

Early warning capacity is strengthened when environmental sensing is paired with anomaly detection, behavioral observation, and predictive analytics rather than relying on periodic manual measurements alone. Aquaculture monitoring platforms now support continuous data transmission, automated warning scores, and real-time visualization, while AI-based systems can detect deviations in fish behavior and water quality patterns quickly enough to support preventive intervention. In parallel, biosensor frameworks and biological early warning systems indicate that physiological or organism-level responses can provide a real-time signal of pollution or other stressors before overt disease develops, which is highly relevant for intensive turbot production under fluctuating environmental loads.

Water quality regulation in turbot systems should focus on preventing the accumulation of nitrogenous wastes, phosphate, and other dissolved metabolites while stabilizing hydraulic and feeding conditions that support biofilter function. In turbot RAS, treatment performance can vary with season, biomass, and recycle rate, and earlier farm-scale work showed instability in solids and nutrient removal under changing outdoor conditions, indicating that regulation must be adaptive rather than static. More recent turbot evidence also shows that feeding frequency affects ammonia and nitrite dynamics, with feeding twice daily producing the highest removal rates and the most stable water environment, likely because this regime better matches digestion and supports nitrification-linked microbial functions.

Biofiltration optimization should therefore integrate engineering control with husbandry management, because microbial treatment efficiency depends on both reactor design and the waste-loading pattern imposed by farming practice. General RAS evidence shows that recirculation can reduce ammonia by more than 80% and phosphate by more than 70%, but persistent high-ammonia zones can still emerge where aeration or local operation is suboptimal. For turbot specifically, continuous phosphate surveillance is now justified because juveniles tolerated 60 mg/L through compensatory tissue repair responses, whereas 120 mg/L caused apoptosis in gill tissue and broader hepatic and immune injury, meaning that dissolved nutrient control should target prevention of chronic sublethal toxicity as well as acute failure.

Probiotic and immunostimulant strategies offer a practical complement to environmental control by strengthening host resilience against the background pathogen pressure typical of intensive turbot farming. In juvenile turbot, dietary oregano oil and *Bacillus coagulans* improved growth, digestive capacity, and resistance to *Aeromonas salmonicida*, while host-associated *Bacillus velezensis* T20 improved intestinal antioxidant capacity, barrier function, microbiota composition, and survival after *Edwardsiella tarda* challenge. Native or host-adapted microbial candidates appear especially promising because prophylaxis is more effective than reactive treatment in early life stages, and beneficial strains can reduce mortality without depending on antibiotic-based control.

Adaptive farming strategies should combine these functional feeds with environmental adjustment of flow, hygiene, and routine operations to reduce chronic stress exposure. In turbot RAS, a flow velocity around 0.9 body lengths per second promoted feed intake, growth, and innate immune indicators, whereas higher velocity acted as a stressor and reduced growth, showing that hydrodynamic settings are a manageable component of health support. Newer dietary interventions also broaden the toolkit: multi-strain probiotics improved enzyme activity and intestinal structure, *B. coagulans* helped restore microbial homeostasis after antibiotics, and postbiotics from *Cetobacterium somerae* improved gut health and disease resistance, supporting a shift toward integrated, low-antibiotic health management in turbot aquaculture.

References

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