Factors affecting feeding of fish cultivated in recirculation aquaculture system: A review

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Abstract. Recirculation systems are characterized by high intensity of production processes and are classified as super-intensive technologies. The normal operation of the recirculation systems is unthinkable without constant monitoring of the main parameters of the water and the technical condition of the various facilities. The main requirement when cultivating fish in a recirculation system is that the water meets certain quality indicators. Of these, the most important are temperature, amount of dissolved oxygen, pH, hardness, biogenic elements, etc. An important element is the quality of the feed. It supplies the necessary nutrients for the growth of fish. The size of the granule should be matched to the size of the fish. The feed should be easy to consume. Of particular importance are the correct amount and the right time of feed administration. Feeding frequency is affected by the amount of feed consumed in one day and it is very important to manage the feeding process in fish because it affects growth, survival, feed conversion ratio, water quality as well as profit. Nutrition is a powerful modulator of the endocrine system governing the feeding behavior and growth of fish. Food availability and feed composition are two of the most influential external factors modulating hormones, regulating appetite, and modulating growth. The provision and setting of optimal conditions specific to the cultured species are of primary importance for successful cultivation in aquaculture. It is through the application of scientific developments in this regard that fish farmers will be able to optimize management practices and provide micro environments for better food intake and utilization.

Key Words: hormones, hydrobionts, nutritional, water quality.

Introduction. One of the fastest growing production sectors in the world is aquaculture. The success of aquaculture depends on providing an optimal environment for rapid growth with minimal expenditure on resources and capital. Recirculation systems are characterized by high intensity of production processes and are classified as super-intensive technologies. Recirculation systems are state-of-the-art fish production facilities that provide optimal conditions for a continuous cycle of growth. At the same time, they are expensive facilities, in terms of construction and normal operation, which makes it necessary to farm fish with a high market price. In general, their essence is expressed in the repeated use of water and the application of various measures to improve its quality. In these systems, all methods for improving the quality of water are applied - temperature regulation, increasing the amount of dissolved oxygen, mechanical and biological treatment, passing the water through a denitrifying unit and others. The processes are fully mechanized and automated, and in most cases, the management of production processes, including water parameters, is carried out by computer systems. The obtained yields of fish are very high, but the production costs are significant, which is why expensive delicacy fish species (eels, sturgeon species, white fish, etc.) are grown in recirculation systems (RAS). The normal operation of the recirculation systems is unthinkable without constant monitoring of the main parameters of the water and the technical condition of the various facilities. A high degree of automation has been introduced, which allows all important water parameters and the operation of the various machines to be monitored. Any deviations are promptly registered and measures are taken for their immediate elimination. The main requirement when cultivating fish in a recirculation system is that the water meets certain quality indicators. Of these, the most important are temperature, amount of dissolved oxygen (DO), pH, hardness, biogenic elements, etc. In fish farming, a significant part of the various technological operations aims to optimize the quality indicators of the water in order to create the best conditions for the development and optimal growth of fish (Verma et al 2022). Optimal nutrition schemes to improve the growth, water quality, survival, size uniformity ultimately increase production (Dwyer et al 2002; Isyagi et al 2009). Growth potential differs between different fish species and it is highly dependent on many factors. Furthermore, the extent to which growth potential is realized is highly dependent on food intake and how well the feed has been adjusted to the nutritional needs of the fish (Eriegha & Ekokotu 2017). Profitability in aquaculture depends on a proper feeding strategy. Important elements are the quality of the feed to supply the necessary nutrients for the growth of fish, the size of the granule, which should be matched to the size of the fish, ease of consumption and decrease the quantity of wasted feed. Of particular importance are the correct amount of feed and the right time to eat. While for domestic animals on a farm excess feed can be removed, in fish farming this practice is difficult to implement. This leads to reduced fish growth, loss of valuable feed nutrients, deterioration of water quality (Makori et al 2017). The result is reduced profitability and eventual fish mortality. A very important factor in good feed utilization by fish is water quality management. When planning high production aquaculture, attention should be paid to this important factor. The set of physical, biological and chemical parameters of water influence the growth and welfare of cultured hydrobionts. Water quality affects the total state of the cultured organism, as it determines the health and growth conditions of the cultivated hydrobiont. Aquatic organisms need a wide range of physical-chemical and biological conditions and have certain requirements for the environment that surrounds them (Bhatnagar & Devi 2013). The physical factors are temperature, light, color and transparency of the water, and the chemical ones are the gas mode, oxidizability, the salt composition of the water, etc. Important water quality variables that affect feed intake are physical, chemical, biological, and nutritional. The aim of this review was to retrace the effects of different factors on the feeding of fish cultivated in recirculation aquaculture systems.

Water Temperature. Water temperature and its dynamics are essential for the life of fish. As poikilothermic organisms with a considerably varied internal temperature, their vital activity and growth are directly related to its values. It directly affects the intensity of feeding, the rate of metabolism and the reproduction of a given species. From the point of view of fish farming, the temperature of the water has a direct effect on the activity of feeding and the full utilization of the received food, which is expressed in intensive growth in the farmed fish. The three important factors influencing fish growth are feeding rate, water temperature and fish size (Gardeur et al 2007). Water temperature is a major factor in aquaculture farming practices and has a major impact on feeding rates. Each fish species is characterized by an ideal temperature range at which it exhibits maximum growth (Person-Le Ruyet et al 2006; Bjornsson et al 2007; Oyugi et al 2011). Several studies have shown that specific water temperatures provide faster growth in pike perch (*Sander lucioperca*) at 20 to 25°C (Molnar et al 2006; Ronyai & Csengeri 2008; Schulz et al 2008). At low temperature, fish become sluggish, slowing down the rate of digestion (Bailey & Alanara 2006). Research has found that the rate of digestion increases with increasing temperature (Turker 2009). Temperature affects the behavior and physiological process of aquatic animals (Xia & Li 2010). In most species, there is a direct relationship between temperature and the rate of embryonic and post-embryonic development of individuals. The higher the temperature, the faster their development, i.e. fewer days are needed to reach a certain stage of ontogenesis. Water temperature is among the most important variables affecting the vital functions of fish (Kasumyan & Doving 2003). It affects the growth rate, feed intake, feed conversion efficiency. In general, there is a decline in feed intake as the upper limit of thermal tolerance for growth is approached. Temperature affects the secretory activity of digestive juices (through its effect on food absorption), gastrointestinal motility, digestive enzyme activity, and the rate of digestion and absorption (Kapoor et al 1976). At a reduced water temperature, fish do not feed optimally. Therefore, it is recommended to stop feeding at temperatures above and below optimal levels. For example, in warm water, feeding is optimal at temperatures between 25–32°C (Boyd & Lichtkoppler 1979). Recirculating systems offer a greater opportunity for environmental control compared to traditional culture systems, and year-round temperature conditions are maintained for enhanced fish growth performance. The optimized RAS environment, however, might also provide multiple maturation triggering cues for Atlantic salmon (*Salmo salar*) (Good & Davidson 2016). For example, relatively warm, consistent water temperature, characteristic of RAS, supports accelerated fish growth (Handeland et al 2008; Thorarensen & Farrell 2011; Ignatz et al 2020) and increase condition factor and lipid reserves (Peterson & Harmon 2005) that correlate with increased maturation (Fjelldal et al 2011; Imsland et al 2019; Good & Davidson 2016).

Light Regime. The light regime in recirculation systems is closely related to the reproduction of aquatic organisms. The gas regime of the water bodies is of decisive importance for the life of fish. Larger quantities of some of the gases dissolved in the water have a positive effect on the development and growth of aquatic organisms, while others have a negative, and sometimes even fatal, effect. Gases dissolved in water are mainly oxygen, nitrogen, carbon dioxide, hydrogen sulfide, etc.

Photoperiod and light regime affect feeding activities of fish species. Photoperiod plays a significant role in fish growth and survival, thereby influencing food intake and feeding behavior (Nwosu & Holzlöhner 2000). Light regime affects the general well-being and routine of fish (Adewolu et al 2008).

The photoperiod and light concentration for different fish species is specific and differs between developmental phases (Nwosu & Holzlöhner 2000). Thus, photoperiod, when applied appropriately, can help increase fish productivity, thereby improving the productivity and sustainability of aquaculture practices. For example, when *Clarias gariepinus* was cultivated under three different photoperiod conditions: 24 h of darkness, 24 h of light, and 12/12 h of darkness and light, it was found that those cultivated under 24 h of darkness had significantly higher food intake, the best feed conversion ratio and the lowest amount of uneaten feed compared to those cultured under 24 h light and 12/12 h dark and light (Adewolu et al 2008). In an experiment with *Lophiosilurus alexandri*, it was found that 24 h of continuous light resulted in the highest food intake (Kitagawa et al 2015). In a study conducted on sea bream (*Diplodus puntazzo*), it was concluded that, although feeding behavior is strictly diurnal, 97% of food requirements are made during light periods (Vera et al 2006). This shows the great importance of photoperiod and influence on feed intake and feeding behavior of fish.

Dissolved Oxygen. Several water quality variables play an important role: temperature, suspended solids, DO concentrations, ammonia, nitrite, carbon dioxide and alkalinity. The most important and critical parameter requiring continuous monitoring in recirculation systems is DO. This is due to the fact that the aerobic metabolism of fish requires DO (Timmons et al 2002). A major factor affecting food intake in cultured fish species is reduced oxygen concentration (Morkore & Rorvik 2001; Nordgarden et al 2003). For successful fish production, there must be good oxygen management in the system. Oxygen is important for breathing and maintaining healthy fish, for bacteria that break down the waste produced by fish and for meeting the biological need for oxygen within the culture system (Dabrowski et al 2004). When the oxygen level is maintained close to saturation or even slight super saturation all the time, it will increase growth rates, reducing feed conversion ratio and increasing total fish production (Thorarensen et al 2017). The health and physiological condition of cultured fish is best if dissolved oxygen is closer to saturation. When levels are lower than those mentioned above, fish growth can be greatly affected by increasing stress, tissue hypoxia, reduction of active swimming and lowering of immunity to diseases (Espmark & Baeverfjord 2009). The required oxygen level depends on the species, the size of the fish and fish activity. In recirculating systems, lethargy and refusal of food is an indicator of poor oxygenation (Ovie & Adeniyi

1990). In a study by Randolph & Clemens (1976) on the relationship between oxygen saturation and food intake of fish, they found that the feeding pattern of channel catfish (*Ictalurus punctatus*) varies with temperature and oxygen availability. When the oxygen content falls below 59%, the fish begin to lose their appetite. In rainbow trout (*Oncorhynchus mykiss*), Jobling (1995) found a decrease in fish appetite when oxygen saturation fell below 60%. Similar results were obtained for European sea bass (*Dicentrarchus labrax*) (Thetmeyer et al 1999), blue tilapia (*Oreochromis aureus*) (Papoutsoglou & Tziha 1996), channel catfish (*Ictalurus punctatus*) (Buentello et al 2000), young turbot (Pichavant et al 2001) and common carp (*Cyprinus carpio*) (Bernier et al 2012), which showed reduced growth when exposed to low oxygen levels. The oxygen content is the main indicator of its qualitative characteristics, and its amount is directly related to temperature. There is an inversely proportional relationship between the two indicators. As a rule, as the temperature increases, the amount of DO in the water decreases. Individual fish species show different sensitivity to oxygen deficiency. Some of them, such as tench (*Tinca tinca*), can withstand a DO of 0.3 mg L^{-1}, and carp die of asphyxia (death caused by lack of oxygen) below 5 mg L^{-1} (Svobodova & Kolarova 2004). Other species, such as trout, need more oxygen and die at significantly higher values of this indicator. The crucian carp (*Carassius carassius*) is very resistant to oxygen deficiency, as it produces it itself through anaerobic metabolism (Dahl et al 2021). The African catfish is highly resistant to low oxygen content, due to the ability to breathe atmospheric air. This is one of its qualities, which in recent years has made it a desirable object of aquaculture. Fish in almost all cases react to oxygen deficiency in the same way: they swim slowly to the surface, with their mouths open and gulp air. Special sensors are installed in the recirculation systems, which signal when there is a danger of oxygen deficiency. Water degassing is considered a mandatory process in recirculation systems, during which the gases accumulated in it are released, most often carbon monoxide and nitrogen (Karimi et al 2020). Their accumulation in the water negatively affects the health of the fish.

The aeration of the water is important for the successful functioning of any recirculation system. Due to the breathing of the fish, when it passes through the baths, the amount of oxygen decreases by about 70% (Summerfelt et al 2000). During aeration, i.e. when a certain amount of oxygen is added, the saturation is over 100%. A very important element in recirculation systems is the ultraviolet irradiation of water, which is carried out with special lamps. They emit light of a certain wavelength, which destroys pathogenic bacteria and single-celled organisms. Sometimes, ozone produced by special ozonators is used for the same purpose as for water aeration. The reduction of oxygen in the water leads to poor fish nutrition, reduced growth, vulnerability to disease and parasite infestation as well as mortality (Bhatnagar et al 2004). DO levels above 5 ppm are essential to maintain good fish production (Bhatnagar & Singh 2010). A study on the influence of oxygen on the feeding and growth of various fish species showed that the fastest growth rate occurred in tanks with high DO, and the slowest in tanks with low oxygen concentration (Colt & Watten 1988). The metabolism of fish is extremely dependent on the concentration of DO available in the growing environment.

The pH. An important indicator of the quality of water is its active reaction (pH) or the so-called hydrogen indicator, which is used as a measure of the acidity or alkalinity of a given aqueous solution. It has been established that the vital activity of fish proceeds normally within certain limits of the hydrogen indicator. The most suitable for them are waters with a neutral and slightly alkaline reaction (pH=7-8) with a slight fluctuation in one direction or another (Boyd et al 2011). Acidic waters adversely affect the vital functions of a large part of fish, and this applies mostly to respiration, metabolism and growth rate. At a pH below 5 and above 10, the life of most cultured fish is in danger and measures must be taken to normalize the pH values (Boyd et al 2016). Usually, in recirculation systems, as a result of nitrification processes, the values of the hydrogen index decrease, which necessitates its adjustment by adding an alkaline source. It is also necessary to ensure a constant circulation of water. Any stoppage of circulation in this type of production system is fatal and within hours the fish will die. This determines the special selection of the pumps that are installed, and reserve options are also provided.

Ammonia Concentration. In recirculation systems, management methods must be in place to control ammonia. The most important of them are: the use of feed that does not contain more protein than necessary; conservative administration of feed; avoiding uneaten feed; achieving a low feed conversion ratio and preventing low DO concentrations (Milne et al 2000). Biofilters are used to remove ammonia nitrogen from water through nitrification in recirculation systems. DO in biofilters needs to be maintained at concentrations above 3-4 mg L^{-1} to avoid a reduction in nitrification rates. The amount of ammonia is closely related to the mineralization of nitrogen compounds, which is carried out under the action of microorganisms in anaerobic conditions. It has a negative effect on fish and above certain amounts (0.2-1 mg L^{-1}) it is toxic to many of them (Brinkman et al 2009).

Ammonia is highly toxic to fish and other aquatic organisms (Riche & Garling 2003). Ammonia concentrations in water have a marked and predictable effect on feed intake. The increased level of ammonia in the water leads to reducing food intake in cultured fish (Haskell 1959). Ammonia level in a recirculation system depends on temperature, type of feeding, feeding rate and fish size. The concentration of ammonia in water begins to increase a few hours after a meal, but peaks at 4-6 h Randall & Tsui 2002).

During the management of the cultivation process, the relationship between nutrition and water quality is very important because they influence each other (Ani et al 2013). The management of the production process and environment play an important role in feed intake and efficiency. Management factors in relation to nutrition and physicochemical properties of water for cultivation have a significant impact on food intake for the fish, as they can affect the physiological state of the fish, like stress and neuro-endocrinological imbalance (Wynne et al 2005).

Feeding Frequency. The main sources of energy and structural substances in the body of fish are carbohydrates, proteins and fats, from the food they consume. The fodder also contains various mineral substances and vitamins that affect various physiological processes in their body and are essential for normal functioning.

The effectiveness of taking different foods is directly dependent not only on their nutritional value, but also on their digestibility. The nutritional value of feeds is determined by their ability to supply and satisfy the fish's needs for plastic and energy substances. On the other hand, in order to digest the foods themselves, they must possess the property of digestibility, i.e. under the action of the separated digestive juices to dissolve and resorb through the walls of the digestive canal. High-quality feed mixtures, in addition to a suitable composition, also have a high digestibility of their structural substances, which for a given food is influenced by a number of factors, such as the species of fish, age, environmental factors, the volume of the ration, the frequency of feeding, and others.

Feeding frequency refers to the number of times in a day that fish are fed in a recirculation system (Riche & Garling 2003). Feeding intervals must be optimally matched because the fish will continue to eat the available food up to the available stomach space and duration to empty stomach contents. The stomach empties at a rate that depends on temperature, fish weight and quantity of feed consumed. Feeding frequency is affected by the amount of feed consumed in one day and it is very important to manage the feeding process in fish because it affects growth, survival, feed conversion, water quality as well as profit maximization (Jobling 1995; Goddard 1995; Ali et al 2005; Davies et al 2006; Ndome et al 2011; Jamabo et al 2015).

For successful cultivation in aquafarms, one of the most important factors is the optimal feeding rate. This is especially true for young fish because of their susceptibility to overfeeding and underfeeding, which can cause disease or mortality. When fish are under- or over-fed, feeding efficiency and growth can decrease and in this situation fish production costs increase and water quality can deteriorate due to overfeeding (Dwyer et al 2002). Optimal feeding rate as well as feeding frequency depend on fish species, size and rearing system (Cho et al 2003). For example, in pikeperch (*Sander lucioperca*), maximum growth was found when feed was supplied in a saturated state (Nyina-Wamwiza et al 2005; Schulz et al 2008).

Hormones. The energy required to maintain biological processes supplied by food intake involves the integration of exogenous and endogenous factors. This is accomplished by the endocrine system, which secretes hormones and regulates cell activity by transferring information between organs. The main organs that secrete hormones involved in appetite regulation are the brain (hypothalamus) and gastrointestinal tissues.

Growth hormone (GH) in fish is involved in almost all physiological processes, including osmotic balance, lipid, protein and CHO metabolism, reproduction and growth. Studies have shown that GH also affects behavioral aspects such as appetite (Johnsson & Bjornsson 1994) and food seeking (Abrahams & Sutterlin 1999) in rainbow trout and transgenic Atlantic salmon, respectively. In fish, GH is released from the adenohypophysis in response to signals from the hypothalamus and exerts its effects on target tissues (Reinecke et al 2005).

The role of nutrition is a powerful modulator of the endocrine system governing the feeding behavior and growth of fish. Food availability and feed composition are two of the most influential external cues modulating hormones, appetite, and growth. Research should therefore be focused on hormonal knowledge and the study of their use to improve fish nutrition and growth. This will lead to an increased yield of the cultured fish (Bertucci et al 2019).

It has been established that several hormones in fish have influence on food intake. A number of fish species stop feeding during the reproductive season. Such periods associated with changes in eating behavior arise in connection with reproductive cycles (National Research Council 1987). Hormones can indirectly affect hunger by affecting the secretion of other hormones or inducing changes in the levels of various plasmas nutrients (Fletcher 1984). Steroid hormones (both androgens and estrogens) have been shown to suppress or increase appetite in fish while altering plasma nutrients (Ince et al 1982). Effects of hormones on food intake in most cases can be attributed to four types of mechanisms, with each hormone acting on one or several (Le Bail & Boeuf 1997). Firstly, hormones can have a direct effect on the central nervous system, related to food intake behavior. The second is an indirect effect that can occur through the gut, which slowly strands it through the gastro in tract and causes bloating. The third is an indirect effect through direct action on intermediate metabolism through glucose, free fats, aminoacids. The fourth action is indirect through direct change or indirect secretion of other hormones involved in the control of food intake. On some of these hormones (cholecystokinin, peptide tyrosine tyrosine, glucagon, adrenaline) that regulate food intake act short-term factors that are most often inhibitory. On the other hand, hormones such as growth hormone, thyroid hormones and leptin require more time to change eating behavior and act as regulators of calorie storage. Research conducted by Chua & Teng (1980) proved that using bovine growth hormone in fish (*Epinephelus salmoides*) significantly improved feed intake and increased growth, as at the same time production costs were reduced.

Physiological Status of the Fish and Feed Intake. Depending on the physiological status, feed intake will vary within a species. Feed intake may decrease before and during spawning (Hepher 2009). It has been established that feed intake per unit of body weight decreases with increase in body weight and increases with increase in water temperature for a given species of fish (Anderson & Fast 1991). Food intake decreases under stressful conditions such as hypoxia or high ambient ammonia levels (Kaushik 2013). Fish tend to consume more food after a period of starvation than before the period of starvation. Therefore, a correction of the food is required for the next meal (Hepher 2009). Ishiwata (1968) found that fish did not take food well immediately after being introduced into a new tank. Most likely, this is due of their need to get used to the new environment or to their new food.

Stress is a disturbance of physiological or biological mechanisms due to internal and external factors or stressors (Ramsay et al 2009). They provoke behavioral and biological sequences through which the living organism makes efforts to restore homeostasis, thereby neutralizing the threat. A distinct behavioral response to stress in fish is a reduction in food intake (Bonga 1997; Bernier 2006). Also, stress can disrupt foraging behavior in fish, including foraging itself, finding, or capturing prey (Beitinger 1990; Conde-Sieira et al 2010; Conde-Sieira et al 2018), leading to declines in growth in various fish species (Bernier 2006). Fish under stress eat less and grow slowly compared to non-stressed fish. Even when food intake levels are maintained, a reduction in the conversion efficiency of the feed consumed has been found, resulting in a reduced growth rate (Paspatis et al 2003; D'Orbcastel et al 2010). Leal et al (2011) found that physical stress caused by cleaning once or three times a week significantly reduced daily and cumulative feeding rates and feed conversion efficiency in sea bass (*Dicentrarchus labrax*). In addition, these stressors have been shown to regulate the control of the endocrine growth factor in fish, such as pituitary growth hormone secretion and others (Rotllant et al 2001; Deane & Woo 2009; Saera-Vila et al 2009).

Conclusions. In recirculation systems, depending on the size and type of fish farmed, as well as the management of conditions and processes, different feeding strategies are required. The composition of the diet should be carefully selected for the size and species of fish. Thus, the source (living or non-living food), particle size, texture, density and taste are important aspects to be considered. Dosage and frequency of feeding are very important for growth rate and feeding efficiency. The provision and setting of optimal conditions specific to the cultured species are of primary importance for successful cultivation in aquaculture. It is through the application of scientific developments in this regard that fish farmers will be able to optimize management practices and will provide micro environments for better food intake and utilization.

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