.

Lee, M.-H.; Shiau, S.-Y. Increase of dietary vitamin C improves haemocyte respiratory burst response and growth of juvenile grass shrimp, *Penaeus monodon* , fed with high dietary copper. *Fish Shellfish Imm*. **2003**, 14, 305-315.

Lehmann, I.; Sack, U.; Lehmann, J. Metal ions affecting the immune system. *Met. Ions Life Sci*. **2011**, *8*, 157-185.

Lemos, D.E.L.; Tacon, A.G.J. Use of phytases in fish and shrimp feeds: a review. *Rev. Aquacult*. **2017**, *9*, 266-282.

Li, M.H.; Robinson, E.H. Comparison of chelated zinc and zinc sulfate as zinc sources for growth and bone mineralization of channel catfish (*Ictalurus punctatus*) fed practical diets. *Aquaculture*, **1996**, *146*, 237-243.

Li, M.-R.; Huang, C.-H. Effect of dietary zinc level on growth, enzyme activity and body trace elements of hybrid tilapia, *Oreochromis niloticus* × *O. aureus*, fed soya bean meal-based diets. *Aquac. Nutr*., **2015**, *22*, 1320–1327.

Liang, J.-J.; Yang, H.-J.; Liu, Y.-J.; Tian, L.-X.; Liang, G.-Y. Dietary zinc requirement of juvenile grass carp (*Ctenopharyngodon idella*) based on growth and mineralization. *Aquac. Nutr*. **2012**, *18*, 380–387.

Limsuwan, T.; Lovell, R.T. Intestinal synthesis and absorption of vitamin B_{12} in channel catfish. *J. Nutr*. **1981**, *111*, 2125-2132.

Lin, Y.-H. Effects of dietary organic and inorganic selenium on the growth, selenium concentration and meat quality of juvenile grouper *Epinephelus malabaricus*. *Aquaculture* **2014**, *430*, 114-119.

Lin, C.H.; Hwang, P.P. The control of calcium metabolism in zebrafish (*Danio rerio*). *Int. J. Mol. Sci*. **2016**, *17*, 1783. doi:10.3390/ijms17111783.

Lin, Y. H.; Shiau, S.Y. Dietary selenium requirements of juvenile grouper, *Epinephelus malabaricus*. *Aquaculture* **2005**, *250*, 356-363.

Lin, Y.H.; Shie Y-Y.; Shiau S-Y. Dietary copper requirements of juvenile grouper, *Epinephelus malabaricus*. *Aquaculture*, **2008a**, *274*, 161-165.

Lin, Y. H.; Lin, S.M., Shiau, S.Y. Dietary manganese requirements of juvenile tilapia, *Oreochromis niloticus x O. aureus. Aquaculture* **2008b**, *284*, 207-210.

Lin, Y.H.; Jiang L.-C.; Shiau S-Y. Dietary zinc requirements of juvenile tilapia, *Oreochromis niloticus* x *O. aureus*. J. Fish. Soc. Taiwan, **2008c**, *35*, 117-125.

Lin Y.H.; Shih C.-C.; Kent, M.; Shiau S-Y. Dietary copper requirement re-evaluation for juvenile grouper, *Epinephelus malabaricus*, with an organic copper source. *Aquaculture* **2010a**, *310*, 173-177.

Lin, Y.-H.; Wu, J.-Y.; Shiau, S.-Y. Dietary cobalt can promote gastrointestinal bacterial production of vitamin B_{12} in sufficient amounts to supply growth requirements of grouper, *Epinephelus malabaricus*. Aquaculture **2010b**, *302*, 89-93.

Linder, M.C. Biochemistry and molecular biology of copper in mammals. In *Handbook of Copper Pharmacology and Toxicology*, Massaro, E.J. Ed.; Humana Press Inc.: Totowa, USA, 2002; pp. 3-32.

Ling, J.; Feng, L.; Liu, Y.; Jiang, J.; Jiang, W.D.; Hu, K.; Li, S.H.; Zhou, X.Q. Effect of dietary iron level on growth, body composition and intestinal enzyme activities of juvenile Jian carp (*Cyprinus carpio* Var. Jian). *Aquac. Nutr*. **2010**, *16*, 616-624.

Liu, K.; Wang, XJ.; Ai, Q.; Mai, K.; Zhang, W. Dietary selenium requirement for juvenile cobia, *Rachycentron canadum* L. *Aquac. Res*. **2010a**, *41*, e594-e601.

Liu, K.; Ai, Q.H.; Mai, K.S.; Zhang, W.B.; Zhang, L.; Zheng, S.X. Dietary manganese requirement for juvenile cobia, *Rachycentron canadum* L., *Aquac. Nutr*. **2012**, *19*, 461-467.

Liu, T.; Wen, H.; Jiang, M.; Yuan, D.; Gao, P.; Zhao, Y; Wu, F.; Liu, W. Effect of dietary chromium picolinate on growth performance and blood parameters in grass carp fingerling, *Ctenopharyngodon idellus*. *Fish Physiol. Biochem*. **2010b**, *36*, 565-572.

Lönnerdal, B. Dietary factors influencing zinc absorption. *J. Nutr*. **2000**, *130*, 1378S-1383S.

Lorentzen, M.; Maage, A.; Julshamn, K. Manganese supplementation of a practical, fish meal based diet for Atlantic salmon parr. *Aquac. Nutr*. **1996**, *2*, 121-125.

Lorentzen, M.; Maage, A.; Julshamn, K. Supplementing copper to a fish meal based diet fed to Atlantic salmon parr affects liver copper and selenium concentrations. *Aquac. Nutr*. **1998**, 4, 67-72.

Loro, V.L.; Nogueira, L.; Nadella, S.R.; Wood, C.M. Zinc bioaccumulation and ionoregulatory impacts in *Fundulus heteroclitus* exposed to sublethal waterborne zinc at different salinities. *Comp. Biochem. Physiol, Toxic., Pharm*. **2014**, *166 C*, 96-104.

Lovell, R.T. Dietary phosphorus requirement of channel catfish (*Ictalurus punctatus*). *Trans. Am. Fish. Soc*. **1978**, *107*, 617-621.

Lovell, R.T.; Limsuwan, T. Intestinal synthesis and dietary non-essentiality of vitamin B_{12} for *Tilapia niloticus*. *Trans. Amer. Fish Soc*. **1982**, *111*, 485-490.

Luo, Z.; Zou, G.-Y.; Gao, Y.; Ye, H.-M.; Xi, W.-Q.; Liu, X. Effect of dietary iron (Fe) levels on growth performance, hepatic lipid metabolism and antioxidant responses in juvenile yellow catfish *Pelteobagrus fulvidraco* . *Aquacul. Nutr*. **2017**, 23, 1475-1482.

Luo, Z.; Tan, X-Y.; Zheng, J-L.; Chen, Q-L.; Liu, C-X. Quantitative dietary zinc requirement of juvenile yellow catfish *Pelteobagrus fulvidraco*, and effects on hepatic intermediary metabolism and antioxidant responses. *Aquaculture* **2011**, *319*,150-155.

Ma, R.; Hou, H.; Mai, K.; Bharadwaj, A.S.; Ji, F.; Zhang, W. Comparative study on the effects of chelated or inorganic manganese in diets containing tricalcium phosphate and phytate on the growth performance and physiological responses of turbot *Scophthalmus maximus*. *Aquac. Nutr*. **2015**, *21*, 780-787.

Maage, A.; Julshamn, K. Assessment of zinc status in juvenile Atlantic salmon (*Salmo salar*) by measurement of whole body and tissue levels of zinc. *Aquaculture* **1993**, *117*, 179-191.

Maage, A.; Lygren, B.; Ali El-Mowafi, A.F. Manganese requirement of Atlantic salmon (*Salmo salar*) fry, *Fish. Sci*. **2000**, *66*, 1-8.

Mai, K.; Zhang, C.; Ai, Q.; Duan, Q.; Xu, W.; Zhang, L.; Liufu, Z.; Tan, B. Dietary phosphorus requirement of large yellow croaker, *Pseudosciaena crocea* R. *Aquaculture* **2006**, *251*, 346-353.

Maret, W. Metalloproteomics, metalloproteomes, and the annotation of metalloproteins. *Metallomics* **2010**, 2,117-25.

Maret, W. Zinc biochemistry: From a single zinc enzyme to key element of life. *Adv. Nutr*. **2013**, 4, 82-91.

Marine, D. Further observations and experiments on goiter in brook trout. *J. Exp. Med.* **1914**, *19*, 70-75.

Mariotti M.; Ridge P.G.; Zhang, Y.; Lobanov, A.V.; Pringle, T.H.; Guigo, R.; Hatfield, D.L.; Gladyshev, V.N. Composition and evolution of the vertebrate and mammalian selenoproteomes. *PLoS ONE* **2012** 7(3): e33066.

Marshall, W.S. Na^+, Cl^-, Ca^{2+}, and Zn^{2+} transport by fish gills: retrospective review and prospective synthesis. *J Exp Zool*. **2002**, 293, 264-283.

Mawson, R.; Heaney, R.K.; Zdunczyk, Z.; Kozlowska, H. Rapeseed meal—Glucosinolates and their antinutritional effects. Part 4. Goitrogenicity and internal organs abnormalities in animals. *Nahrung* **1994**, *38*, 178–191.

McDonald, D.G.; Wood, C.M. Branchial mechanism of acclimation to metals in freshwater fish. Fish Ecophysiol. *Fish. Ser*. **1993**, *9*, 297-321.

McGeer, J.C., Niyogi, S., Scott Smith, D. Cadmium. In *Homeostasis and Toxicology of Non-Essential Metals;* Wood, C.M., Farrell, A.P., Brauner, C.J., Eds.; Academic Press: San Diego, USA, 2012; pp. 125-184.

McIntyre, D.O.; Linton, T.K. Arsenic. *Fish Physiol.* **2012**, 31B, 297-349. In *Homeostasis and Toxicology of Non-Essential Metals;* Wood, C.M., Farrell, A.P., Brauner, C.J., Eds.; Academic Press: San Diego, USA, 2012; pp. 297–349.

McLain, W.; Gatlin, III, D.M. Dietary zinc requirement of *Oreochromis aureus* and effects of dietary calcium and phytate on zinc bioavailability. *J. World Aquac. Soc*. **1988**, *19*, 103-108.

Mechlaoui, M.; Dominguez, D.; Robaina, L.; Geraert, P.-A.; Kaushik, S.; Saleh, R.; Briens, M.; Montero, D.; Izquierdo, M. Effects of different dietary selenium sources on growth performance, liver and muscle composition, antioxidant status, stress response and expression of related genes in gilthead seabream (*Sparus aurata*). *Aquaculture* **2019**, *507*, 251-259

Mertz, W. Review of the scientific basis for establishing the essentiality of trace elements. Biol. Trace *Elem. Res.* ***1998***, *66*, 185-191.

Miller D.W.; Vetter R.J.; Atchison G.J.. Effect of temperature and dissolved oxygen on uptake and retention of ^{54}Mn in fish. *Health Phys*. **1980**, *38*, 221-225.

Miller, E.P.; Wu, Y.; Carrano, C.J. Boron uptake, localization, and speciation in marine brown algae. *Metallomics* **2016**, *8*, 161-169.

Miller, P.A., Lanno, R.P., McMaster, M.E.; Dixon, D.G. Relative contribution of dietary and waterborne copper to tissue copper burdens and waterborne copper uptake in rainbow trout (*Oncorhynchus mykiss*). *Can. J. Fish. Aquat. Sci.* **1993**, *50*, 1683-1689.

Moazenzadeh, K.; Islami, H.R.; Zamini, A.; Soltani, M. Dietary zinc requirement of Siberian sturgeon (*Acipenser baerii*, Brandt 1869) juveniles, based on the growth performance and blood parameters. *Int'l. Aquat. Res*. **2017**, *9*, 25-35.

Mohan, K.; Ravichandran, S.; Muralisankar, T.; Uthayakumar, V.; Chandirasekar, R.; Seedevi, P.; Abirami, R.G.; Rajan, D.K. Application of marine-derived polysaccharides as immunostimulants in aquaculture: A review of current knowledge and further perspectives. *Fish Shellfish Immun*. **2019**, *86*, 1177-1193.

Moren, M.; Sloth, J.J.; Hamre, K. Uptake of iodide from water in Atlantic halibut larvae (*Hippoglossus hippoglossus* L.). *Aquaculture* **2008**, *285*, 174-178.

Morgan, J.L. Evaluation of elevated dietary iron and aluminum on growth and survival of Pacific white shrimp *Litopenaeus vannamei*. M.Sc. thesis, Texas A & M University, College Station, Texas, USA. 2013. Available online https://hdl.handle.net/1969.1/151839

Morris, A.L.; Hamlin, H.J.; Francis-Floyd, R.; Sheppard, B.J.; Guillette ,L.J. Nitrate-induced goiter in captive white spotted bamboo sharks C*hiloscyllium plagiosum*. *J. Aquat. Animal Health* **2011**, *23*,92-99.

Musharraf, M.; Khan, M.A. Dietary zinc requirement of fingerling Indian major carp, *Labeo rohita* (Hamilton). *Aquaculture* **2019**, *503*, 489-498.

Nakamura, Y.; Yamada, J. Effects of dietary calcium levels. Ca/P ratios, and calcium components on calcium absorption rate in carp. *Bull. Fac. Fish. Hokkaido Univ.* **1980**, *31*, 277-282.

Naser, N. Role of iron in Atlantic salmon (*Salmo salar*) nutrition: Requirement, Bioavailability, Disease Resistance and Immune Response. Ph.D. Thesis, Dalhousie University, Halifax, Nova Scotia, 2000, pp. 282

Ng, W.-K.; Wilson, R. P. Chromic oxide inclusion in the diet does not affect glucose utilization or chromium retention by channel catfish, *Ictalurus punctatus*. *J. Nutr*. **1997**, *127*, 2357-2362.

Nose, T.; Arai, S. Recent advances on studies on mineral nutrition of fish in Japan. In *Advances in Aquaculture,* Pillay, V.R., Dill, W.A. Eds.; Fishing News: Farnam, UK, 1979; pp. 584-590.

NRC (National Research Council) Nutrient Requirements of Fish. The National Academies Press: Washington, USA, 1993.

NRC (National Research Council) Mineral Tolerance of Animals. The National Academies Press: Washington, USA, 2005.

NRC (National Research Council) Nutrient Requirements of Fish and Shrimp. The National Academies Press: Washington, USA, 2011.

NRC (National Research Council) Nutrient Requirements of Swine. The National Academies Press: Washington, USA, 2012.

Nie, J.-Q.; Dong, X.-H.; Tan, B.-P.; Chi, S.-Y.; Yang, Q.-H.; Liu, H.-Y.; Shuang, Z. Effects of dietary manganese sources and levels on growth performance, relative manganese bioavailability, antioxidant activities and tissue mineral content of juvenile cobia (*Rachycentron canadum* L). *Aquac. Res*. **2016,** *47*, 1402-1412.

Nielsen, F.H. Update on human health effects of boron. *J. Trace Elem. Med. Biol*. **2014**, *28*, 383-387.

Ning, L.; Yuwen, T.; Wang, W.; Wu, S.; Chen, F.; Zhang, H.; Pan, Q. Optimum selenium requirement of juvenile Nile tilapia, *Oreochromis niloticus*. *Aquacul. Nutr.***2020**, *26*, 528-535.

Niyogi, S.; Wood, C.M. Biotic ligand model, a flexible tool for developing site-specific water quality guidelines for metals. *Environ. Sci. Technol*. **2004**, *38*, 6177–6192.

Nwanna, L.C.; Adebayo, I.A.; Omitoyin, B.O. Phosphorus requirements of African catfish, *Clarias gariepinus*, based on broken-line regression analysis methods. *Sci. Asia* **2009**, 35, 227–233.

O'Dell, B.L. Mineral-ion interaction as assessed by bioavailability and ion-channel function. In *Handbook of Nutritionally Essential Elements;* O'Dell, B.L., Sunde, R.A., Eds.; Marcel Dekker, Inc.: New York, USA, 1997; pp. 641–659.

Ogino, C.; Takeda, H. Mineral requirements in fish. 3. Calcium and phosphorus requirements of carp. *Bull. Jpn. Soc. Sci. Fish*. **1976**, *42*, 793–799

Ogino, C.; Yang G.Y. Requirement of rainbow trout for dietary zinc. *Bull. Jpn. Soc. Sci. Fish*. **1978**, 44, 1015-1018.

Ogino, C.; Yang, G.Y. Requirement of carp for dietary zinc. *Bull. Jpn. Soc. Sci. Fish*. **1979**, *45*, 967-969.

Ogino, C.; Yang, G Y. Requirements of carp and rainbow trout for dietary manganese and copper. *Bull. Jap. Soc. Sci. Fish*. **1980**, *46*, 455-458.

Ogino, C.; Takashima, F.; Chiou, J.Y. Requirement of rainbow trout for dietary magnesium. *Bull. Jpn. Soc. Sci. Fish.* **1978**, 44, 1105-1108

Ogino, C.; Takeuchi, L.; Takeda, H.; Watanabe, T. Availability of dietary phosphorus in carp and rainbow trout. *Bull. Jpn. Soc. Sci. Fish*. **1979**, *45*, 1527-1532.

Oikari, A.O.J.; Rankin, J.C. Renal excretion of magnesium in a freshwater teleost, *Salmo gairdneri*. *J. Exp. Biol.* **1985**, *117*, 319–333.

Ojo, A.A.; Wood, C.M. *In vitro* analysis of the bioavailability of six metals via the gastro-intestinal tract of the rainbow trout (*Oncorhynchus mykiss*). *Aquat. Toxicol*. **2007**, *83*, 10-23.

Olivia-Teles, A.; Pimentel-Rodrigues, A. Phosphorus requirement of European sea bass (*Dicentrarchus labrax* L.) juveniles. *Aquacult*. *Res*. **2004**, *35*, 636-642.

Pacitti, D.; Lawan, M.M.; Feldmann, J.; Sweetman, J.; Wang, T.; Martin, S.A.M.; Secombes, C.J. Impact of selenium supplementation on fish antiviral responses: a whole transcriptomic analysis in rainbow trout (*Oncorhynchus mykiss*) fed supra nutritional levels of Sel-Plex®. *BMC Genomics* **2016**, *17*, 1-26

Pacitti, D.; Lawan, M.M.; Sweetman, J.; Martin, S.A.M.; Feldmann J.; Secombes, C.J. 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* **2015**, 10, e0127041.

Pagenkopf, G.K. Gill surface interaction model for trace-metal toxicity to fishes: Role of complexation, pH, and water hardness. *Environ. Sci. Technol*. **1983**, *17*, 342-347

Pan, L.; Zhu, X.; Xie, S.; Lei, W.; Han, D.; Yang, Y. Effects of dietary manganese on growth and tissue manganese concentrations of juvenile gibel carp, *Carassius auratus* gibelio. *Aquac. Nutr*. **2008**, 14, 459-463.

Pan, L.; Xie, S.; Lei, W.; Han, D.; Yang, Y. The effect of different dietary iron levels on growth and hepatic iron concentration in juvenile gibel carp (*Carassius auratus* gibelio*). J. Appl. Ichthyol* **2009**, *25*, 428–431.

Papp, L.V.; Lu, J.; Holmgren, A.; Khanna, K.K. From selenium to selenoproteins: synthesis, identity, and their role in human health. *Antiox. Redox Signal*. **2007**, 9, 775–806.

Partridge, G.J.; Lymbery, A.J. The effect of salinity on the requirement for potassium by barramundi (*Lates calcarifer*) in saline groundwater. *Aquaculture* **2008**, *278*, 164–170.

Passerini, A.; Andreini, C.; Menchetti, S.; Rosato, A.; Frasconi, P. Predicting zinc binding at the proteome level. *BMC Bioinf*. **2007**, *5*, 8-39.

Pedersen, T. V.; Block, M.; Part, P. Effect of selenium on the uptake of methyl mercury across perfused gills of rainbow trout *Oncorhynchus mykiss*. *Aquat. Toxicol.* **1998**, *40*, 361-373.

Penglase, S.; Harboe, T.; Sæle, Ø.; Helland, S.; Nordgreen, A.; Hamre, K. Iodine nutrition and toxicity in Atlantic cod (*Gadus morhua*) larvae. *Peer J 1* **2013**, *e20* https://doi.org/10.7717/peerj.20

Penglase, S.; Hamre, K.; Ellingsen, S. The selenium content of SEPP1 versus selenium requirements in vertebrates. PeerJ3, **2015**, *e1244*.

Pentreath, R. J. The accumulation and retention of ^{65}Zn and ^{54}Mn by the plaice, *Pleuronectes platessa* L. J. *Exp. Mar. Biol. Ecol*. **1973**, *12*, 1–18.

Persson, P.; Sundell, K.; Björnsson, B.T.; Lundqvist, H. Calcium metabolism and osmoregulation during sexual maturation of river running Atlantic salmon. *J. Fish. Biol.* **1998**, *52*, 334–349.

Peters, A.; Lofts, S.; Merrington, G.; Brown, B.; Stubblefield, W.; Harlow K. Development of biotic ligand models for chronic manganese toxicity to fish, invertebrates, and algae. *Env. Toxicol. Chem*., **2011**, *30*, 2407-2415.

Petersen, W.; Wallman, K.; Pinglin, L.; Schroeder, F.; Knauth. H.D. Exchange of trace elements at the sediment-water interface during early diagenesis processes. *Mar. Freshwater Res*. **1995**, *46*, 19-26.

Pimentel Rodrigues, A.; Oliva Teles, A. Phosphorus requirements of gilthead sea bream (*Sparus aurata* L.) juveniles. *Aquacult. Res*. **2001**, *32*, 15-161.

Ponce, R.; Forja, J.M.; A. Gomez-Parra. Influence of anthropogenic activity on the vertical distribution of Zn, Cd, Pb and Cu in interstitial water and coastal marine sediments (Cadiz Bay, SW Spain). Ciencias Marinas **2000**, *26*, 479-502

Poston, H.A.; Combs, G.F.; Leibovitz, L. Vitamin E and selenium interrelations in the diet of Atlantic salmon *(Salmo salar*): gross, histological and biochemical deficiency signs. *J. Nutr*. **1976**, *106*, 892-904.

Potts, J.T. Parathyroid hormone: past and present. *J. Endocrinol*. **2005**, 187, 311-325.

Power, D.M.; Einarsdóttir, I.E.; Pittman, K.; Sweeney, G E.; Hildahl, J.; Campinho, M.A.; Silva, N.; Sæle, Ø.; Galay-Burgos, M.; Smáradóttir, H.; Björnsson, B.T. The molecular and endocrine basis of flatfish metamorphosis. *Rev. Fish. Sci*., **2008**, *16*, 95–111.

Prohaska, J.R. Impact of copper limitation on expression and function of multicopper oxidases (ferroxidases). *Adv. Nutr.* , **2011**, *2*, 89-95

Qiao, Y.-G.; Mai, K.-S.; Ai, Q.-H; Zhang, W.-D.; Xu, W. Evaluation of iron methionine and iron sulphate as dietary iron sources for juvenile cobia (*Rachycentron canadum*). *Aquac. Nutr*. **2013**, *19*, 721-730.

Rayman, M.P. The use of high-selenium yeast to raise selenium status: how does it measure up? *Br. J. Nutr*. **2004**, *92*, 557-553.

Read, E.S.; Barrows, F.T.; Gaylord, T.G.; Paterson, J.; Petersen, M.K.; Sealey, W.M. Investigation of the effects of dietary protein source on copper and zinc bioavailability in fishmeal and plant-based diets for rainbow trout. *Aquaculture* **2014**, *432*, 97-05.

Reid, S.D. Molybdenum and chromium. *Fish Physiol.* **2012**, 31A, 376-415.

Ribeiro, A.R.A.; Ribeiro, L.; Saele, O.; Dinis, M.T.; Moren M. Iodine and selenium supplementation increased survival and changed thyroid hormone status in Senegalese sole (*Solea senegalensis*) larvae reared in a recirculation system. *Fish Physiol. Biochem*. **2012**, *38*, 725-734.

Richards, J.D.; Zhao, J.; Harrell, C.A.; Atwell, A.; Dibner, J.J. Trace mineral nutrition in poultry and swine Asian-Aust. *J. Anim. Sci*. **2010**, 23, 1527-1534.

Richardson, N.L.; Higgs, D.A.; Beames, R.M.; McBride, J.R. Influence of dietary calcium, phosphorus, zinc and sodium phytate level on cataract incidence, growth and histopathology in juvenile chinook salmon (*Oncorhynchus tshawytscha*). *J. Nut*. **1985**, *115*, 553-567.

Rider, S.A.; Davies, S.J.; Jha, A.N.; Fisher, A.A.; Knight, J.; Sweetman, J.W. Supra-nutritional dietary intake of selenite and selenium yeast in normal and stressed rainbow trout (*Oncorhynchus mykiss*): implications on selenium status and health responses. *Aquaculture* **2009**, *295*, 282-291.

Rider, S.A.; Davies, S.J.; Jha, A.N.; Clough, R; Sweetman, J.W. Bioavailability of co-supplemented organic and inorganic zinc and selenium sources in a white fishmeal-based rainbow trout (*Oncorhynchus mykiss*) diet. *J. Anim. Physiol. Anim. Nutr*. **2010**, *94*, 99-110.

Robinson, E.; Rawles, S.D.; Yette, H.E.; Greene, L.W. An estimate of the dietary calcium requirement of fingerling *Tilapia aurea* reared in calcium-free water. *Aquaculture* **1984**, *41*, 389-393.

Robinson, E.; Rawles, S.D.; Yette, H.E.; Greene, L.W. Dietary calcium requirement of channel catfish (*Ictalurus punctatus*), reared in calcium-free water. *Aquaculture* **1986**, *53*, 263-270.

Robinson, E.H.; LaBomascus, D.; Brown, P.B.; Linton, T.L. Dietary calcium and phosphorus requirements of *Oreochromis aureus* reared in calcium-free water. *Aquaculture* **1987**, *64*, 267-276.

Rodehutscord, M. Response of rainbow trout (*Oncorhynchus mykiss*) growing from 50 to 200 g to supplements of dibasic sodium phosphate in a semipurified diet. *J. Nutr.* **1996**, *126*, 324-331.

Roman, M.; Jitaru, P.; Barbante, C. Selenium biochemistry and its role for human health. *Metallomics*. **2014**, 6, 25-54.

Rouleau, C.; Tjalve, H.; Gottofrey, J.; Pelletier, E. Uptake, distribution, and elimination of 54Mn(II) in brown trout (*Salmo trutta*). *Environ. Toxicol. Chem*. **1995**, *14*, 483–490.

Rowe. R.I.; Eckhert, C.D. Boron is required for zebrafish embryogenesis. *J. Exp. Biol*. **1999**, *202*, 1649-1654.

Roy, P.K.; Lall, S.P. Dietary phosphorus requirement of juvenile haddock (*Melanogrammus aeglefinus* L.). *Aquaculture* **2003**, *221*, 451-468.

Sakamoto, S.; Yone, Y. Effect of dietary calcium/phosphorus ratio upon growth, feed efficiency and blood serum Ca and P level in red sea bream. Bull. *Jpn. Soc. Sci. Fish*. **1973**, *39*, 343–348.

Sakamoto, S.; Yone, Y. Requirement of red sea bream for dietary Fe - 1. *Rep. Fish. Res. Lab. Kyushu Univ*. **1976**, 3, 53–58.

Sakamoto, S.; Yone, Y. Effect of dietary phosphorus level on chemical composition of red sea bream. *Bull. Jpn. Soc. Sci.* Fish. **1978a**, *44*, 227–229.

Sakamoto, S.; Yone, Y. Iron deficiency symptoms of carp. *Bull. Jap. Soc. Sci. Fish*. **1978b**, *44*, 157–160.

Sakamoto, S.; Yone, Y. Requirement of red sea bream for dietary iron II. *Bull. Jap. Soc. Sci. Fish*. **1978c**, *44*, 223–225.

Sakamoto, S.; Yone, Y. Availabilities of three iron compounds as dietary iron sources for red sea bream. *Bull. Jpn. Soc. Sci. Fish*. **1979a**, *45*, 231–235.

Sakamoto, S.; Yone, Y. Requirement of red sea bream for dietary Mg. *Bull. Jap. Soc. Fish*. **1979b**¸ *45*, 57–60.

Satoh, S.; Yamamoto, H.; Takeuchi, T.; Watanabe,T. Effects on growth and mineral composition of carp of deletion of trace elements or magnesium from fish meal diet. *Nippon Suisan Gakkaishi* **1983a**, *49*, 431-435.

Satoh, S.; Takeuchi, T.; Narabe, Y.; Watanabe, T. Effects of deletion of several trace elements from fish meal diets on growth and mineral composition of rainbow trout fingerlings. *Nippon Suisan Gakkaishi* **1983b**, *49*, 1909-1916.

Satoh, S.; Tabata, K.; Izume, K.; Takeuchi, T.; Watanabe, T. Effect of dietary tricalcium phosphate on availability of zinc to rainbow trout. *Nippon Suisan Gakkaishi*, **1987a**, *53*, 1199-1205.

Satoh, S.; Takeuchi, T.; Watanabe, T. Availability to carp of manganese in white fish meal and of various manganese compounds. *Nippon Suisan Gakkaishi* **1987b**, *53*, 825–832.

Satoh, S.; Poe, W.E.; Wilson, R.P. Effect of supplemental phytate and/or tricalcium phosphate on weight gain, feed efficiency and zinc content in vertebrae of channel catfish. *Aquaculture* **1989**, *80*, 155-161.

Schrauzer, G.N. Selenium yeast: Composition, quality, analysis, and safety. *Pure Appl.Chem*. **2006**, *78*, 105-109

Scott, M.L.; Thompson, J.N. Selenium content of feedstuffs and effects of dietary selenium levels upon tissue selenium in chick and poults. *Poult. Sci*. **1971**, *50*, 1742-1748.

Schultz, R.; Hermanutz, R. Transfer of toxic concentrations of selenium from parent to progeny in the fathead minnow (*Pimephales promelas*). Bull. Environ. Contam. Toxicol. **1990**, 45, 568-573.

Sele, V.; Ørnsrud, R.; Sloth, J.J.; Berntssen, M.H.G.; Amlund, H. Selenium and selenium species in feeds and muscle tissue of Atlantic salmon. *J. Trace Elem. Med. Biol*. **2018**, *47*, 124-133.

Shao, Q.; Ma, J.; Xu, Z.; Hu, W.; Xu, J.; Xie, S. Dietary phosphorus requirement of juvenile black seabream, *Sparus macrocephalus*. *Aquaculture* **2008**, *277*, 92-100.

Shaw, B.J.; Handy, R.D. Dietary copper exposure and recovery in Nile tilapia, *Oreochromis niloticus*. *Aquat. Toxicol*. **2006**, *76*, 111-121.

Shaw,B.J.; Handy, R.D. Physiological effects of nanoparticles on fish: A comparison of nanometals versus metal ions. *Environ Int*. **2011**, 37, 1083-109.

Shearer, K.D.; Åsgård, T. The effect of water-borne magnesium on the dietary magnesium requirement of rainbow trout (*Oncorhynchus mykiss*). *Fish Physiol. Biochem*. **1992**, 9, 387-392.

Shen, H.M.; Chen, X.R.; Chen, W.Y.; Lin, S.M.; Chen, Y.J.; Zhang, L.; Luo, L. Influence of dietary phosphorus levels on growth, body composition, metabolic response and antioxidant capacity of juvenile snakehead (*Channa argus* × *Channa maculata*). *Aquac. Nutr*. **2016**, *23*, 662-670.

Sherrill, J.; Whitaker, B.R.; Wong, G.T.F. Effects of ozonation on the speciation of dissolved iodine in artificial seawater. J. *Zoo Wild. Med*., **2004**, *35*, 347-355.

Shi, B.; Xu, F.; Zhou, Q.; Regan, M.K.; Betancor, M.B.; Tocher, D.R.; Sun, M.; Meng, F.; Jiao, L.; Jin, M. Dietary organic zinc promotes growth, immune response and antioxidant capacity by modulating zinc signaling in juvenile Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture Reports*. **2021**, 19, 100638.

Shiau, S.; Jiang, L. Dietary zinc requirements of grass shrimp, *Penaeus monodon*, and effects on immune responses. *Aquaculture* **2006**, *254*, 476-482.

Shiau, S.Y.; Lin, S.F. Effects of supplementation of dietary chromium and vanadium on the utilisation of different carbohydrates in tilapia, (*Oreochromis niloticus* x *O. aureus*). *Aquaculture* **1993**, *110*, 321-330.

Shiau, S.Y.; Lung, C.Q. No dietary vitamin B_{12} required for juvenile tilapia *Oreochromis niloticus* × *O. aureus*. *Comp. Biochem. Physiol*. **1993**, *105A*, 147–150.

Shiau, S.; Ning, Y. Estimation of dietary copper requirements of juvenile tilapia, *Oreochromis niloticus x O. aureus*. *Anim. Sci*., **2003**, *77*, 287-292

Shiau, S.Y.; Shy, S.M. Dietary chromic oxide inclusion level required to maximize glucose utilization in hybrid tilapia (*Oreochromis niloticus* x *O. aureus*). *Aquaculture* **1998**, *161*, 357-364.

Shiau, S.Y.; Su, L.W. Ferric citrate is half as effective as ferrous sulfate in meeting the iron requirement of juvenile tilapia, *Oreochromis niloticus* × *O. aureus*. *J. Nutr*., **2003**, *133*, 483-488.

Silva, M.S.; Kröckel, S.; Jesu Prabhu, P.A.; Koppe, W.; Ørnsrud, R.; Waagbø, R.; Araujo, P.; Amlund, H. Apparent availability of zinc, selenium and manganese as inorganic metal salts or organic forms in plant-based diets for Atlantic salmon (*Salmo salar*). *Aquaculture* **2019**, *503*, 562-570.

Sissener, N.H.; Julshamn, K.; Espe, M.; Lunestad, B.T.; Hemre, G.-I.; Waagbø, R.; Måge, A. Surveillance of selected nutrients, additives and undesirables in commercial Norwegian fish feeds in the years 2000-2010. *Aquacul. Nutr*. **2013**, *19*, 555-572.

Skonberg, D.I.; Yogev, L.; Hardy, R.W.; Dong, F.M. Metabolic response to dietary phosphorus intake in rainbow trout (*Oncorhynchus mykiss*). Aquaculture **1997**, *157*, 11-24.

Sloth, J.J.; Julshamn, K.; Lundebye, A.-K. Total arsenic and inorganic arsenic content in Norwegian fish feed products. Aquac. Nutr. **2005**, *11*, 61-66

Specker, J.L.; Eales, J.G.; Tagawa, M.; Tyler III, W.A. Parr-smolt transformation in Atlantic salmon: thyroid hormone deiodination in liver and brain and endocrine correlates of change in rheotactic behavior. *Can. J. Zool*. **2000**, *78*, 696-705.

Spears, J.W., Hansen, S.L. Bioavailability criteria for trace minerals in monogastric and ruminants. In *Trace Elements in Animal Production Systems*, Schlegel, P., Durosoy, S., Jongbloed, A.W., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp.161-170.

Spehar, R.L.; Fiandt, J.T. Acute and chronic effects of water quality criteria-based metal mixtures on three aquatic species. *Environ. Toxicol. Chem*. **1986**, *5*, 917–931.

Spry, D.I.; Hodson, P.V.; Wood, C.M. Relative contributions of dietary and waterborne zinc in rainbow trout, *Salmo gairdneri*. *Can. J. Fish. Aquat. Sci*. **1988**,*45*, 32-41.

Sugiura, S.H.; Hardy, R.W.; Roberts, R.J. The pathology of phosphorus deficiency in fish – a review J. *Fish Dis*. **2004**, *27*, 255-265.

Sun, Y.; Li, B.; Zhang, X.; Chen, M.; Tang, H.; Yu, X. Dietary available phosphorus requirement of crucian carp, *Carassius auratus* . *Aquac. Nutr.* **2018**, *24*, 1494-1501.

Sundby, B.; Martinez, P.; Gobeil.C. Comparative geochemistry of cadmium, rhenium, uranium, and molybdenum in continental marine sediments. *Geochim. Cosmochim. Acta* **2004**, *68*, 2485-2493.

Sundell, K.; Bishop, J.E.; Bjornsson, B.T.; Norman, A.W. 1,25- Dihydroxyvitamin-D_3 in the Atlantic cod -plasma-levels, a plasma binding component, and organ distribution of a high affinity receptor. *Endocrinology* **1992**, *131*, 2279-2286.

Suttle, N. Mineral Nutrition of Livestock. 4th Ed.; Commonwealth Agricultural Bureaux International: Oxfordshire, UK., 2010; pp.579.

Tacon, A.G.J.; Beveridge, M.M. Effects of dietary trivalent chromium on rainbow trout. *Nutr. Rep. Int*. **1982**, 25, 49-56.

Tacon, A.G.J.; Metian, M.; McNevin, A.A. Future Feeds: Suggested guidelines for sustainable development, *Rev. Fish. Aquacul*., **2021**, DOI: 10.1080/23308249.2021.1898539

Takeuchi, T.; Watanabe, T.; Ogino, C.; Saito, M.; Nishimura, K.; Nose, T. Effects of low protein-high calorie diets and deletion of trace elements from a fish meal diet on reproduction of rainbow trout. *Bull. Jap. Soc. Sci. Fish*. **1981**, *47*, 645-654.

Tan, X.Y.; Luo, Z.; Liu, X.; Xie, C.X. Dietary copper requirement of juvenile yellow catfish *Pelteobagrus fulvidraco*. *Aquac. Nutr*. **2011a**, 17, 170-176.

Tan, L.-N.; Feng, Liu, Y.; Jiang, J.; Jiang, W.-D.; Hu, K.; Li, S.-H.; Zhou, X.-Q. Growth, body composition and intestinal enzyme activities of juvenile Jian carp (*Cyprinus carpio* var. Jian) fed graded levels of dietary zinc. *Aquac. Nutr*., **2011b**, *17*, 338-345.

Tan, X.Y.; Xie, P.; Luo, Z.; Lin, H.Z.; Zhao, Y.H.; Xi, W.Q. 2012. Dietary manganese requirement of juvenile yellow catfish *Pelteobagrus fulvidraco*, and effects on whole body mineral composition and hepatic intermediary metabolism. *Aquaculture* **2012**, *326-329*, 68-73.

Tang, Q.Q.; Feng, L.; Jiang, W.D.; Liu, Y.; jiang, J.; Li, S.H.; Kuang, S.Y.; Tang, L.; Zhu, X.Q. Effects of dietary copper on growth, digestive, and brush border enzyme activities and antioxidant defense of hepatopancreas and intestine for young grass carp (*Ctenopharyngodon idella*). *Biol. Trace. Elem. Res*., **2013**, *155*, 370-380.

Tashjian, D.H.; Teh, S.J.; Sogomonyan, A.; Hung, S.S.O. Bioaccumulation and chronic toxicity of dietary l-selenomethionine in juvenile white sturgeon (*Acipenser transmontanus*). *Aquat. Toxicol.*, **2006**, *79*, 401-409.

Taylor, V.; Goodale, B.; Raab, A.; Schwerdtle, T.; Reimer, K.; Conklin, S.; Karagas, M.R.; Francesconi, K.A. Human exposure to organic arsenic species from seafood. *Sci. Total Environ*. **2017**, *580*, 266-282.

Taylor, L.N.; Wood, C.M.; McDonald, D.G. An evaluation of sodium loss and gill metal binding properties in rainbow trout and yellow perch to explain species differences in copper tolerance. *J. Exp. Biol*. **2003**, *22*, 2159-2166

Teas, J.; Pino, S.; Critchley, A.; Braverman, L.E. Variability of iodine content in common commercially available edible seaweeds. *Thyroid* **2004**,14, 836-841.

Thiry, C.; Ruttens, A.; De Temmerman, L.; Schneider, Y.-J.; Pussemier, L. Current knowledge in species-related bioavailability of selenium in food. *Food Chem*., **2012**, *130*, 767-784.

Tonacchera, M.; Pinchera, A.; Dimida, A.; Ferrarini, E.; Agretti, P.; Vitti, P.; Santini, F.; Crump, K.; Gibbs, J. Relative potencies and additivity of perchlorate, thiocyanate, nitrate, and iodide on the inhibition of radioactive iodide uptake by the human sodium iodide symporter. *Thyroid* **2004**, 14, 1012-1019

Truong, H.H.; Moss, A.F.; Bourne, N.A. Simon, C.J. Determining the importance of macro and trace dietary minerals on growth and nutrient retention in juvenile *Penaeus monodon*. *Animals* **2020**, *10*, 2086.

Uyan, O.; Koshio, S.; Ishikawa, M.; Uyan, S.; Ren, T.; Yokoyama, S.; Komilus, F.C.; Michael, F.R. Effects of dietary phosphorus and phospholipid level on growth, and phosphorus deficiency signs in juvenile Japanese flounder, *Paralichthys olivaceus*. *Aquaculture* **2007**, *267*, 44-54.

Vallee, B.L.; Falchuk, K.H. The biochemical basis of zinc physiology. Physiol. Rev. **1993**, *73*, 79-118.

Vanderpas, J. Nutritional epidemiology and thyroid hormone metabolism. *Ann. Rev. Nutr*., **2006**, *26*, 293-322.

Van Der Velden, J.A.; Kolar, Z.I.; Flik, G. Intake of magnesium from water by freshwater tilapia fed on a low-Mg diet. *Comp. Biochem. Physiol*. **1991**, *99 A*, 103-105.

Verlhac-Trichet, V.; Vielma, J.; Dias, J.; Rema, P.; Santigosa, E.; Wahli, T.; Vogl, K. The efficacy of a novel microbial 6-phytase expressed in *Aspergillus oryzae* on the performance and phosphorus utilization of cold- and warm-water fish: rainbow trout, *Oncorhynchus mykiss*, and Nile tilapia, *Oreochromis niloticus*. *J. World Aquacult. Soc*. **2014**, *45*, 367–79.

Vieira, M.C.; Torronteras, R.; Córdoba, F.; Canalejo, A. Acute toxicity of manganese in goldfish *Carassius auratus* is associated with oxidative stress and organ specific antioxidant responses. *Ecotox. Environ. Safety*, **2012**, 78, 212–217.

Vielma, J.; Lall, S.P. Control of phosphorus homeostasis of Atlantic salmon (*Salmo salar*) in fresh water. *Fish Physiol. Biochem*. **1998a**, 19, 83-93.

Vielma, J.; Lall, S.P. Phosphorus utilization by Atlantic salmon (*Salmo salar*) reared in freshwater is not influenced by higher dietary calcium intake. *Aquaculture* **1998**, *160*, 117-128.

Vielma, J.; Lall, S.; Koskela, J.; Mattila, P. Influence of low dietary cholecalciferol intake on phosphorus and trace element metabolism by rainbow trout (Oncorhynchus mykiss, Walbaum). *Comp. Biochem. Physiol. Mol. Integr. Physiol*. **1999**, *122B*, 117–125.

Verbost, P.M.; van Rooij, J.; Flik, G.; Lock, R.A.C.; Wendelaar Bonga, S.E. The movement of cadmium through freshwater trout branchial epithelium and its interference with calcium transport. J. *Exp. Biol.* **1989**, *145*, 185-197.

Vincent, J.B. The biochemistry of chromium. *J. Nutr*. **2000**, *130*, 715–718.

Vincent, J.B. New evidence against chromium as an essential trace element J *Nutr*., **2017**, *147*, 2212-2219.

Vohra, A.; Satanarayana, T. Phytases: microbial sources, production, purification, and potential biotechnological applications. *Crit. Rev. Biotech*. **2003**, 23, 29-60.

Waagbø, R.; Tröße, C.; Fontanillas, R., Breck, O. Dietary histidine supplementation prevents cataract development in adult Atlantic salmon, *Salmo salar* L., in seawater. *Br. J. Nutr*., **2010**, *104*, 1460-1470.

Wagner, G.F. Stanniocalcin: structure, function, and regulation. In *The Biochemistry and Molecular Biology of Fishes;* Hochachka, P,W, Mommsen, T. Eds.; Elsevier Science: Amsterdam, The Netherlands, 1993; pp. 419-434.

Wagner, G.F., Jaworski, E.M.; Haddad, M. Stanniocalcin in the seawater salmon: structure, function, and regulation. Am. J. Physiol. **1998**, *274*, R117-R118.

Wang, C.; Lovell, R.T. Organic selenium sources, selenomethionine and selenoyeast, have higher bioavailability than an inorganic selenium source, sodium selenite, in diets for channel catfish (*Ictalurus puncatatus*). *Aquaculture* **1997**, *152*, 223-234.

Wang, X.J.; Choi, S.; Park, S.; Yoo, G.; Kim, K.; Kang, J.C.; Bai, S.C. Optimum dietary phosphorus level of juvenile Japanese flounder *Paralichthys olivaceus* reared in the recirculating system. *Fish. Sci*. **2005**, *71*, 168-173.

Wang, J.; Ai, Q.; Mai, K.; Xu, H.; Zuo, R. Dietary chromium polynicotinate enhanced growth performance, feed utilization, and resistance to *Cryptocaryon irritans* in juvenile large yellow croaker (*Larmichthys crocea*). *Aquaculture* **2014**, *432*, 321-326.

Wang, L.; Xiao, J.-X.; Hua, Y.; Xiang, X.-W.; Zhou, Y.-F.; Ye, L.; Shao, Q.-J. Effects of dietary selenium polysaccharide on growth performance, oxidative stress and tissue selenium accumulation of juvenile black sea bream, *Acanthopagrus schlegelii*. *Aquaculture* **2019**, *503*, 389-395.

Wang, Q.; Zhang, Y.; Bai, D.; Chen, C.; Guo, Y.; Xing, K. Estimation of dietary copper (Cu) requirement of *Cynoglossus semilaevis* Günther. In *Adv. Appl. Biotech. In: Lecture Notes in Electrical Engineering;* Zhang, T.C., Nakajima, M. Eds.; Springer: Berlin, DE, 2015; Vol. 332.245-255.

Wang, H.; Li, E.; Zhu, H.; Du, Z.; Qin, J.; Chen, L. Dietary copper requirement of juvenile Russian sturgeon *Acipenser gueldenstaedtii.* Aquaculture **2016**, *454*, 118-124.

Wang, J.; Gatlin, III, D.M.; Li, L.; Wang, Y.; Jin, N.; Lin, H.; Zhou,C.; Huang, Z.; Yu, W.; Guo, Y. Dietary chromium polynicotinate improves growth performance and feed utilization of juvenile golden pompano (*Trachinotus ovatus*) with starch as the carbohydrate. *Aquaculture* **2019**, *505*, 405-411.

Wang, L.; Zhang, X.; Wu, L.; Liu, Q.; Zhang, D.; Yin, J. Expression of selenoprotein genes in muscle is crucial for the growth of rainbow trout (*Oncorhynchus mykiss*) fed diets supplemented with selenium yeast. *Aquaculture* **2018**, *492*, 82-90.

Wang, L.; Li, X.; Lu, K.; Song, K.; Wang, G.; Zhang, C. Dietary hydroxyl methionine selenium supplementation enhances growth performance, antioxidant ability and nitrite tolerance of *Litopenaeus vannamei*. *Aquaculture* **2021**,*537*, 736513.

Watanabe, T.; Murakami, A.; Takeuchi, L.; Nose, T.; Ogino, C. Mineral requirements in fish 9. Requirement of chum salmon held in fresh-water for dietary phosphorus. Bull. Jpn. Soc. Sci. Fish. **1980,** 46, 361-367.

Watanabe, K.; Satoh, S.; Takeuchi, T. Availability of minerals in fish meal. *Asian Fish. Soc*. **1988**, *1*, 175-195.

Watanabe, T.; Kiron, V.; Satoh, S. Trace minerals in fish nutrition. *Aquaculture* **1997**, *151*, 185-207.

Wekell, J.C.; Shearer, K.D.; Gauglitz, E.J., Jr. Zinc supplementation of trout diets: tissue indicators of body zinc status. *Prog. Fish-Cult*. **1986**, *48*, 205-212.

Wekell, J.C.; Shearer, K.D.; Houle, C.R. High zinc supplementation of rainbow trout diets. *Prog. Fish-Cult*. **1983**, *45*, 144-147.

Welker, T.; Barrows, F.; Overturf, K.; Gaylord, G.; Sealey, W. Optimizing zinc supplementation levels of rainbow trout (*Oncorhynchus mykiss*) fed practical type fishmeal- and plant-based diets. *Aquac. Nutr*. **2016**, *22*, 91-108.

Wendalaar Bonga, S.E.; Flik, G. Calcium regulation in fish. In *Aquaculture: Fundamental and Applied Research;* Lahlou, B., Vitiello, P. Eds.; American Geophysical Union: Washington, USA, 1995; pp. 47-59.

Whitehead, M.W.; Thompson, R.P.H., Powell, J.J. Regulation of metal absorption in the gastrointestinal tract. *Gut* **1996**, *39*, 625-628.

Wilson, R.P.; Robinson, E.H.; Gatlin III; D.M.; Poe, W.E. Dietary phosphorus requirement of channel catfish. *J. Nutr*. **1988**, *112*, 1197-1202.

Wilson, R.W.; Wilson, J.M.; Grosell, M. Intestinal bicarbonate secretion by marine teleost fish—why and how? *Biochim. Biophys. Acta* **2002**, *1566*, 182-193.

Wischhusen, P.; Parailloux, M.; Geraert, P.-A.; Briens, M.; Bueno, M.; Bouyssiere, B.; Antony Jesu Prabhu, P.; Kaushik, S.J.; Fauconneau, B.; Fontagné-Dicharry, S. Effect of dietary Se in rainbow trout (*Oncorhynchus mykiss*) broodstock on antioxidant status, its parental transfer and oxidative status in the progeny. *Aquaculture* **2019**, *507*, 126-138

Witten, P.E.; Fjelldal, P.G.; Huysseune, A.; McGurk, C.; Obach, A.; Owen, M.A.G. Bone without minerals and its secondary mineralization in Atlantic salmon (*Salmo salar*): the recovery from phosphorus deficiency. *J. Exp. Biol.* **2019**, *222* (3): jeb188763.

Witten, P.E.; Owen, M.A.G.; Fontanillas, R.; Soenens, M.; McGurk, C.; Obach, A. A primary phosphorus-deficient skeletal phenotype in juvenile Atlantic salmon *Salmo salar*: the uncoupling of bone formation and mineralization. J. Fish Biol. **2016**, *88*, 690-708.

Wood, C.M. An introduction to metals in fish physiology and toxicology: Basic principles. *Fish Physiol.* **2012**, 31A, 1-53.

Wood, C.M.; Farrell, A.M.; Brauner, C. J. Homeostasis and toxicology of essential metals. *Fish Physiol.* , **2012a,** 31A, 495 pp.

Wood, C.M.; Farrell, A.M.; Brauner, C. J. Homeostasis and toxicology of non-essential metals, *Fish Physiol.* **2012b,** 31B, 531 pp.

Woodall, A.N.; LaRoche, G. Nutrition of salmonid fishes. 11. Iodide requirements of chinook salmon. *J. Nutr.* **1964**, *82*, 475-482.

Xie, D., Han, D., Zhu, X., Yang, Y., Jin, J., Liu, H., Xie, S. Dietary available phosphorus requirement for on-growing gibel carp (*Carassius auratus* gibelio var. CAS III). *Aquacul. Nutr.* **2017**, *23*, 1104–1112.

Xu, Z.; Dong, X.; Liu, C. Dietary zinc requirement of juvenile cobia (*Rachycentron canadum*). *Fish. Sci*. **2007**, *26*, 138-141

Yamamoto, H.; Satoh, S.; Takeuchi, T.; Watanabe, T. Effects on rainbow trout of deletion of manganese or trace elements from fish meal diet. *Nippon Suisan Gakkaishi*, **1983**, *49*, 287-293.

Yao, Y.F.; Jiang, M.; Wen, H.; Wu, F.; Liu, W.; Tian, J.; Yang, C.G. Dietary phosphorus requirement of GIFT strain of Nile tilapia *Oreochromis niloticus* reared in fresh water. *Aquac. Nutr*. **2014**, *20*, 273-280.

Yu, H.-R.; Zhang, Q.; Xiong, D.-M.; Huang, G.-Q.; Li, W.-Z.; Liu, S.-W. Dietary available phosphorus requirement of juvenile walking catfish, *Clarias leather*. *Aquac. Nutr*. **2012**, 19, 483–490.

Ye, C.X.; Liu, Y.J.; Tian, L.X.; Mai, K.S.; Du, Z.Y.; Yang, H.J.; Niu, J. Effect of dietary calcium and phosphorus on growth, feed efficiency, mineral content and body composition of juvenile grouper, *Epinephelus coioides*. *Aquaculture* **2006**, *255*, 263-271.

Ye, C.X.; Liu, Y.-J.; Mai, K.-S.; Tian, L.-X.; Yang, H.-J.; Niu, J.; Huang, J.-W. Effect of dietary iron supplement on growth, haematology and microelements of juvenile grouper, E*pinephelus coioides*. *Aquac. Nutr*. **2007**, *13*, 471-477.

Ye C.X.; Tian L.X.; Yang H.J.; Liang J.J.; Niu J.; Liu Y.J. Growth performance and tissue mineral content of juvenile grouper (*Epinephelus coioides*) fed diets supplemented with various levels of manganese. Aquac. Nutr. **2009**, *15*, 608-614.

Yu, H.-R.; Zhang, Q.; Xiong, D.-M.; Huang, G.-Q.; Li, W.-Z.; Liu, S.-W. Dietary available phosphorus requirement of juvenile walking catfish, *Clarias leather*. *Aquac. Nutr*. **2012**,*19*, 483-490.

Yu, Q.; Fu, Z; Huang, M.; Xu, C.; Wang, X.; Qin, J.G.; Chen, L.; Han, F.; Li, E. Growth, physiological, biochemical, and molecular responses of Pacific white shrimp *Litopenaeus vannamei* fed different levels of dietary selenium. *Aquaculture* **2021**, *535*, 736393.

Yuan, Y.C.; Yang, H.J.; Gong, S.Y.; Luo, Z.; Yu, D.H.; Yan, J.L.; Yang, X.F. Dietary phosphorus requirement of juvenile Chinese sucker *Myxocyprinus asiaticus*. *Aquac. Nutr*. **2011**. *17*, 159-169.

Zafar, N.; Khan, M.A. Determination of dietary phosphorus requirement of stinging catfish *Heteropneustes fossilis* based on feed conversion, growth, vertebrae phosphorus, whole body phosphorus, haematology and antioxidant status. *Aquac. Nutr*. **2018**, *24*, 1577-1586.

Zafar N.; Khan M.A. Dietary copper requirement of fingerling *Heteropneustes fossilis* for formulating copper-balanced commercial feeds. *Aquac. Nutr*. **2020**, *26*, 248-260.

Zee, J.; Patterson, S.; Wiseman, S.; Hecker, M. Is hepatic oxidative stress a main driver of dietary selenium toxicity in white sturgeon (*Acipenser transmontanus*). *Ecotox. Environ. Safety*. **2016**. *133*, 334-340.

Zhang, C.; Mai, K.; Ai, Q.; Zhang, W.; Duan, Q.; Tan, B.; Ma, H.; Xu, W.; Linfu, Z.; Wang, X. Dietary phosphorus requirement of juvenile Japanese seabass, *Lateolabrax japonicus*. *Aquaculture* **2006**, *255*, 201-209.

Zhang, H.; Sun, R.; Xu, W.; Zhou, H.; Zhang, W.; Mai, K. Dietary manganese requirement of juvenile large yellow croaker *Larimichthys crocea* (Richardson, 1846). *Aquaculture* **2016**, *450*, 74-79.

Zhao, L.; Xia, Z.; Wang, F. Zebrafish in the sea of mineral (iron, zinc, and copper) metabolism. *Front. Pharmacol*. **2014**, 5-33 doi:10.3389/fphar.2014.00033.

Zhu, L.; Han, D.; Zhu, X.; Yang, Y.; Jin, J.; Liu, H.; Xie, S. Dietary selenium requirement for on-growing gibel carp (*Carassius auratus* gibelio var. CAS III). *Aquac. Res*. **2016**, *48*, 2841-2851.

Zhu, Y.; Chen, Y.; Liu, Y.; Yang, H.; Liang, G.; Tian, L. Effect of dietary selenium level on growth performance, body composition and hepatic glutathione peroxidase activities of largemouth bass *Micropterus salmoide*. *Aquac. Res*. **2011**, *43*, 1660-1668.

Zimmer, A.M.; Brix, K.V.; Wood, C.M. Mechanisms of Ca2+ uptake in freshwater and seawater-acclimated killifish, *Fundulus heteroclitus*, and their response to acute salinity transfer. J. Comp. Physiol. B, **2019**, *189*, 47-60.

Table 1. Iron and copper requirement of fish

Fish species	**Copper^{a}**			**Iron^{e}**		
	mg kg^{-1}	Main response criteria	Reference	mg kg^{-1}	Main response criteria	Reference
Atlantic salmon	5-10	Liver Cu	Lorentzen et al., (1998)	60-100 60	H^{f}, Liver Fe Weight gain, H^{f}, Liver Fe	Andersen et al., (1996) Naser (2000)
Rainbow trout	3	Body, vertebrae, liver Cu	Ogino and Yang (1980)			
Channel catfish	5	Liver Cu-Zn SOD	Gatlin and Wilson (1986b)	30	WG, H^{f}	Gatlin and Wilson (1986a)
Yellow catfish	3.1-4.2	WG^{b}, Cu retention	Tan et al., 2011a	55.7		Luo et al., (2017)
Common carp	3^{c}	Body, vertebrae, liver Cu	Ogino and Yang (1980)	147.4	Serum Fe	Ling et al., (2010)
				202	Hematocrit, liver Fe	Pan et al., (2009)
Grass carp	4.7-5	WG, plasma ceruplasmin activity	Tang et al., (2013)			
Hybrid tilapia	4	WG, body Cu retention	Shiau and Ning (2003)	150-160^{g} 85^{e}	Weight gain, hemoglobin, Liver Fe	Shiau and Su, 2003
Japanese eel				170		Nose and Arai (1979)
Asian stinging catfish	5.2-5.7	WG, plasma ceruplasmin activity	Zafar and Khan (2020)			
Russian sturgeon	7-8	WG, whole-body Cu, liver Cu–Zn SOD, serum ceruloplasmin activity	Wang et al. (2016)			

Red sea bream				150		Sakamoto and Yone, (1978c)
Tongue sole	11-12	WG, serum Cu–Zn SOD activity	Wang et al., 2015			
Malabar grouper	4-6	WG, Liver Cu–Zn SOD activity, body Cu retention	Lin et al., (2008a)	100[h]	Liver Fe	Ye et al., (2007)
	2-3[d]	WG, Liver Cu–Zn SOD activity, body Cu retention	Lin et al., (2010a)			
Yellow croaker	3.4-7	Serum Cu–Zn SOD activity, body and vertebrae Cu	Cao et al., (2014)			
Cobia				80.5-94.7[e] 71.3–75.1[i]	WG, serum catalase activity	Qiao et al., (2013)

[a]Unless specified $CuSO_4·5H_2O$ used as Cu supplement ; [b]Weight gain; [c]$CuCl_2$ used as Cu supplement ; [d]Copper peptide used as Cu supplement; [e]Unless specified $FeSO_4·6H_2O$ used as Fe supplement ; [f]Hematology; [g]Ferric citrate used as Fe supplement; [h]Requirement for orange- spotted grouper (*Epinephelus coioides*); [i]Iron methionine used as Fe supplement

Table 2. Manganese requirement of certain fish[a]

Fish species	**mg kg^{-1}**	**Main response criteria**	**Reference**
Atlantic salmon	15 7.5-10.5	Body and vertebrae Mn Body Mn	Lorentzen et al., (1996) Maage et al., (2000)
Rainbow trout	12-13	WG[b]	Ogino and Yang (1980)
Channel catfish	2.4	WG	Gatlin and Wilson (1984a)
Yellow catfish	5.5-6.4	WG, vertebrae Mn, liver Mn-SOD[c]	Tan et al., (2012)
Common carp	12-13	Growth rate	Ogino and Yang, (1980)
Gibel carp	13.8	WG, body and vertebrae Mn	Pan et al., (2008)
Hybrid tilapia	7	Body Mn, Liver Mn-SOD	Lin et al. (2008b)
Grouper[d]	15	Body and vertebrae Mn	Ye et al., (2009)
Yellow croaker	16.4	Growth rate, liver Mn-SOD	Zhang et al., (2016)
Cobia	21.7-24.9 10.5-15.4[e]	WG, Body and vertebrae Mn Specific growth rate, liver Mn-SOD	Liu et al., (2012) Nie et al. (2016)

[a]Unless specified $MnSO_4{\cdot}H_2O$ used as Mn supplement; [b]Weight gain; [c]Liver Mn-SOD activity; [d]Orange spotted grouper (*Epinephelus coiodes*) ; [e]$MnSO_4{\cdot}H_2O$, manganese glycine and manganese 2-hydroxy-4-(methylthio)butyrate showed Mn requirement of 15.4, 11.2 and 10.5 mg kg^{-1} respectively

Table 3. Selenium requirement of certain fish

Fish species	**Requirement, mg kg^{-1}**	**Selenium source**	**Main response criteria**	**Reference**
Atlantic salmon	0.27^a(0.65)	Na_2Se0_3 or SeMet^b	Body and tissue Se	Antony Jesu Prabhu et al.,(2020)
Rainbow trout	0.15-0.38	Na_2Se0_3	Plasma GPx	Hilton et al., (1980)
Channel catfish	0.25	Na_2Se0_3	Liver and plasma GPx	Gatlin and Wilson, (1984b)
			WG^c, GPx	
	0.28, 0.17	Na_2Se0_3	WG, GPx	Wang and Lovell, (1997)
	0.09, 0.12	SeMet	WG, GPx	
	0.11, 0.12	Se-yeast		
Gibel carp	1.18	SeMet	WG, Liver GPx, tissue Se	Han et al., (2011)
	0.73-1.19	SeMet	Liver Se, Liver SOD, T-AOC	Zhu et al.,(2016)
Nile tilapia	0.57	SeMet	WG, Liver GPx	Ning et al., (2020)
Largemouth bass	1.60-1.85	Na_2Se0_3	Liver GPx	Zhu et al., (2011)
Gilthead sea bream	0.94	Na_2Se0_3	Growth. Liver Se	Dominguez et al.,(2019)
Black sea bream	0.86	Se-polysaccharide^d	Liver SOD and GPx	Wang et al., (2019)
Malabar grouper	0.7	SeMet	WG. Se retention	Lin and Shiau, (2005)
	0.9	SeMet	WG, Flesh Se	Lin, (2014)
	0.98	Na_2Se0_3		
Cobia	0.8	SeMet	Liver and serum GPx, Whole body Se	Liu et al., (2010a)

^{a}Based on available Se ; ^{b}Se-methionine used as Se supplement; ^{c}Weight gain ; ^{d}Se-polysachharide used as Se supplement

Table 4. Zinc requirement of certain fish[a]

Fish species	**Requirement, mg kg^{-1}**	**Main response criteria**	**Reference**
Atlantic salmon	37 - 67	Body and serum Zn	Maage and Julshamn (1993)
Rainbow trout	15-30 30.1	WG[b], vertebrae Zn WG	Ogino and Yang (1978) Welker et al., (2016)
Channel catfish	20	WG, vertebrae Zn	Gatlin and Wilson (1983)
Yellow catfish	17.1-20.9	WG, PER[c]	Luo et al., (2011)
Common carp	15	WG, vertebrae Zn	Ogino and Yang (1979)
Jian carp	43.2-48.7[d]	WG, serum, Zn	Tan et al., (2011b)
Grass carp	55	WG, whole body, vertebrae, scale and tissue Zn	Liang et al., (2012)
Indian major carp	47.8-52.9	WG, vertebrae, scale serum and liver Zn	Musharraf and Khan (2019)
Hybrid tilapia	26-29 105-115[e]	WG, whole body Zn WG, whole body and plasma Zn	Lin et al., (2008c) Li and Huang, (2016)
Blue tilapia	20	Scale and vertebrae Zn	McClain and Gatlin (1988)
Nile tilapia	30 37.2-52.1	WG, vertebrae and serum Zn WG, bone Zn	Eid and Ghonim (1994) Huang et al., (2015)
Russian sturgeon	28.2-34.6	WG and Liver Zn	Moazenzadeh et al., (2017)
Red drum	20	WG, serum and bone Zn	Gatlin et al., (1991)
Blunt snout sea bream	52.1[f], 86.2[f]	WG, whole body Zn	Jiang et al., (2016)
Malabar grouper	28.9-33.7	WG, vertebrae and scale Zn	Huang-Yung et al., (2014)
Cobia	42.9	WG, vertebrae Zn	Xu et al., (2007)

[a]Unless specified $ZnSO_4{\cdot}7H_2O$ used as Zn supplement ; [b]Weight gain;[c]Protein efficiency ratio; [d]Zinc lactate ($C_6H_{10}O_6Zn$); [e]Diet based on soybean meal ; [f]Requirements based on weight gain and whole body Zn respectively