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Opinion

Nutritional Signaling Mechanisms and Metabolic Adaptation in Aquaculture

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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 responds to amino acid availability and the energy condition of the cell. When nutrients are sufficient, mechanistic target of rapamycin complex 1 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 mechanistic target of rapamycin-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.

Cellular energy monitoring is another important part of nutritional regulation. Adenosine monophosphate-activated protein kinase responds to changes in the energy status of cells. When energy availability falls, adenosine monophosphate-activated protein kinase can stimulate processes that generate adenosine triphosphate while limiting selected activities that consume substantial energy. In fish experiencing fasting, restricted feeding, temperature variation, or other metabolic pressures, adenosine monophosphate-activated protein kinase-related responses may affect lipid breakdown, glucose use, and feeding behavior. The relationship between adenosine monophosphate-activated protein kinase and mechanistic target of rapamycin allows cells to balance energy conservation with growth-related activity.

Insulin and insulin-like growth factor systems provide additional routes for communicating nutritional conditions. Feeding can change circulating insulin levels and influence downstream signaling through phosphoinositide 3-kinase and protein kinase B. 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.

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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.

CONCLUSION

Overall, nutritional signaling forms an interconnected system through which aquatic animals interpret dietary and energetic conditions. Networks involving mechanistic target of rapamycin, adenosine monophosphate-activated protein kinase, insulin-related pathways, amino acid recognition, lipid-responsive transcription, and intestinal hormone release work together to regulate growth, metabolism, appetite, immunity, and physiological maintenance. 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.