

Recent modeling approaches increasingly combine biological realism with predictive accuracy. Mechanistic and nutrient-based frameworks can simulate fish growth, composition, and nutrient utilization under varying feeding levels, feed composition, and environmental conditions, making them useful as decision-support tools for precision farming (Soares et al., 2023). In parallel, newer nutritional bioenergetic models based on dynamic energy budget theory explicitly incorporate digestion and macronutrient composition, allowing prediction not only of weight gain but also of oxygen consumption, ammonia production, and waste outputs under different feeding schedules (Stavrakidis-Zachou et al., 2025).

#### **4.2 Nutritional factors affecting feeding performance**

Nutritional factors affect feeding performance through both requirement matching and physiological regulation. Precision nutrition frameworks argue that optimal feeding cannot be defined only by feed amount, because nutrient supply must also align with genetic background, metabolism, environmental conditions, and production goals to minimize waste while sustaining performance (Zhang et al., 2020). Likewise, feed efficiency depends on meeting qualitative and quantitative nutrient requirements simultaneously, while digestibility remains a key determinant because better nutrient digestibility generally improves FCR and nutrient utilization (Hancz, 2020).

Feed composition also influences performance by altering intake regulation, health status, and metabolic use of nutrients. Adequate nutrition is necessary not only to prevent deficiency but also to maintain health and productive performance, and strategic supplementation above minimum requirement for selected amino acids, fatty acids, vitamins, or minerals can improve disease resistance and functional status. More recent work further shows that intake regulation in fish reflects coordinated behavioral and physiological control, and that feed intake is shaped not only by nutrients themselves but also by ingredient inclusion, environmental stressors, ontogeny, and other biological factors that must be represented in advanced predictive models (Soengas et al., 2024).

#### **4.3 Intelligent feeding strategies based on computational prediction**

Intelligent feeding strategies increasingly rely on sensors, machine vision, and machine learning to translate fish behavior and environmental data into real-time feeding decisions. Review evidence shows that intelligent feeding control can automatically determine feeding demand by integrating mathematical models, acoustic methods, and computer vision, although practical deployment still depends on improvements in accuracy and robustness under farm conditions. This transition is important because fixed-time or fixed-quantity feeding often fails to reflect dynamic appetite, creating avoidable risks of overfeeding, underfeeding, and water quality deterioration (Zhang et al., 2023).

Applied studies demonstrate that computational prediction can improve feeding precision and production outcomes. A near-infrared computer vision system coupled with a neuro-fuzzy model achieved 98% feeding-decision accuracy and reduced FCR by 10.77% relative to feeding-table management, while also lowering water pollution. More advanced predictive systems have expanded this logic by using optimized neural networks, support vector machines, and dynamic control architectures to infer biomass, uneaten pellets, and feeding endpoints, thereby enabling adaptive rationing in fish and shrimp culture and supporting more efficient smart aquaculture operations (Chen et al., 2022; Wang et al., 2022).

### **5 Integration of Environmental, Nutritional, and Biological Data for Predictive Aquaculture**

#### **5.1 Multivariate analysis of factors affecting aquaculture production**

Aquaculture production is governed by interacting environmental, nutritional, and biological variables, so predictive analysis requires multivariate rather than single-factor evaluation. In intensive production systems, growth, survival, feed conversion, and health are simultaneously influenced by stocking density, feeding rate, water temperature, dissolved oxygen, pH, ammonia, nitrite, and tank system conditions, which makes isolated interpretation inadequate for management (El-Hack et al., 2022). This same logic is reflected in recirculating systems, where principal component analysis has been used to convert many correlated water-quality variables into a smaller set of interpretable components that reveal internal data structure and support early prediction of critical events (Silva et al., 2021).