

4.2 Beneficial and health-associated microorganisms

Positive indicators can be as informative as pathogens if they represent persistent organisms associated with a resilient host or culture environment. Candidate beneficial bacteria may suppress pathogens through competition, antimicrobial production, resource exclusion, or modification of the local environment. Roseobacter-group *Phaeobacter*, for example, has been studied as a probiotic candidate because some strains inhibit important aquaculture pathogens (Sonnenschein et al., 2021).

Yet “beneficial” should not become another taxonomic shortcut. Performance depends on strain, host, diet, dose, environment, and microbial community context. Dietary supplementation with *Pseudoalteromonas piscicida* and fructooligosaccharide has produced beneficial outcomes in experimental whiteleg shrimp, but such results do not justify classifying every *Pseudoalteromonas* as beneficial (Nababan et al., 2022). Positive indicators should therefore be validated at strain or function level and against defined production outcomes.

4.3 Microbial diversity and community stability

Diversity metrics are attractive because they compress complex communities into simple numbers, but their biological meaning is context dependent. A sudden diversity loss can accompany dysbiosis, yet high diversity is not automatically equivalent to health. Communities may naturally change during host development, system maturation, feed transitions, or seasonal shifts. Biofloc shrimp culture, for instance, shows substantial stage-dependent succession even during successful production (Kim et al., 2022).

Temporal stability, resilience after disturbance, and deviation from a farm-specific reference state may therefore be more useful than an isolated Shannon or Chao1 value. Clinton et al. (2024) found specific Atlantic salmon gill taxa associated with different health states even though general richness and diversity were not consistently related to pathology. This supports a multidimensional interpretation in which diversity is contextual evidence rather than a stand-alone diagnosis.

4.4 Microbial dysbiosis as an early-warning indicator

Dysbiosis is especially promising for early warning because disease may emerge from a broader ecological destabilization rather than a single pathogen crossing a universal threshold. Candidate warning signals include unusual community turnover, expansion of opportunists, disappearance of persistent taxa, loss of network complexity, and changed community functions. Reviews of aquaculture microbiomes identify these patterns as plausible biomarkers but emphasize their strong host and environmental dependence (Mougin and Joyce, 2023; Xavier et al., 2024).

The timing of dysbiosis is decisive. A useful warning indicator must change before irreversible host deterioration, not merely describe a sick animal. In oyster larvae, community structure at an early developmental stage showed associations with later batch performance, while many taxa appearing during crashes were probably secondary responders (Cram et al., 2024). This distinction argues strongly for dense longitudinal sampling in biomarker-discovery studies.

4.5 Functional microbial indicators

Functional markers may sometimes generalize better than specific taxa because similar ecological functions can be performed by different organisms. Potential examples include virulence genes, antimicrobial-resistance determinants, nitrogen-cycle genes, oxidative-stress responses, and metabolite-production pathways. Metagenomic surveys can therefore ask not only “who is present?” but also “what biological capabilities are becoming more or less abundant?” (Liu et al., 2024).

A practical monitoring system might eventually combine a small taxonomic panel with a functionally informative gene panel. This would be particularly valuable where strain-level pathogenicity differs within a genus. Functional indicators still require careful interpretation because gene presence does not prove expression, while metatranscriptomic or metabolomic activity can be transient. Their main advantage is thus mechanistic specificity, not automatic diagnostic certainty.