However, the same water-saving and high-density features that make RAS efficient can also concentrate biological and chemical risks when management is suboptimal. Reduced water exchange can permit the accumulation of growth-inhibiting factors, bacterial metabolites, and dissolved contaminants, while treatment performance may become unstable across season, hydraulic regime, and biomass load. Net pen systems differ in that they rely on natural water exchange rather than closed-loop treatment, so they generally experience greater direct exposure to fluctuations in temperature, oxygen, and other environmental drivers that can precipitate stress-linked disease events (Ahmed and Turchini, 2021).

8.2 Multi-factorial stress interaction (temperature-oxygen-ammonia coupling effects)

Disease risk in intensive turbot farming is rarely driven by a single variable, because temperature, oxygen, and ammonia interact at both physiological and production levels. Elevated temperature is a major stressor in this cold-water species and has been linked with rapidly increasing disease-induced mortality above 20°C, while high ammonia exposure activates the hypothalamic-pituitary-interrenal axis and suppresses humoral immune indicators such as lysozyme, complement, and IgM. This means that warming and ammonia accumulation can jointly weaken host resistance even before a specific pathogen is identified.

Oxygen availability modifies the severity of ammonia toxicity and therefore changes outbreak risk under intensive culture. In juvenile turbot, chronic un-ionised ammonia above 0.17 mg L^-1 reduced growth under normoxic conditions, whereas hyperoxia increased tolerance to ammonia, indicating that oxygen management can partly buffer toxic nitrogen stress (Gao et al., 2023). Evidence from another marine fish model points in the same direction mechanistically: ammonia exposure under higher temperature increased cortisol and *hsp70*, disrupted antioxidant balance, and reduced innate immune functions, supporting the view that coupled thermal and nitrogen stress can intensify physiological collapse in aquaculture systems.

8.3 Disease outbreak case analysis and management implications

Field and farm observations show that bacterial disease outbreaks remain the dominant health problem in intensive turbot production. A three-year epidemiological survey in China found that bacteria were isolated from 137 of 155 investigated disease cases, with Edwardsiella piscicida and *Aeromonas salmonicida* together accounting for about 71% of all cases, demonstrating that stress-sensitive bacterial pathogens dominate real farm losses (Gao et al., 2023). A separate RAS study detected potential pathogens such as Photobacterium damselae, Tenacibaculum discolor, Tenacibaculum soleae, and Serratia marcescens throughout multiple system compartments even in the absence of overt disease, indicating that intensive systems can harbor persistent background pathogen pressure.

Management implications therefore center on preventing environmental deterioration before it converts latent pathogen presence into clinical outbreak. During an Edwardsiella outbreak in turbot RAS, higher ozone treatment improved survival and reduced heterotrophic bacteria, *Vibrio* loading, and nitrite relative to lower-control conditions, suggesting that tighter water-quality control can reduce outbreak severity even when it does not fully remove infection pressure. At the population level, the marked decline in E. piscicida case proportion after vaccine introduction further indicates that outbreak control is strongest when environmental management is combined with targeted prophylaxis rather than relying on antibiotics alone, especially given the reported increase in antibiotic resistance over time (Gao et al., 2023).

9 Integrated Management Strategies for Health Improvement

Environmental monitoring and early warning systems are increasingly central to health management in turbot farming because intensive aquaculture depends on detecting water-quality instability before it causes physiological stress or mortality. In recirculating aquaculture systems, real-time monitoring of basic parameters such as dissolved oxygen, pH, temperature, turbidity, and salinity is already technically feasible, and IoT-based systems combined with artificial intelligence can generate warnings when conditions approach critical thresholds. This is especially important in turbot culture because emerging evidence shows that dissolved wastes such as phosphate can cause gill, liver, and spleen injury at high concentrations, reinforcing the need to expand monitoring beyond only traditional variables.