

Temperature also alters digestive efficiency by changing enzyme activity, gut processing, and the energetic scope available for postprandial metabolism. In fish generally, digestibility usually declines outside the optimal thermal window because digestive enzyme activities are temperature sensitive, and in turbot, pepsin activity increases from 14°C to 18°C before dropping sharply at 21°C, identifying 16°C-18°C as the practical optimum for feed intake, growth, and digestive performance in larger fish (Volkoff and Rønnestad, 2020). Older radiographic work further showed that gastric emptying time in turbot decreases as temperature rises, indicating faster meal processing at warmer temperatures, but this benefit should be interpreted together with the decline in appetite and enzyme performance once temperatures exceed the optimal range.

7.2 Nutritional regulation of immune competence

Nutritional status is a direct regulator of immune competence in turbot, because both adequate baseline nutrition and targeted supplementation can shape innate and adaptive defense functions. Broad aquaculture reviews agree that balanced nutrient supply is required for efficient host defense and that specific nutrients supplied above minimum requirement can improve fish health and disease resistance. In turbot, this principle is supported by vitamin D3 studies showing that dietary supplementation reduced mortality and spleen bacterial load after *Edwardsiella tarda* infection, while also elevating serum lysozyme activity, haemocyte reactive oxygen species production, and macrophage bactericidal capacity (Liu et al., 2021).

Other micronutrients similarly regulate turbot immunity through antioxidant protection and immune-gene modulation. Dietary vitamin E supplementation increased growth, lysozyme activity, phagocytic index, superoxide dismutase activity, and the expression of immune-related genes including *c3*, *tnf-α*, and *il-1β*, with the best overall response reported at 480 mg kg⁻¹. Vitamin C supplementation also enhanced non-specific immunity in juvenile turbot, particularly by increasing serum lysozyme and phagocytic capacity, whereas both deficient antioxidant supply and oxidized dietary lipid exposure suppressed head-kidney phagocyte function and increased mortality after *Vibrio anguillarum* challenge.

7.3 Feed quality deterioration under environmental stress

Environmental stress can degrade feed quality before ingestion, thereby weakening nutritional value and increasing toxicological risk. Storage studies show that humidity and temperature strongly influence the formation of mycotoxins in compounded fish feeds, and even short-term exposure to unsuitable storage conditions can deteriorate feed quality and promote fungal contamination. Warm, humid storage is particularly problematic because ochratoxin A was detected after treatment at about 25°C and >60% relative humidity, demonstrating how rapidly hazardous contaminants can develop in stored aquafeeds (Pietsch et al., 2020).

The biological consequences of feed deterioration extend beyond reduced nutrient density to impaired immunity and poorer production performance. Reviews on aquafeed contamination note that plant-based ingredients such as maize and oilseeds are favorable substrates for mycotoxigenic fungi and that mycotoxin exposure in fish is associated with reduced weight gain, poorer feed conversion, immune impairment, higher mortality, and possible carryover risks along the food chain. In turbot specifically, nutritionally damaged feed can also act through oxidative deterioration: fish given oxidized fish oil with antioxidant deficiency showed depressed phagocyte chemiluminescent response and higher mortality after bacterial challenge, confirming that environmentally induced feed spoilage can translate directly into reduced disease resistance (Pietsch et al., 2020).

8 Case Study: Environmental Stress-Driven Disease Outbreaks in Intensive Turbot Farming Systems

8.1 Overview of typical industrial recirculating aquaculture systems (RAS) and net pen systems

Industrial turbot farming is increasingly centered on land-based recirculating aquaculture systems because they permit intensive production under controlled indoor conditions and reduce exposure to external climatic variability. In turbot RAS, production water typically passes through linked compartments that include fish tanks, sedimentation units, biofilters, and ozone or protein-skimming chambers, allowing continuous control of temperature, dissolved oxygen, salinity, and nitrogenous wastes (Ahmed and Turchini, 2021). This engineering design supports high stocking density and stable production, which is one reason RAS has become widely used in turbot culture.