

treatment were accompanied by restructuring of skin, gill, and gut microbiomes, with tissue-specific changes in diversity and taxonomic composition (Rosado et al., 2023).

The appropriate conclusion is not that antimicrobial treatment should never be used, but that it should be justified diagnostically and accompanied by good biosecurity and follow-up monitoring. This aligns with international guidance emphasizing responsible antimicrobial use and resistance surveillance in aquatic animals. Microbiome recovery after treatment may itself become a useful future management endpoint.

## 5.6 Biological and microbial interventions

Probiotics, prebiotics, synbiotics, biofloc, and microbial consortia aim to steer microbial ecology rather than simply eliminate microorganisms. Their mechanisms can include competition with pathogens, production of inhibitory metabolites, stimulation of host immunity, and improved transformation of wastes. Research on *Phaeobacter* and other candidate probiotics provides a mechanistic basis for such approaches, while shrimp feeding experiments demonstrate that microbial and prebiotic combinations can influence disease resistance under controlled conditions (Sonnenschein et al., 2021; Nababan et al., 2022).

More ambitious strategies—microbiome transplantation, synthetic communities, and microbiome engineering—remain largely experimental in aquaculture. Their promise should not be confused with readiness for routine farm use. Ecological persistence, biosafety, host specificity, horizontal gene transfer, regulatory requirements, and unintended community effects all need evaluation before deliberate microbiome manipulation becomes a standard management practice.

## 6 Microbial Monitoring for Disease Risk Assessment and Early Warning

### 6.1 From pathogen detection to ecosystem-level health monitoring

A pathogen-centered test asks whether a particular agent is present. Ecosystem-level surveillance asks a broader question: is the biological system moving away from its normal operating state? The second approach incorporates environmental microbiota, host-associated microbiota, water quality, husbandry, and clinical observations. It does not weaken pathogen diagnostics; instead, it determines when targeted diagnostics should be intensified.

This shift is supported by evidence that aquaculture disease is often accompanied by community-wide restructuring. In shrimp, fish, and oysters, disease-associated microbial patterns extend beyond the nominal pathogen, while environmental conditions can strongly modify these patterns (Huang et al., 2020; Clinton et al., 2024). A useful surveillance hierarchy is therefore broad screening first, targeted confirmation second, and intervention only after biological context has been considered.

### 6.2 Microbial signatures associated with pre-disease states

The most valuable biomarker is not necessarily the organism most abundant in a diseased sample. From a management perspective, earlier and moderately predictive signals can be more useful than perfect post-disease classification. Oyster hatchery observations are instructive because microbial differences were detectable before later production failure, whereas several organisms that dominated during crashes appeared to be consequences of deteriorating host condition (Cram et al., 2024).

This temporal requirement changes experimental design. Cross-sectional comparisons of “healthy” and “diseased” animals are valuable for generating hypotheses, but they cannot reliably determine whether microbial change precedes pathology. Longitudinal studies that repeatedly sample the same production units, record host outcomes, and retain environmental metadata are more appropriate for discovery of genuine early-warning signals. Recent commercial barramundi monitoring further demonstrates that even nominally similar tanks can develop distinct microbial trajectories, so replication at the tank level is essential (Bui et al., 2026).

### 6.3 Integration of microbial and environmental indicators

Microbial data become operationally meaningful when linked to conditions that farmers can observe or modify. A rising opportunistic-pathogen signal has different implications under stable temperature and oxygen than during