

farms showed that mortality decreased when temperature and dissolved oxygen increased or salinity decreased, while early mortality occurred when temperature increased, oxygen decreased, or ponds were larger. A related dynamic stock analysis for acute hepatopancreatic necrosis disease found that mortality was more severe when salinity was high and pond productivity was low, and that warmer water was associated with earlier outbreaks.

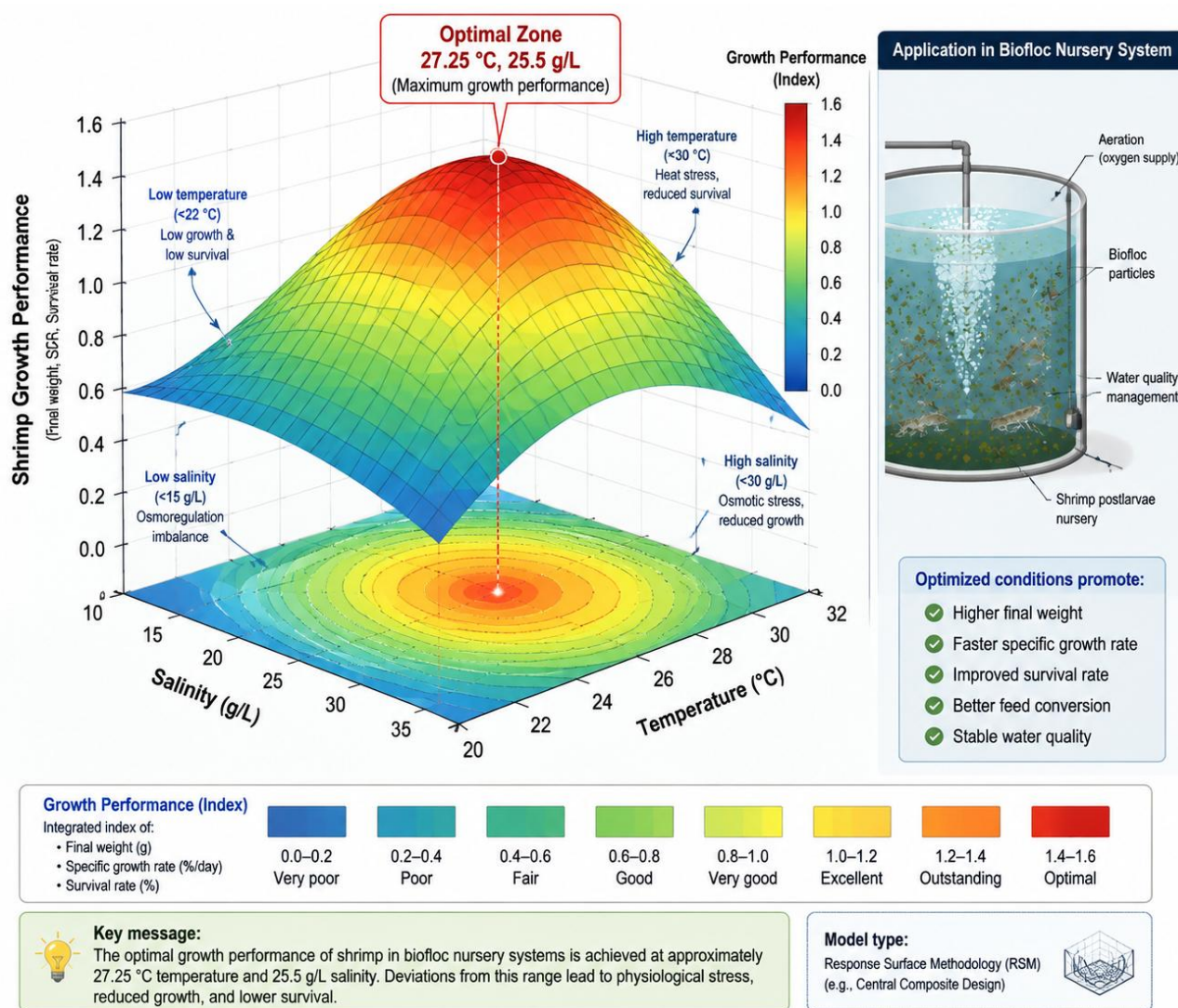


Figure 1 Response surface optimization of shrimp growth performance under different temperature and salinity combinations in intensive nursery systems. The three-dimensional model illustrates the interaction between temperature and salinity and identifies the optimal environmental zone for maximizing growth, productivity, and survival

Machine-learning approaches extend these analyses by predicting survival rate directly from multivariable water-quality data. A Random Forest survival model based on dissolved oxygen, temperature, pH, salinity, and total dissolved solids reported strong fit statistics and identified dissolved oxygen and salinity as the most influential predictors of survival. Logistic regression has also been used at farm scale to estimate the probability of disease occurrence under climatic, operational, and biosecurity conditions, showing that longer crop duration and more years of farm operation increased disease risk, while adaptive management and training reduced it (Le et al., 2024).

5.3 Early-warning systems based on environmental monitoring data

Early-warning systems aim to detect environmental deterioration before it produces mortality, and recent shrimp studies increasingly combine sensors, automation, and predictive analytics for this purpose. IoT-based monitoring systems have been developed to track dissolved oxygen, pH, and temperature continuously and to send real-time alerts when threshold values are exceeded, reducing dependence on manual pond checks. Broader evidence from