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Opinion

Nutritional Signaling and Metabolic Adaptation in Aquatic Species

Quanquan Han*

Department of Aquaculture, Ghent University, Ghent, Belgium

DESCRIPTION

Nutritional signaling systems enable aquatic animals to recognize changes in the supply of proteins, amino acids, carbohydrates, lipids, minerals, and other dietary substances. These systems connect feeding conditions with cellular metabolism, tissue formation, energy use, appetite, immune activity, and reproductive performance. In aquaculture, examining how cultured species respond to different nutrients can help improve feed design, promote efficient growth, and limit the release of unused nutrients into the surrounding water. Nutritional communication is not controlled by one pathway. Instead, several molecular networks operate together in tissues such as the intestine, liver, muscle, pancreas, brain, and, in crustaceans, the hepatopancreas.

Amino acids serve as major nutritional signals in fish and crustaceans. In addition to supporting protein formation, they activate intracellular mechanisms that influence cell growth and metabolic function. The mechanistic target of rapamycin complex 1, or mTORC1, responds to amino acid availability and the energy condition of the cell. When nutrients are sufficient, mTORC1 can promote protein production, ribosome formation, and cellular development. When nutrients become scarce, its activity commonly declines, allowing cells to reduce costly processes and adjust their metabolic priorities. This relationship is especially important in young, rapidly growing fish, in which protein quality and amino acid supply strongly affect muscle formation.

Leucine has attracted particular interest because it can influence mTOR-associated signaling. The amount of dietary leucine may affect protein production in skeletal muscle, although the outcome depends on species, age, previous feeding conditions, and the balance of other essential amino acids. A feed may contain a high total protein level yet produce a weaker biological response if its amino acid pattern is unsuitable. Conversely, a diet with a well-balanced supply of essential amino acids may support more effective tissue development. This illustrates why aquafeed evaluation should consider amino acid composition rather than relying only on crude protein values.

Insulin and insulin-like growth factor systems provide additional routes for communicating nutritional conditions. These pathways regulate glucose transport, protein formation, lipid processing, and cell survival. Insulin-like growth factor signaling is closely associated with body growth because it interacts with endocrine control of muscle development and tissue formation. Nutritional status can therefore influence growth through both the amount of feed consumed and the way tissues respond to the nutrients delivered.

The intestine plays a central role in nutritional detection because it is the first major organ to encounter digested feed. Enterocytes and enteroendocrine cells can recognize amino acids, fatty acids, glucose, and other dietary compounds, then release chemical messengers that communicate with the nervous and endocrine systems. These messengers may influence appetite, digestive secretions, and the movement of material through the gastrointestinal tract. In farmed fish, changes in intestinal nutrient recognition may consequently affect feed intake, digestion, and the efficiency of nutrient absorption.

In crustaceans, the hepatopancreas carries out important digestive, storage, and metabolic functions. Dietary changes can alter enzyme activity, lipid accumulation, carbohydrate processing, and protein turnover in this organ. Nutrient-responsive signaling within hepatopancreatic cells may help coordinate the storage and use of nutrients after feeding. This information is valuable when developing diets for shrimp and related species, particularly as producers replace traditional marine ingredients with plant, microbial, insect-based, or algal alternatives.

Lipid recognition is another major element of metabolic control. Fatty acids function both as energy sources and as signaling compounds. Some fatty acids interact with transcriptional regulators that control lipid oxidation, synthesis, transport, and storage. Peroxisome proliferator-activated receptors are examples of nuclear receptors involved in these processes. Their activity can modify the expression of genes associated with fatty acid utilization. In fish, the resulting response depends on species-specific metabolism and on the proportions of saturated,

Correspondence to: Quanquan Han, Department of Aquaculture, Ghent University, Ghent, Belgium, E-mail: quanquan.han@ugent.be

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monounsaturated, and polyunsaturated fatty acids present in the feed.

Carbohydrate handling differs widely among aquatic species. Some fish use dietary carbohydrates efficiently, while others have a limited ability to maintain stable glucose levels after consuming carbohydrate-rich meals. Glucose-related regulation involves insulin activity, cellular energy monitoring, and changes in gene expression. These differences have practical importance because excessive carbohydrate inclusion may increase lipid deposition or disturb metabolic balance in species with lower carbohydrate tolerance. Measuring molecular responses can therefore reveal effects that may not be visible through growth performance alone.

Environmental conditions can also influence nutritional signaling. Temperature, dissolved oxygen, salinity, stocking density, and feeding schedule affect energy requirements and metabolic activity. Temperature is especially important because it changes enzyme function and overall metabolic rate in ectothermic animals. A feed that performs well under one thermal condition may produce a different physiological response under another. Nutritional signaling networks help aquatic animals adjust their metabolism according to the combined effects of diet and environment.

CONCLUSION

Such knowledge may support more precise feed formulation, improved nutrient retention, and better control of waste production. Overall, nutritional signaling forms an interconnected system through which aquatic animals interpret dietary and energetic conditions. Studying these systems provides a detailed explanation of how feed composition affects cultured species. Applying this knowledge to aquaculture nutrition can help produce diets that match the metabolic characteristics of individual animals while improving nutrient use and reducing nutrient discharge into culture environments.