

Among individual water-quality stressors, ammonia is especially important because it affects both physiology and immunity. Review evidence shows that elevated ammonia inhibits molting-related processes, suppresses phenoloxidase and antimicrobial activity, and weakens innate immune responses, thereby compromising shrimp growth and resilience (Zhao et al., 2020). Mechanistic work in *L. vannamei* gills further demonstrates that ammonia exposure damages gill structure and disrupts redox balance, apoptosis, energy metabolism, and osmoregulation, confirming that poor nitrogen management can destabilize the physiological systems required for survival under culture conditions.

2.3 Environmental interactions

Environmental stress in shrimp ponds rarely results from a single factor acting alone; instead, temperature, salinity, oxygen, pH, and waste-related variables interact over time to shape health and performance. Reviews of shrimp disease ecology emphasize that fluctuations in abiotic conditions increase physiological stress and disease susceptibility, especially in intensive systems with high stocking densities and limited waste removal (Kautsky et al., 2000; Millard et al., 2020). This interaction perspective is important because the biological effects of one variable may depend on the level or rate of change of another, making single-factor interpretations incomplete for real farm environments (Millard et al., 2020).

Experimental studies support this cumulative-stress view by showing that combined stressors impose larger physiological costs than isolated exposures. Under simultaneous high temperature and low pH, Pacific white shrimp increased food intake, oxygen uptake, and ammonia excretion, yet failed to translate that metabolic effort into improved growth, indicating energetic compensation at the expense of production. Likewise, integrated comparisons of ammonia, nitrite, and sulfide stress found tissue injury, altered antioxidant responses, and disrupted immune and metabolic pathways across all treatments, with nitrite producing the most severe overall effects (Han et al., 2025).

3 Data Collection and Statistical Methodology for Environmental Impact Assessment

3.1 Experimental design and environmental monitoring strategies

Environmental impact assessment in shrimp aquaculture depends on a design that captures both pond-level variation and time-dependent changes in water conditions. Farm-based studies have therefore used multiple ponds as observational units and monitored key production outcomes such as growth, survival, and biomass alongside environmental and management variables across an entire production cycle (Ruiz-Velazco et al., 2022). This approach is strengthened when monitoring covers physicochemical variables concurrently with biological performance, because it allows environmental measurements to be directly aligned with shrimp response over time (Nazarudin et al., 2025).

Effective monitoring strategies also depend on sampling frequency and method. Semi-intensive pond studies have measured temperature and dissolved oxygen twice daily while salinity was measured weekly, whereas other culture studies combined in situ multiprobe measurements with ex situ spectrophotometric and titration analyses to cover a broader set of variables including nutrients, alkalinity, and organic matter (Ruiz-Velazco et al., 2022). This mixed monitoring design is useful because some variables fluctuate rapidly and require frequent field measurement, while others are better captured through laboratory-based analyses with higher analytical specificity (Akbarurrasyid et al., 2023).

3.2 Statistical approaches for analyzing environmental-growth relationships

Conventional statistical analysis in shrimp environmental studies usually begins with variance and correlation methods to identify which factors differ among ponds and which variables track biological outcomes. In commercial *Penaeus vannamei* production, analysis of variance was used to test whether environmental conditions differed among ponds, and correlation analysis was then applied to link environmental and management variables with final weight and survival. Similar pond studies used regression analysis specifically to quantify the level of relationship between water-quality parameters and shrimp growth, supporting an empirical basis for variable screening before predictive modeling (Akbarurrasyid et al., 2023).