

The value of multivariate analysis lies not only in dimensionality reduction but also in discriminating among production environments with different ecological signatures. Comparative pond studies using discriminant analysis showed that fourteen physicochemical variables could clearly separate intensive and less intensive production systems, with dissolved oxygen, temperature, nutrient-related variables, and solids contributing most strongly to classification accuracy (Figure 1) (Delgado-Villafuerte et al., 2026). At the same time, endocrine evidence indicates that growth itself is biologically multicausal, because GH and IGF-I expression responds jointly to diet, temperature, photoperiod, salinity, pollutants, and stocking density, linking external farm conditions with internal physiological regulation.

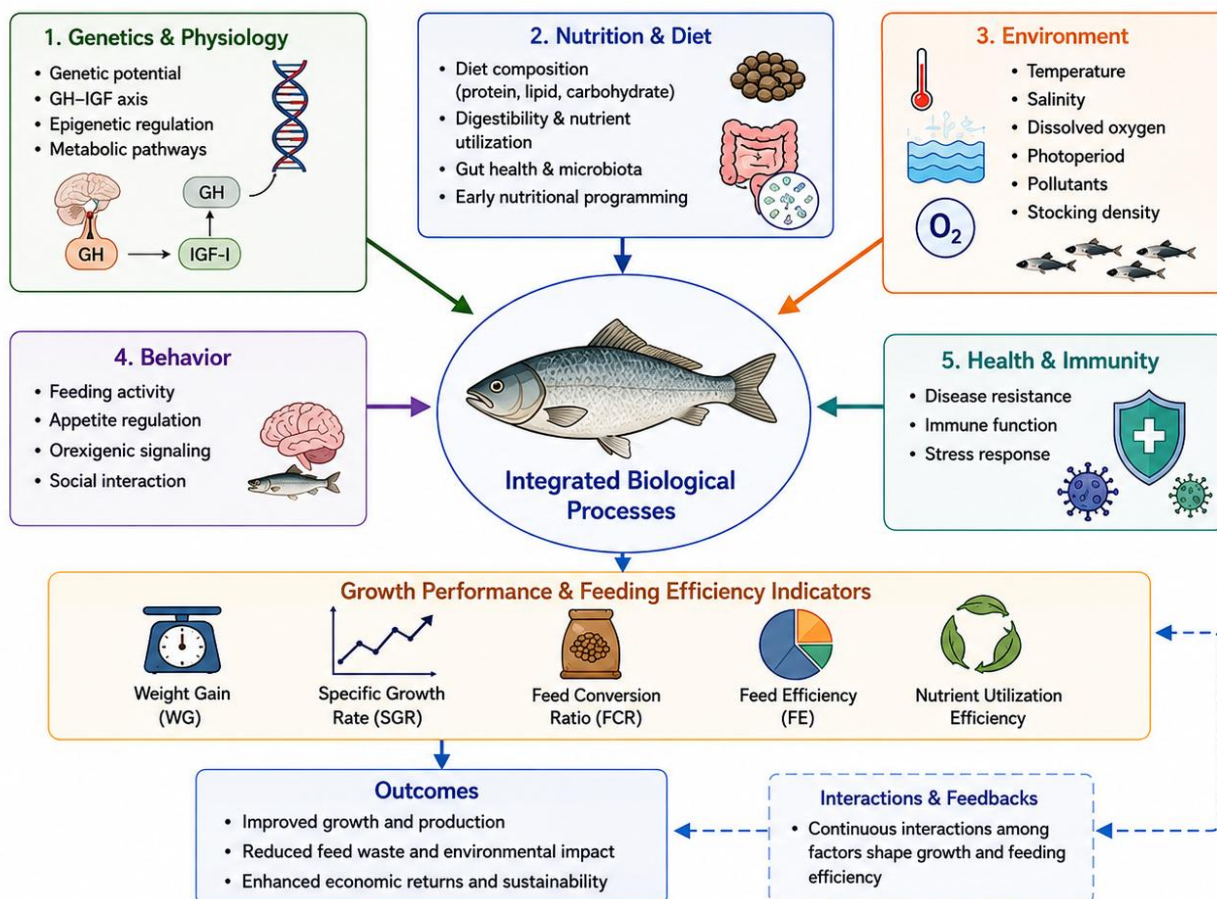


Figure 1 Aquaculture growth performance and feeding efficiency: key biological and environmental determinants

5.2 Digital twin and simulation approaches in aquaculture management

Digital twin approaches extend multivariate analysis by coupling real-time data streams with mechanistic or hybrid models that reproduce the behavior of aquaculture systems in virtual form. In aquaculture, this technology is still at an early stage, but it is increasingly viewed as a solution to the industry's difficulty in observing underwater biological and physical processes continuously and safely. Land-based case studies further show that digital twins under the Precision Fish Farming framework can integrate sensors, IoT infrastructure, and predictive mathematical models to support feeding control, oxygen management, and fish population management in real time.

The main management value of digital twins is that they enable simulation of present and future scenarios rather than passive monitoring alone. Review evidence shows that digital twin systems can support predictive analytics for risk mitigation, feeding optimization, and system-performance improvement, although interoperability and data handling remain major challenges (Huang and Khabusi, 2025). More specialized frameworks such as FishMet demonstrate how a digital twin can incorporate appetite, feeding decisions, feed intake, energetics, and growth into a modular computational service, allowing autonomous model execution and integration with broader farm management platforms.