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Review Article

Fundamentals of Fish Farming: Overview of Key Considerations for Fish Culture

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ABSTRACT

In aquaculture, understanding the specific feed requirements of fish at various developmental stages and the appropriate feeding frequency is essential for successful production. Feeding systems in aquaculture are generally categorized based on feed type and availability into extensive (no feed provided), semi-intensive, and intensive production methods. Fertilization and hatching of fish eggs and milt, whether from cultured or wild sources, can achieve success rates of up to 97%. However, the survival and growth of fry and larvae heavily depend on appropriate feeding strategies, as improper feeding can result in significant losses. Fish feeding behavior and efficiency are influenced by a range of factors classified as external and internal stressors. External factors include changes in water quality, feed quality, and environmental disturbances, while internal factors relate to the physiological status of fish, such as reproductive cycles. A thorough understanding of fish behavior, ecology (the interaction between fish and their environment), nutritional needs, energy metabolism, and feed characteristics (type and particle size) is vital for optimizing aquaculture outcomes. Feed utilization in fish metabolism is a complex but critical process. Metabolic activities begin with the ingestion of feed, supplying energy necessary for maintaining vital functions, compensating for energy loss through excretion and wear, and supporting growth. Metabolism concludes with the excretion of nitrogenous wastes via urine and feces. Metabolic rates vary with activity: basal metabolism during rest, routine metabolism during regular swimming and foraging, and active metabolism during intense physical exertion. For optimal growth, fish should be maintained in low-stress environments with optimal water conditions and high-quality feed formulations that promote efficient feed conversion and weight gain. In conclusion, sustainable aquaculture relies on the integration of optimal nutrition, environmental stewardship, species-specific practices, and continued technological advancement. This review summarizes essential considerations in fish farming, focusing on feeding strategies, metabolism, and environmental management, supported by a broad literature base. It presents practical recommendations for improving growth performance, feed efficiency, and environmental sustainability.

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INTRODUCTION

Aquaculture plays a vital role in the global economy by providing employment opportunities, generating income, and contributing significantly to food security. With ongoing investments, technological advancements, and the adoption of sustainable practices, the aquaculture sector is expected to experience substantial growth in the coming years (Yanik, 2022). Fish farming, a major component of aquaculture, has become a pivotal industry in global food production, supplying an increasing share of the world's seafood to meet rising consumer demand (FAO, 2022). As wild fisheries face pressures from overfishing and environmental degradation, aquaculture emerges as a sustainable alternative capable of supporting food security and fostering the economic development of coastal and rural communities (Pradeepkiran, 2019). However, achieving long-term success and environmental sustainability in fish farming requires the optimization of biological, technological, and environmental management factors.

Despite its potential, fish farming is confronted by environmental challenges such as pollution, overuse of antibiotics, and disease outbreaks (Arshad *et al*., 2024). These issues have stimulated growing interest in sustainable aquaculture approaches, including integrated multi-trophic aquaculture (IMTA) systems and the development of novel feeds such as plant-based or synthetic alternatives to reduce dependence on fishmeal and fish oil (John and Okuthe, 2024).

In regions with favorable geographical conditions and abundant water resources, there is an urgent need to intensify support for small-scale rural fish farming.

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Sustainable production in these areas depends on establishing standardized guidelines that are adaptable regardless of water characteristics, fish species, or regional differences. The successful integration of fish farming into rural economies hinges on developing a critical mass of well-trained fish farmers who can provide expertise and services to smaller producers, thereby ensuring sustainability without ongoing institutional or governmental intervention. Implementing minimum acceptable standards across all regions could significantly increase production levels. Moreover, simplifying and clarifying the concept of fish farming is essential for improving public acceptance. Prior to making financial investments in aquaculture, presenting a clear, straightforward mission to all stakeholders is crucial (Yanik, 2022; Shankar and Yanik, 2024).

Key factors in effective fish farming include water quality management, efficient feeding regimes, selective breeding programs, disease control, and waste management. Maintaining optimal water parameters such as temperature, salinity, and dissolved oxygen is fundamental to ensuring healthy fish stocks (Jana and Sarkar, 2005). Advances in nutrition and the formulation of specialized feeds have contributed to improved growth rates and enhanced disease resistance in cultured species (Rombenso *et al*., 2022). Furthermore, genetic improvement programs focusing on breeding for disease resistance and productivity have become widely adopted, promoting more resilient and sustainable aquaculture practices (Gjedrem and Baranski, 2009).

This overview aims to discuss essential considerations in fish farming, emphasizing the scientific principles that underpin sustainable practices and address current challenges within the sector.

ESSENTIAL CONSIDERATIONS OF FISH FARMING

Both cultured and wild fish eggs and milt can achieve hatching success rates of up to 97%. However, improper feeding of fry and larvae may result in the loss of the entire batch, highlighting the critical importance of understanding the feeding process in fish culture. A thorough knowledge of key factors such as fish behavior, nutrient requirements, energy metabolism, and the type and size of feed is essential for successful aquaculture (Volkoff, 2016).

The coordinated act of food searching and ingestion involves complex interactions between the nervous and endocrine systems (Kuz'mina, 2019). Control of feeding behavior is multifaceted, involving communication between central brain structures and peripheral signals (Volkoff *et al*., 2009). Metabolic sensors in the central nervous system enable the hypothalamus to monitor the nutritional status of fish, providing qualitative regulation of food intake (Conde-Sieira *et al*., 2010). Neural effectors from the hypothalamus integrate hunger and satiety signals to regulate the amount of food consumed (Lin *et al*., 2000). Hunger signals include peptides such as apelin and neuropeptide Y (Aldegunde and Mancebo, 2006), whereas satiety signals involve amylin and the cocaine- and amphetamine-regulated transcript (Thavanathan and Volkoff, 2006; Volkoff and Peter, 2001). Additionally, tachykinins may exert an anorectic effect in fish. The hypothalamic region of the brain is linked to the control of food intake, although areas beyond the hypothalamus also play a role in this process (Lin *et al*., 2000). Understanding these regulatory mechanisms is particularly relevant to fisheries and aquaculture, as manipulation of feeding behavior and endocrine responses can optimize fish growth and reproduction.

The nutritional requirements of fish vary depending on species, size, age, reproductive status, and environmental conditions. Nonetheless, all fish require essential nutrients, including proteins, lipids (fats), carbohydrates, vitamins, minerals, essential amino acids, dietary fiber, antioxidants, and essential fatty acids. Balancing these nutrients in the diet is crucial to support optimal growth, health, and reproductive success. Commercial fish feeds are formulated to provide a balanced nutrient profile tailored to the specific needs of different species and life stages.

Photoperiod and light regimes also influence biological functions in fish (Biswas and Takeuchi, 2003). Studies across various species have demonstrated that the duration of light exposure can significantly affect feeding behavior, growth, and survival rates (Nwosu and Holzlöhner, 2000). Additionally, photoperiod plays a key role in regulating the overall well-being and daily rhythms of fish (Adewolu *et al*., 2008).

Proper feeding practices are essential for fish welfare. Since dietary needs differ between species, understanding the specific nutritional requirements of the cultured fish is vital. In aquaculture, the choice of feed type and size depends on factors such as species, life stage, nutritional demands, feeding behavior, and production objectives. Selecting appropriate feed types and sizes is critical to maximize feed conversion efficiency, growth performance, and profitability. Moreover, formulated feeds must meet the nutritional needs of the target species while being managed carefully to minimize waste and reduce environmental impacts. Feed type and particle size, determined by ingredient origin and processing method are crucial to feed acceptance and utilization. Feeds are classified by moisture content (wet, moist, dry) and processing technique (compressed, expanded, extruded pellets). Physical characteristics such as pellet density, size, shape, color, and texture influence feeding efficiency.

Research shows optimal pellet size correlates with approximately 25–50% of fish mouth width (Wankowski and Thorpe, 1979; Tabachek, 1988; Tucker, 1998). Larger pellets attract quicker responses but may increase handling time, as seen in Arctic charr, where intermediate-sized pellets minimized rejection and handling time (Linnér and Brännäs, 1994).

KNOWLEDGE OF FEEDING BEHAVIOR OF FISH FOR EFFECTIVE MANAGEMENT STRATEGIES

Feeding behavior

The feeding behavior of fish is governed by the interpretation of both external and internal environmental signals via receptors and signaling molecules. This behavior is influenced by various internal and external stressors, such as changes in water and food quality, reproductive status, photoperiod, temperature, water flow, weather conditions, salinity, oxygen levels, CO_2 concentration, ammonia levels, pH, food availability, composition, and social interactions. The hypothalamus plays a central role in this regulatory process, alongside other brain regions (Volkoff, 2016; Kuz'mina, 2019; Assan *et al*., 2021). Feeding acts as one of the most influential external factors that stimulate growth and modulate feeding behavior (Conde-Sieira *et al*., 2017). The availability and composition of food significantly impact these processes by affecting hormone levels that regulate appetite and metabolism (Bertucci *et al*., 2019). Even a single meal can trigger fluctuations in the expression and secretion of appetite-regulating hormones in both the brain and peripheral tissues (Wall and Volkoff, 2013).

A comprehensive understanding of fish feeding behavior is essential for aquaculturists, anglers, ecologists, and fisheries managers. Such knowledge provides valuable insights into dietary preferences, habitat utilization, trophic interactions, and overall ecosystem dynamics. By studying feeding behavior, researchers can better understand the ecological roles of different fish species and develop effective strategies for their conservation and sustainable management.

Fish feeding behavior exhibits significant diversity across species, habitats, and environmental conditions. Common feeding strategies include carnivory, herbivory, and omnivory, alongside variations in feeding frequency, feeding zones, social and territorial behaviors, selective feeding, and adaptive learning processes. Extensive research on feeding behavior in both wild and cultured populations has enhanced our ecological understanding of these processes (Houlihan *et al*., 2001; Gerking, 2014).

Fish responses to feeding stimuli are influenced by factors such as feeding techniques, habits, regularity, feed detection mechanisms, and preferences (Lall and Tibbetts, 2009). Changes in dietary behavior and appetite often correspond to alterations in gene expression and protein levels of appetite-regulating hormones or their receptors. Such shifts in mRNA and protein expression, triggered by starvation or feeding, illuminate the physiological roles of these hormones in regulating feed intake. However, feeding regulation is multifactorial; compensatory mechanisms may modulate behavior, and fluctuations in hormone levels do not always directly correlate with changes in feed consumption (Volkoff *et al*., 2010).

PROVISION OF OPTIMAL LIVING ENVIRONMENT

Providing an optimal living environment is crucial for fish health and well-being, whether in captivity or the wild. Key factors influencing this environment include water quality, temperature, stocking density, habitat complexity (decorations and hiding places), lighting, diet, species compatibility, water movement, and maintenance practices. Proper management of these variables significantly contributes to fish health and longevity.

Water quality plays a pivotal role in fish growth and development, with chemical parameters such as hardness, pH, oxygen concentration, and salinity, as well as physical characteristics like temperature and color, requiring regular monitoring. For example, cold-water species such as salmon thrive at 14–16°C, while warm-water species like channel catfish prefer approximately 30°C (Jiang *et al*., 2021). Deviations from these optimal temperatures can increase nutrient demands without yielding growth benefits, as temperature directly influences metabolic processes essential to health and development.

Lighting and photoperiod regimes also profoundly affect fish biology. Species-specific requirements vary with developmental stages, and manipulating photoperiod can enhance aquaculture productivity and sustainability (Nwosu and Holzlöhner, 2000). Studies on species such as *Clarias gariepinus* demonstrated that 24 h of darkness yielded the highest feed intake and feed conversion ratios (Adewolu *et al*., 2008). Similar findings with *Lophiosilurus alexandri* and *Diplodus puntazzo* reinforce the critical role of photoperiod in regulating feeding behavior and growth (Kitagawa *et al*., 2015; Vera *et al*., 2006). These findings underscore the necessity of further research into photoperiod effects across diverse species.

Fish exhibit species-specific feeding times aligned with circadian rhythms; some feed diurnally (e.g., Atlantic salmon, redbelly tilapia, rohu, common carp), while others are nocturnal feeders (e.g., European catfish, zebrafish) (Isorna *et al*., 2017; Boujard, 1995; del Pozo *et al*., 2011). Feeding schedules aligned with natural rhythms improve feed efficiency and growth, as demonstrated in rainbow trout and goldfish (Noeske and Spieler, 1984; Gelineu *et al*., 1998).

The processes of starvation, craving, and satiation describe the physiological states governing food intake. Starvation elicits active searching and hunger behaviors, whereas satiation signals fullness after feeding. Appetite or craving is influenced by sensory stimuli such as food appearance, odor, and taste (Hoskins and Volkoff, 2012). Environmental factors, food availability, and fish physiological status modulate these behaviors.

NUTRIENT REQUIREMENTS OF FISH

Fish growth depends on the quantity and quality of feed consumed and efficiently metabolized. Maintaining optimal environmental conditions including water quality and temperature is fundamental for maximizing growth potential. A balanced diet tailored to species-specific nutrient needs is essential.

Nutrient requirements vary significantly among species, ages, sizes, and environmental contexts. Protein is the most critical nutrient supporting growth and physiological functions such as immunity and reproduction. However, excessive feeding of high-energy diets can cause undesirable fat deposition, compromising fish health and marketability. Thus, promoting lean, protein-rich muscle development is paramount. The majority of herbivorous and omnivorous fish studied thus far necessitate a diet containing 25 to 35 percent crude protein; in contrast, carnivorous species may need 40 to 50 % crude protein (Wilson, 2003).

Proteins are the major organic material in fish tissue, making up about 65–75% of the total on a dry-weight basis. Fish consume protein to obtain amino acids. A regular intake of protein or amino acids is required because amino acids are used continually by the fish, either to build new proteins (as during growth and reproduction) or to replace existing proteins (maintenance) (Wilson, 2003). Fish primarily use protein as an energy source, though fats and carbohydrates also contribute according to their caloric content. Vitamins and minerals are indispensable micronutrients regulating metabolism, skeletal integrity, and physiological processes. Deficiencies in any essential nutrient can limit growth, illustrating the law of the minimum, whereby a single nutrient shortage restricts overall performance. The protein needs for various fish species vary between 28 and 56 percent of their dry diets. It appears that carnivorous species from both marine and freshwater environments necessitate 40-55 percent of dietary protein, whereas the majority of freshwater omnivorous and herbivorous species require 30-40% of their dry diet to consist of protein. Similar to finfish, most crustaceans examined thus far exhibit relatively high protein requirements, ranging from 30 to 60 % of the dry diet (Hasan, 2001).

In summary, aquaculture success hinges not only on feed quantity but also on feed quality and composition, tailored to the nutritional requirements of target species. Properly balanced diets optimize growth, health, and fish product quality.

UNDERSTANDING METABOLISM OF FISH

Understanding fish metabolism is vital for optimizing feeding regimens, ensuring fish welfare, and promoting sustainable aquaculture. Fish metabolism encompasses the biochemical processes converting feed into energy and essential compounds for growth, maintenance, and reproduction. Influential factors include water quality, diet composition, feeding frequency, and environmental conditions.

In intensive aquaculture, fish are typically fed high-protein, energy-dense diets in controlled environments. Feed utilization efficiency is influenced by temperature, physiological condition, stress, and water parameters (pollution, pH, oxygen). Metabolic processes initiate with feed consumption, providing energy for basal maintenance, activity, growth, and culminate in excretion of nitrogenous waste via urine and feces.

Metabolic rate varies with activity level: basal metabolism during rest, routine metabolism during swimming and feeding, and active metabolism during heightened activity (Treberg *et al*., 2026). Energy use is quantified through measurements such as digestible energy (feed energy minus fecal energy), metabolic energy (digestible energy minus endogenous nitrogen energy), gross energy, and metabolizable energy, using methods like bomb calorimetry and respirometry (Dickson and Kramer, 1971). The energy consumed through food incurs energetic expenses known as specific dynamic action (SDA), and a portion of this energy will be lost by the animal through egestion (indigestible materials and unassimilated carbon) or nitrogenous excretion (Fig. 1). The remaining energy is utilized to cover the costs of living, which include basal expenses such as the maintenance of ion gradients and the repair of proteins and DNA. Any energy that exceeds these basal requirements is directed towards growth and storage, locomotion, physical labor, or reproduction, which may manifest as the production of gametes or be retained as gonadal investment (Treberg *et al*., 2016).

Fish size, temperature, oxygen concentration, salinity, activity, food intake, and fasting affect metabolism. Being ectothermic, fish do not regulate body temperature internally; thus, external temperature significantly influences metabolic rates. Smaller fish have higher metabolic activity relative to larger individuals, with metabolic rates decreasing approximately 90% from 10 mg fry to 1 kg adults.

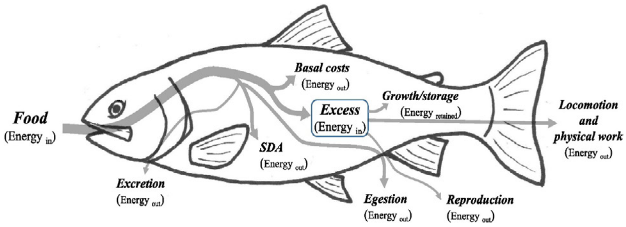

Fig. 1. Energy budget in a fish (Treberg *et al*., 2016).

Optimal growth temperatures vary by species, with salmonids favoring 14–16°C. Metabolic scope, defined as the difference between active and standard metabolic rates, reflects oxygen consumption during activity. Studies on salmon and rainbow trout illustrate how metabolic rates correspond with swimming velocity and feeding state (Brett, 1965; Albrecht, 1974).

CHALLENGES

The aquaculture industry faces significant challenges due to the limited availability of fish meal and fish oil, resources increasingly controlled by a small number of entities. Although alternative sources of amino acids are abundant, they often exhibit imbalanced nutritional profiles and lack desirable flavor characteristics. Furthermore, reliance on alternative proteins may adversely affect the productivity and resilience of farmed fish. The supply of essential fatty acids is also constrained; substitution with alternative lipids can reduce the nutritional quality of fish fillets and impair reproductive performance, posing additional challenges for sustainable aquaculture development. Major challenges include limited fishmeal and oil supply, imbalances in alternative protein sources, and reduced fillet quality or reproductive performance from suboptimal lipid sources (Paspatis *et al*., 1999; John and Okuthe, 2024).

CONCLUSIONS AND RECOMMENDATIONS

Aquaculture is currently the fastest-growing food production sector worldwide, driven by the expansion of both intensive and semi-intensive farming systems. Recent advancements have concentrated on sustainability, genetic improvement, alternative feed development, traceability, certification, and technological innovation all aiming to optimize fish production and ensure sector resilience.

The future of aquaculture is promising, with its capacity to provide a reliable protein source for a growing global population. To meet increasing demand, however, the industry must enhance production efficiency, minimize environmental impacts, and improve resource use. Key trends expected to shape the sector include continued technological innovation, heightened emphasis on sustainability, and increased attention to social and environmental responsibility.

Moreover, external influences such as rising energy costs, evolving government regulations, societal acceptance, and climate change will significantly affect aquaculture's trajectory over the next fifty years. Both domestic policies and international market forces are propelling global aquaculture growth, underscoring its critical role in feeding future generations.

DECLARATIONS

Generative AI and AI-assisted technology statement

The authors have declared that no generative AI or AI-assisted technologies were used to create this manuscript.

Statement of conflict of interest

The author has declared no conflict of interest.

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