REVIEW PAPERS

WATER AS A SOURCE OF MACRONUTRIENTS AND MICRONUTRIENTS FOR FISH, WITH SPECIAL EMPHASIS ON THE NUTRITIONAL REQUIREMENTS OF TWO FISH SPECIES: THE COMMON CARP (*CYPRINUS CARPIO*) AND THE RAINBOW TROUT (*ONCORHYNCHUS MYKISS*)

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ABSTRACT

In contrast to terrestrial animals, fish can ingest minerals from food or directly from water. Although micro- and macro-elements are needed in small quantities, they play a key role in many metabolic processes. Trace mineral and macromineral deficiencies may go unnoticed due to an absence of clear clinical symptoms in fish. Absorption processes are determined by various factors, mostly mineral concentrations in water but also other water parameters. The required dietary supplementation of macronutrients and micronutrients is very difficult to determine, and the amount of nutrients absorbed by fish from water is equally difficult to measure. Interactions between elements should also be taken into consideration. Many authors emphasize that phosphates may reduce the absorption of most micronutrients. Also, the current parameters of the water can affect the bioavailability. Some elements such as calcium, chlorine and sodium can be absorbed from ambient water in a quantity sufficient to meet the demand for this element. Other elements, however, require supplementation in a diet. For example, studies indicate the need for supplementation of phosphorus, zinc, copper and manganese. Most research concentrates on feedstuff as a source of micro- and macronutrients. Meanwhile, information

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concerning bioavailability of minerals directly from water is scarce. The aim of this study was to analyse literature from a different perspective, and concentrate on water as a source of minerals in fish nutrition. Measurements of water parameters such as temperature, pH, nitrate and nitrite levels and the amount of dissolved oxygen are a regular component of environmental control in fish farming. Determination of micro- and macro-element levels, however, remains uncommon in aquaculture. Measurements of these parameters could suggest which elements need to be supplemented and which are found in water in amounts that satisfy the needs of the fish.

Keywords: fish nutrition, minerals, macronutrients, micronutrients, common carp, rainbow trout.

INTRODUCTION

All living organisms are composed of organic and inorganic compounds, which are equally important for growth and development. The quantitative and qualitative proportions of those compounds depend on a fish species, fish biology and environmental conditions. Subject to their concentrations in an organism, mineral nutrients are generally classified into two major groups: trace minerals – below 50 mg kg^{-1} BW and macrominerals – above 50 mg kg^{-1} BW (Poczyczyński, Woźniak 2014).

Fish can ingest minerals from food or directly from water. Absorption processes are determined by various factors, mostly mineral concentrations in water. The nutritional requirements of farmed fish are met by a balanced diet that contains protein, fat, carbohydrates, minerals and vitamins and is specifically formulated for fish of a given age and species. Trace mineral and macromineral deficiencies may go unnoticed due to an absence of clinical symptoms in fish. Mineral deficiencies can lead to health problems, lower feed conversion efficiency and lower weight gains. Mineral concentrations in water should be determined before starting any supplementation regimes in fish farms.

Marine fish live in a hypertonic environment, where they are exposed to constant risk of dehydration due to loss of water through gills. They have to compensate for that loss by regularly consuming small quantities of water, equivalent to 50% of their body weight, on a daily basis (NRC 1983). Most marine fish receive their daily dose of micronutrients, such as calcium, copper, iron, magnesium, potassium, sodium, selenium and zinc from water rather than from food (Davis, Gatlin 1996). Microelements are absorbed from water, which is ingested through the mouth and taken through the gills, skin and fins.

Freshwater fish are at constant risk of overhydration and salt loss in a hypotonic environment. They drink very small amounts of water to compensate for the minerals lost with urine and receive mineral nutrients from water through gills. In contrast to freshwater fish, marine fish have a lower demand for dietary minerals as they absorb most of them from ambient wa-

ter (Cowey 1977). The required dietary supplementation with macronutrients and micronutrients is very difficult to determine, and the amount of nutrients absorbed by fish from water is equally difficult to measure. The interactions between elements should also be described. Due to mutual interactions between ions and chemical compounds, the biological effect of an element is determined by the presence of other ions or chemical substances. Two types of reactions are generally reported: synergism (increased effect) and antagonism (decreased effect). Many authors have observed that phosphates can limit the absorption of most micronutrients by forming insoluble phosphates. Most mineral nutrients reach the heart, liver, kidneys and brain within minutes after absorption. They are then transported to muscles, skin and adipose tissue. This process is slower, and a mineral balance in bodily tissues is achieved within 30 minutes to several hours. Mineral nutrients are distributed throughout the body mainly by the circulatory system. They are carried with the bloodstream to organs and tissues, and excess nutrients are excreted at rates that are determined by the blood flow through bodily tissues. Physiological blood parameters are highly differentiated in fish, and they are determined by individual variation, age, type of farm, diet and season. They can fluctuate widely in healthy fish, which is why physiological reference values are much more difficult to determine in fish than in endothermic animals (Allen 1993, Thomas et al. 1999).

The mineral content of tissues may vary, and mineral concentrations are a species-specific trait. For example, the analyzed fish species are characterized by the following iron levels in bodily organs, in decreasing order (Brucka-Jastrzębska et al. 2009):

- carp: gills>kidneys>blood>liver>muscles>skin;
- trout: kidneys>liver>gills>blood>muscles>skin.

The health status also affects the micronutrient and macronutrient content of fish tissues. Excessive levels of zinc and magnesium are noted in bacterial and viral diseases and when hepatocyte activity is high (Pouramahad, O'Brein 2000, Lushchak et al. 2005). Macronutrient and macronutrient levels in tissues should be monitored to support early detection of pathological changes. The concentrations of mineral nutrients change rapidly and precede behavioral changes and other symptoms of disease (Brucka-Jastrzębska et al. 2009).

This article reviews the literature dedicated to mineral nutrition in fish diets, with special emphasis on the nutritional requirements of two fish species: the common carp (*Cyprinus carpio)* and the rainbow trout (*Oncorhynchus mykiss).* The analyzed macrominerals and trace minerals are presented in Tables 1 and 2, with an indication of their sources (water or feed) and the consequences of mineral deficiency and excess.

Table 1

The effect of selected macronutrients on carp (*Cyprinus carpio*) and rainbow trout (*Oncorhynchus mykiss*)

Nutrient	Requirements		Symptoms of nutrient deficiency		Remarks	References
	carp	trout	carp	trout		
Calcium	calcium deficiencies are not reported when calcium concentrations in water reach 20 mg Ca^{-1}			observed only in a laboratory: lower appetite, retarded growth, lower feed conversion efficiency (if $CaCO_3$ concentrations in water drop below 5 ppm)	limits the absorption of selected nutrients	Ogino, Takeda (1976), Poczyczyński, Woźniak (2014)
Phosphorus	0.5 to 0.8 g 100 g^{-1} feed (when phosphorus concentrations in water reach 0.002 mg l^{-1}) 0.6% of feed (on a dry matter basis)		lower weight gains, lower feed conversion efficiency, skeletal deformations, rib ossification problems, soft pectoral fin radials, skull deformations, more visceral fat	lower weight gains, lower feed conversion efficiency, bone demineralization	decreased absorption of selected nutrients	Ogino, Takeda (1976), Poczyczyński, Woźniak (2014)
Magnesium	0.05-0.07 g 100 g^{-1} feed (at low concentrations in water)		lower weight gains, apathy, lack of appetite, tremor, high mortality, cataract	lower weight gains, lack of appetite, cataract, apathy, kidney calcification, higher mortality, scoliosis, degeneration of muscle fibers and gills		Cowey et al. (1977), Knox et al. (1981), Knox et al. (1983), Ogino, Takeda (1976), Satoh et al. (1983*a*), Satoh et al. (1983*b*)
Potassium	no data	1.1 g 100 g^{-1} feed	no data	lack of appetite, tremor, tetany, death		Davis, Gatlin (1996), Kalantarian et al. (2013)

Table 2

The effect of selected micronutrients on carp (*Cyprinus carpio*) and rainbow trout (*Oncorhynchus mykiss*)

Nutrient	Requirements		Symptoms of nutrient deficiency		Remarks	References
	carp	trout	carp	trout		
Iron	150 μg g^{-1} feed	60 mg kg^{-1} feed	microcytic anemia		toxic at concentrations higher than 1380 mg kg^{-1} feed (trout)	Poczyczyński, Woźniak (2014), Watanabe et al (1997)
Cobalt	0.05 mg kg^{-1} feed (it is generally present in concentrations of 1-6 mg kg^{-1} feed, therefore, additional supplementation is not required)		lower production of vitamin B$_{12}$, which leads to poor health status, reduced appetite, retarded growth, low hemoglobin levels and anemia.		0.1-5 g kg^{-1} feed can lead to hemorrhage in the digestive tract and changes in white blood cells	Watanabe et al. (1997)
Zinc	15-30 mg kg^{-1} feed (at concentration of 10 μg l^{-1} in water)	15-30 mg kg^{-1} feed (at concentration of 11 μg l^{-1} in water) 40 mg kg^{-1} feed (4% calcium phosphate) 80 mg kg^{-1} feed (8% calcium phosphate) 20-40 mg kg^{-1}	lower weight gains, cataract, lack of appetite, higher mortality, skin and fin lesions, higher Fe and Cu levels in the hepatopancreas and intestines	lower weight gains, higher mortality, cataract, fin lesions, dwarfism, compromised immune response	toxic at concentration of 1 mg l^{-1} in water, lower weight gains (carp – more than 300 mg kg^{-1} feed), lower hemoglobin levels, lower hematocrit levels, lower copper concentrations (trout – 1.00 mg kg^{-1} feed).	Satoh et al. (1983a); Satoh et al. (1983b); Satoh et al. (1987) Watanabe et al. (1997)
Manganese	12-13 mg kg^{-1} feed		lower weight gains, dwarfism, cataract	cataract, lower weight gains, dwarfism, abnormal development of caudal fin, low hatch rate		Davis, Gatlin (1996), Satoh et al. (1983a), Satoh et al. (1983b), Watanabe et al. (1997)
Copper	3 mg/kg feed		retarded growth, cataract		toxic at 0.8-1.0 mg l^{-1} in water. At concentration higher than 730 mg kg^{-1} feed, Cu slows down growth and decreases feed conversion efficiency. Symptoms of toxicity: gill damage, necrotic foci in liver and kidneys	Satoh et al. (1983a), Watanabe et al. (1997)
Iodine	no data	2.8 mg kg^{-1} feed 1,1 mg kg^{-1}	no data	hypothyroidism		Poczyczyński, Woźniak (2014), Watanabe et al. (1997)
Selenium	no data	0.07-0.38 mg kg^{-1} (at 0.4 μg l^{-1} in water)	no data	lower weight gains, reduced appetite, lower muscular tone – muscular dystrophy, higher mortality, kidney calcification	toxic at 40-130 μg l^{-1}	Poczyczyński, Woźniak (2014), Watanabe et al. (1997)

MACRONUTRIENTS

Calcium (Ca)

In general, Ca and P co-exist together in bodies of animals, and a deficiency of one nutrient limits the availability of both minerals. 99% of calcium and 80% of phosphorus are stored in bones, teeth and scales. The remaining calcium is widely distributed among various organs and tissues. Calcium is one of the most abundant cations in the body of a fish. It is closely related to the development and maintenance of the skeletal system and participates in several physiological processes, including the maintenance of acid–alkaline equilibrium, osmoregulation, muscle contraction, bone mineralization, blood clotting, nervous signal transmission, maintenance of cell membrane integrity, and activation of several important enzymes. This macronutrient is readily derived from the water and occurs in adequate amounts in most diets consumed by fish. Regulation of Ca influx and efflux occurs at the gills, fins, and oral epithelia. The endocrine control of Ca metabolism in fish is also regulated by hyper- and hypocalcemic hormones. Teleosts possess two hormones with hypocalcemic action: calcitonin, secreted by the ultimobranchial gland, and stanniocalcin (STC), secreted by the corpuscles of Stannius. Symptoms of Ca deficiency were observed only in experimental conditions, and they are rarely detected in natural habitats, where Ca is absorbed from water and food. Fish may be deficient in Ca if $CaCO_3$ concentrations in water drop below 5 mg l^{-1}. KALANTARIAN et al. (2013) compared weight gains in juvenile rainbow trout administered feed with a different Ca content: 0.95%, 1.21%, 1.41% and 1.61%. There were no significant differences observed between the groups, which suggests that main source of Ca is water.

Phosphorus (P)

Phosphorus is a component of various organic phosphates, such as nucleotides, phospholipids, coenzymes, deoxyribonucleic acid (DNA), and ribonucleic acid (RNA). Inorganic phosphates also serve as important buffers to maintain normal pH of intra- and extracellular fluids. In contrast to calcium, the main source of P is diet (DAVIS, GATLIN 1996). The phosphorus requirements of rainbow trout and carp were determined in the range of 0.5 to 0.8 g 0.1 kg^{-1} of feed. The availability of phosphorus is largely influenced by its form and source. Phosphorus absorption is low from rice bran, average from fish meal and high from casein and brewer's yeast, which is due to different forms of phosphorus. The more soluble phosphate salt is, the higher the absorption. Acidic Ca, Na and K phosphates are characterized by high availability. Fish with less active gastric juices (thermophilic species such as the carp) absorb dietary P less efficiently (TACON 1987). In general, the bioavailability of phosphorus is positively correlated with the solubility of the mineral in water. For rainbow trout, monobasic phosphates of sodium and potassium are highly available (90 to 95%) sources of phosphorus. For com-

mon carp, the bioavailability of phosphorus from a diet is more variable, ranging from 13% (tribasic calcium phosphate) to 94% (monobasic calcium phosphate). Some nutrients affect the availability of certain minerals. For example, large intakes of iron, aluminum and magnesium may reduce the absorption of phosphorus by forming insoluble phosphates (DAVIS, GATLIN 1996).

Magnesium (Mg)

Magnesium is essential for maintenance of intra- and extracellular homeostasis of fish. Fish absorb magnesium supplied with water through gills or from the gastrointestinal tract. Research has demonstrated that Mg concentrations of 46 mg l^{-1} in water are sufficient to meet the rainbow trout's demand for this nutrient. At Mg concentrations of 1 to 3 mg l^{-1} in water, fish feed should be supplemented with magnesium at 0.025 to 0.07%. Seawater contains high levels of Mg (1350 mg l^{-1}), which is absorbed directly from water, and therefore this element does not have to be additionally supplemented in feed. The majority of nutrients, in particular those of plant origin, are a rich source of Mg and fully meet the demand for this mineral in fish (DAVIS, GATLIN 1996). Higher levels of magnesium in blood plasma were observed in fish from water rich in this element (KOPP et al. 2013). Magnesium in fish meal is characterized by low availability (WATANABE et al. 1988), and selected commercial feeds may not fully satisfy Mg requirements of fish. Dietary magnesium deficiency signs include poor growth, anorexia, lethargy, muscle flaccidity, convulsions, vertebral curvature, high mortality, and depressed magnesium levels in the whole body, blood serum and bone (DAVIS, GATLIN 1996).

Sodium, potassium, chlorine (Na, K, Cl)

Sodium, potassium and chlorine levels in water are generally sufficient to meet fish's basic nutritional requirements, but fish diets should be characterized by optimal Na, K and Cl concentrations for the optimal growth and development. In a study on juvenile rainbow trout, the highest weight gains were observed in a group whose diet was supplemented with 1.1% K. The lowest weight gains were noted in fish fed diets with the addition of 0.9% and 1.3% K (KALANTARIAN et al. 2013). Symptoms of potassium deficiency, such as poor appetite, tremor, tetany and death, are rarely reported. Symptoms of Na and Cl deficiency are not observed. However, at low pH, Na and Cl intake through gill epithelium is decreasing, and absorption of these elements from a diet is higher (KOPP et al. 2013).

Dietary levels of K significantly influence the growth of fish. NaCl supplementation can also create additional benefits. NaCl supplements stimulate the Na/K pump activity in gill microsomes and facilitate adaptation to new environments. Higher chloride concentrations in water protect fish against the harmful effects of nitrates (KRUPOWA et al. 2005). In fish farms with

water recirculation systems, chloride concentrations are increased to produce the above effect.

MICRONUTRIENTS

Iron (Fe)

Iron is a highly dispersed element in nature, and it is mobilized during rock weathering. Iron concentrations in water vary considerably due to the influence of numerous factors. Iron levels are determined at 0.06-44 μg l^{-1} in saltwater and 10-1400 μg l^{-1} in fresh water. Iron compounds are highly soluble in water with pH<7, but they are readily oxidized and precipitated as oxides in surface water. Colloidal iron oxides play an important role in the sorption and coagulation of other colloidal substances and ions, in particular trace metals. In river water, Fe binds to other compounds, and in saltwater with high pH, it is accumulated in bottom deposits. Iron concentrations in animal tissues range from XO to XOO ppm, and sea organisms may contain more iron. Natural water resources are a poor source of iron, and the element has to be supplied with food. Iron is essential for life, being involved in oxygen transfer, respiratory chain reactions, DNA synthesis, and immune function. Iron can be absorbed through gills, and the addition of iron sulfate has been found to stimulate growth and increase hemoglobin levels. Fe^{2+} ions are more bioavailable than Fe^{3+} ions. Reducing substances such as vitamin C increase Fe absorption, not bound to heme (TACON 1987). There are no mechanisms that control Fe excretion, but iron absorption is strictly regulated to balance Fe levels in the body (SHI, CAMUS 2006). The nutritional value of waterborne iron compared to dietary iron has not been elucidated, but the gills may play a vital role in iron homeostasis at times of developmental need, for example after yolk-sac absorption and prior to feeding (BURY et al. 2003). When dietary levels of Fe are low, more iron is absorbed from water, and up to 85% of Fe can be supplied through gills (COOPER, BURY 2007). Higher levels of iron in water leads to elevated level of this element in blood plasma. This proves that ambient water can be a source of iron for fish (KOPP et al. 2013).

An iron overdose can have adverse effects, including retarded growth, higher mortality, diarrhea and liver damage (iron levels higher than 1.380 mg kg^{-1} feed are toxic for trout).

Cobalt (Co)

Its main role is to be an intrinsic part of vitamin B$_{12}$ (cobalamin). Fish are not capable of synthesizing this vitamin and are therefore dependent on bacterial production of this essential compound. Cobalt is absorbed from water through gills or ingested with food. Cobalt absorption from water incre-

ases with a rise in water temperature and decreases with a rise in Ca levels (COMHAIRE et al. 1994, 1997). A study on the carp has revealed that in fish fed diets without additional supplementation, the highest Co concentrations are noted in the kidneys, followed by the stomach, liver and gills. At higher dietary concentrations of Co, its levels increased in the kidneys and liver, and when the recommended dietary allowance was exceeded, Co concentrations increased in the stomach, kidneys, gills and liver. The above results suggest that cobalt undergoes homeostatic regulation and that the highest dietary doses can exceed the healthy range in tissues (MURKHERJEE, KAVIRAJ 2009). Dietary Co supplementation increases weight gains, improves hematological parameters (higher red blood cell counts) and survival of hatchlings, and it stimulates protein synthesis (WATANABE et al. 1997). MURKHERJEE and KAVIRAJ (2009) demonstrated that supplementation of carp diets with 0.1% to 1.0% cobalt improved weight gains. Higher weight gains without additional cobalt deposition in tissues were reported at 0.1% supplementation, whereas high levels of supplementation (1%) increased cobalt accumulation in various tissues. Very high doses of dietary cobalt (0.1-5 g kg^{-1} feed) can contribute to hemorrhage in the digestive tract and changes in white blood cells (WATANABE et al. 1997).

Zinc (Zn)

Zinc is essential due to its vital structural and catalytic function in over 300 proteins that play important roles in fish growth, reproduction, development, vision and immune function (BURY et al. 2003).

Fish absorb Zn from water and food, but dietary Zn is more bioavailable. Absorption from water can be increased up to 50% in some cases, e.g. when a diet is deficient in this element. Also, absorption from food decreases if the water concentration of Zn is very high (NIYOGI et al. 2007). Gills may act to supplement absorption when required. Ca and P reduce the absorption of Zn by binding it to insoluble phosphate complexes that are not absorbed from intestines. The bioavailability of zinc from feeds containing phytates and calcium phosphate is low, and its dietary levels should be increased through supplementation (TACON 1987). When zinc was supplemented at 20 mg kg^{-1} feed, the highest weight gains were observed in fish fed zinc sulfate, and the lowest gains occurred in fish fed zinc chloride (WATANABE et al. 1997).

Zn is not abundantly stored in tissues because it is absorbed mainly through gills, where the highest zinc concentrations are found. Changes in tissue concentrations of Zn can be attributed to this element's affinity to the membranes of erythrocytes and serum proteins participating in its transport. Zinc is characterized by low toxicity, and its negative influence on the body is mainly due to secondary copper deficiency. Zinc absorption is determined by feed quality and interactions with other elements. Zinc is a major antagonist of Cd and Cu, and zinc absorption can also be reduced by Ca and Mg (BRUCKA-JASTRZĘBSKA et al. 2010).

Excessive Zn levels decrease weight gains (in the carp, weight gains decrease when Zn concentrations exceed 300 mg kg^{-1}), hemoglobin levels, hematocrit levels and Zn concentrations (at 1000 mg kg^{-1} in the trout). Symptoms of poisoning may be observed already at very low Zn levels of 1 mg l^{-1} water (Watanabe et al. 1997). Hardness of water (i.e. water Ca^{2+}) offers a protective effect against waterborne zinc toxicity (Bury et al. 2003).

Manganese (Mn)

Manganese can be absorbed from water through gills, but dietary manganese is more bioavailable for fish. Its availability is limited at high concentrations of Ca and in the presence of phytates (Watanabe et al. 1997). In dietary supplements, Mn is more available when supplied in the form of manganese sulfate or manganese chloride than manganese carbonate (Satoh et al. 1987). Higher weight gains, increased protein synthesis and decreased lipid synthesis in the liver were observed in carp whose diet was supplemented with manganese sulfate (Watanabe et al. 1997).

Copper (Cu)

In fish, the demand for copper is met mainly from dietary sources, but copper is also absorbed directly from water. When adequate amounts of Cu are supplied with feed and water, 10% of copper requirements are met through absorption across the gill epithelium. When dietary concentrations of Cu are insufficient, gill absorption is intensified to cover up to 60% of demand. When dietary Cu is overdosed, gill absorption drops below 1% (Miller et al. 1993, Kamunde et al. 2002). The majority of feeds and water are adequate sources of Cu, but Cu requirements are largely determined by the physiological state of fish and the concentrations of Zn, Fe, Cd and Mo, which are antagonists of Cu (Watanabe et al. 1997). Copper is found in all types of water and it concentration ranges from 0.X to X000 µg l^{-1}. At present, Cu concentrations of 1-2 µg l^{-1} are rarely encountered in rivers. Copper levels fluctuate subject to geological conditions and anthropogenic pollution. Copper accumulated in bottom deposits is a potent indicator of pollution caused by human activities. The discussed element can be transported to underground water resources. Excessive Cu levels in water are highly detrimental to self-cleaning mechanisms. Cu concentrations of 20 µg l^{-1} in acidic soft water and 250 µg l^{-1} in hard alkaline water can be toxic to trout (Hellawell 1988).

An overdose of Cu retards the growth and reduces feed conversion efficiency and hematocrit levels (at 730 mg kg^{-1} Cu in trout). Cu concentrations of 0.8-1.0 mg l^{-1} water are toxic, but pathological symptoms appear only at very high levels of Cu supplementation (feed containing 600 mg kg^{-1} Cu did not exert a harmful impact on rainbow trout). Adverse effects of copper are mitigated by gastric mucosa, which acts as a barrier to toxic metals (Handy 1993). Dietary levels of Cu higher than 730 mg kg^{-1} inhibited the growth and decreased feed intake. A copper overdose can also lead to gill damage and

the appearance of necrotic foci in the liver and kidneys (WATANABE et al. 1997).

In view of the growing risk of copper deposition in fish meat and the resulting threat to human health, the European Union set maximum levels of copper in fish feed at 35 mg kg^{-1} (LUNDABYE et al. 1999).

Iodine (I)

Iodine is found in all animal tissues, and sea organisms are particularly rich in this element. Iodine is easily absorbed from food, water and air. It is a mobile element, which is not accumulated in the body. Up to 80% of absorbed iodine is transported to the thyroid gland. Iodine levels in the blood of freshwater fish range from 0.5 to 2000 µg l^{-1} (WATANABE et al. 1997). They are determined by iodine concentrations in feed, water and tissues as well as the ability of blood proteins to bind this element. Triiodothyronine (T_3) is the major thyroid hormone and an active precursor of thyroxine (T_4). Fish differ from mammals in their utilization of iodine and extrathyroidal metabolism of T_3 and T_4 (WATANABE et al. 1997). T_3 binds more strongly to blood proteins than T_4, and its plasma levels are lower in comparison with T_4. Both T_3 and T_4 are evacuated mainly with bile, but also through gills and kidneys (WATANABE et al. 1997). Iodine absorption is determined by physiological and dietary factors, and a secondary deficiency is not always associated with low iodine doses. Se and Fe as well as As, Co, Cu, Ca and Mn affect thyroid functions, decrease iodine absorption or disrupt iodine metabolism. Iodine-deficient feed and feed ingredients that promote goiter formation, such as rapeseed, are harmful to farm animals. Hyperthyroidism (goiter) induced by iodine deficiency is more frequently observed in carnivorous than herbivorous and omnivorous fish (WATANABE et al. 1997). Excessive dietary intake also leads to thyroid dysfunction. In animals, symptoms of iodine overdose include mucosal inflammation, cell necrosis and iodine allergy. In iodine intolerance, even small doses of iodine lead to skin changes and mucosal inflammation. In a laboratory experiment, rainbow trout absorbed 80% of iodine from water, 19% from feed and less than 1% from decomposition of thyroid hormones. High Ca concentrations in water and high Co intake inhibit iodine absorption. Saltwater is more abundant in iodine, which is why saltwater fish are rarely deficient in this element. Fish feed should be supplemented with minimum 2.8 mg kg^{-1} I (WATANABE et al. 1997). Iodine requirements are significantly determined by stress exposure as well as the age and physiological condition of fish.

Selenium (Se)

Fish absorb selenium from both water and feed. Selenium is ingested in much larger quantities with water through gills, and it is stored in various tissues, excluding the liver, in the inorganic form. Dietary selenium is accumulated in the organic form, but the threshold between healthy and toxic

selenium concentrations is relatively narrow. Symptoms of toxicity are observed at 13-15 mg Se kg^{-1} feed or 40-130 µg Se l^{-1} water. In water, selenium levels generally remain below 0.1 µg l^{-1} (WATANABE et al. 1997).

DISCUSSION AND CONCLUSIONS

Water parameters such as temperature, pH, nitrate and nitrite concentrations, and dissolved oxygen levels are regularly monitored in fish farms. In contrast, macronutrient and micronutrient levels are rarely controlled in fish breeding practice. Nutrient concentrations in water provide vital information about supplementation needs. Many breeders supplement fish diets without analyzing nutrient levels in water. This approach can be detrimental to fish health because selected elements, when overdosed, can interact with one another and produce toxic effects. Fish are physiologically adapted to absorb various elements from water, and the information about nutrient levels is vital when planning mineral fertilization of ponds in fish farms. The differences in the tissue composition of fish from various regions could be attributed to differences in the mineral content of water and/or feed. Mineral nutrition is an important consideration in disease prevention, health maintenance and livestock production. It is a crucial element of good farming practice and the content of mineral nutrients determines the quality of food products. Water parameters change seasonally, also in the smallest water streams, drainage ditches and ponds in fish farms (BOJARSKI et al. 2014). Those variations are often determined by changes in the flow of effluents and run-offs, and they are particularly important for the carp in spring months and for the trout in summer months. Mineral metabolism disorders can compromise immunity, oxidative potential, tissue and organ functions. In farms, many health problems are reported on a seasonal basis, including bacterial infections caused by *Aeromonas* sp., *Pseudomonas* sp. and *Flavobacterium* sp. (own observations). To address those issues, attempts are made to identify predisposing factors in etiopathogenesis. Many minerals are absorbed across gills, therefore nutrient concentrations should be monitored in pond water to prevent mineral deficiencies that could adversely affect the health and well-being of fish. Research findings revealed that mineral concentrations decrease in all tissues of fish suffering from disease. This article discusses the nutritional requirements of two fish species: the carp and the rainbow trout. The examined species thrive in different habitats. Carp ponds are characterized by a highly structured biocenosis and stable mineral composition, whereas trout ponds are supplied with river water distinguished by high levels of biocenotic (including mineral) variation. Critical biological processes have to be monitored individually in fish farms for health protection. The quality and processing suitability of farmed fish are largely determined by their origin (own observations). Fish reared in farms that are supplied with hard and

highly ionized water are more valued (unpublished data). Organic matter is decomposed in rivers and ponds, and it is a source of mineral nutrients in water. The chemical composition of water is largely determined by rock weathering, precipitation levels, composition of rainwater and distance from the sea or ocean. The seasonal nature of changes in water composition is influenced by water flows, precipitation and biological activity in the watercourse. The ionic balance of water is influenced by carbon dioxide, carbonic acid, bicarbonate and carbonate ion buffering systems. Buffering systems stabilize pH, which is difficult to achieve in waters that are diluted or deprived of buffering ions. Such waters have a low biological value. Chemical composition of water also varies and has to be adjusted in fish farms. Balanced feed can limit the influence of seasonal variations on fish health. In a field study by SIEMIANOWSKA et al. (unpublished data), no significant differences were reported between micronutrient concentrations in water and the muscle tissue of rainbow trout reared in various types of farms in Poland. The above results testify to high quality of fish feed and high availability of nutrients. The study was conducted in periods of stability in aquatic habitats, when disease prevalence in fish is very low. Guidelines for nutrient supplementation in periods marked by high risk of disease and during disease have not been formulated thus far.

CONCLUSIONS

This article was written by ichthyology experts who have many years of experience in clinical diagnosis, prevention and treatment of fish diseases. The information presented in the paper supports the formulation of the following conclusions:

1. Health protection programs in fish farms should rely on detailed and regular analyses of the water environment, early identification of threats and changes in the concentrations of mineral nutrients.

2. In the event of an outbreak of disease, mineral metabolism disorders should be monitored and fish diets should be supplemented to address any nutritional deficiencies.

3. Comprehensive health protection programs should be developed in fish farms to promote fish welfare and guarantee high quality of the final product.

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