

panels. The emergence of direct LAMP workflows for shrimp-culture water illustrates how eliminating complex DNA extraction can materially improve field practicality (Pu et al., 2026).

9.6 Integration of multi-omics, artificial intelligence, and smart aquaculture

The strongest future prediction systems are likely to combine microbial and non-microbial data. Environmental sensors can continuously measure variables such as temperature, dissolved oxygen, pH, and salinity, whereas microbial sampling provides biological information that sensors cannot. Multi-omics can identify functionally meaningful features, and machine learning can integrate heterogeneous variables across time.

The risk is technological excess. More variables and more complex models do not guarantee better management. Flow-cytometry studies demonstrate both the promise and limits of data-driven microbial fingerprints: community information can be predicted rapidly, but accuracy differs among taxa and tasks (Heyse et al., 2021). Future smart-aquaculture systems should therefore prioritize external validation, interpretability, uncertainty estimates, and actionable outputs over algorithmic novelty.

9.7 From microbial monitoring to microbiome management

The long-term direction of the field is a transition from observing microbial communities to deliberately maintaining desirable ecological functions. In the near term, this means avoiding unnecessary disturbance, maintaining stable environmental conditions, using validated probiotics where appropriate, and recognizing microbial deterioration before clinical disease. More advanced interventions may eventually include precision probiotics, defined microbial consortia, phage-based strategies, and ecological engineering of water and biofilms.

That transition should remain evidence-led. Marine aquaculture systems are connected to wider coastal ecosystems, so interventions that alter microbial communities may have consequences beyond the farm boundary. The most defensible health-management model is therefore not one that attempts to control every microorganism, but one that combines surveillance, ecological understanding, proportional intervention, and learning from repeated production cycles. In this framework, the practical endpoint of microbial monitoring is neither sequencing nor pathogen enumeration. It is better timing of management: recognizing instability while it is still reversible, confirming risk before acting, and evaluating whether intervention restores both animal health and microbial resilience.

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