

Research Insight

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Microbial Monitoring-Based Health Management Models for Marine Aquaculture

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Abstract Marine aquaculture is moving toward greater production intensity while facing persistent challenges from infectious disease, environmental instability, and antimicrobial resistance. In this setting, microbial communities should no longer be treated only as a background component of the culture environment. They participate in nutrient cycling, organic matter transformation, host nutrition, mucosal defense, pathogen exclusion, and disease development. This review examines how microbial monitoring can be translated from a descriptive research tool into a practical component of marine aquaculture health management. Conventional culture, PCR-based assays, 16S rRNA gene sequencing, metagenomics, multi-omics approaches, flow cytometry, biosensors, and field-deployable molecular methods provide complementary information at different levels of taxonomic, functional, quantitative, and temporal resolution. Particular attention is given to potential pathogens, health-associated microorganisms, community stability, dysbiosis, and functional genes as candidate indicators. Current evidence indicates, however, that no single microbial taxon or diversity metric can serve as a universal marker of health. Monitoring is most informative when microbial signals are interpreted against farm-specific baselines and integrated with water quality, production stage, and host-health observations. On this basis, the review proposes a tiered framework linking routine surveillance, early warning, risk classification, proportionate intervention, and post-intervention feedback. The framework intentionally avoids fixed universal thresholds because microbial communities vary substantially among species, farms, seasons, and production systems. Future progress will depend on standardized sampling, absolute microbial quantification, longitudinal and multi-farm validation, functional confirmation of biomarkers, and integration of rapid microbial monitoring with environmental sensors and data-driven decision support. Microbial monitoring can therefore support a gradual shift from reactive treatment of disease toward preventive, adaptive, and precision health management in sustainable marine aquaculture.

Keywords Marine aquaculture; Microbial monitoring; Microbiome; Microbial dysbiosis; Health management; Disease early warning; Microbial indicators; Sustainable aquaculture

1 Introduction

Aquaculture has become increasingly important to global aquatic food production, and its continued expansion is central to meeting demand for aquatic foods without relying solely on capture fisheries. The Food and Agriculture Organization reported that aquaculture surpassed capture fisheries in aquatic animal production in 2022, highlighting both its growing contribution and the need to improve biological and environmental sustainability. Intensification, however, concentrates animals, feed inputs, organic matter, and microorganisms within comparatively restricted environments. Disease remains one of the major biological constraints on aquaculture, while environmental change, pathogen transmission, and antimicrobial resistance complicate conventional health management (Naylor et al., 2021).

Traditional aquatic animal health management has largely focused on recognizable pathogens: detect the causative agent, confirm disease, and then intervene. Such a strategy remains essential during outbreaks, but it is inherently reactive. It may also overlook the ecological transition that occurs before obvious clinical signs appear. International aquatic animal health guidance increasingly combines disease control with biosecurity, surveillance, prevention, and responsible antimicrobial use rather than relying on treatment alone. At the farm level, the unresolved question is how to recognize a deteriorating biological state early enough for low-impact intervention to be useful.