

environmental forcing interacts with life stage to shape disease patterns (Fleury et al., 2025). Other stressors, including salinity fluctuations, low flow and hypoxia, affect host-pathogen interactions and immune competence. Experimental manipulation of flow, temperature, salinity and dissolved oxygen showed that oysters in low-flow, high-sedimentation microhabitats had the greatest *Perkinsus marinus* infection prevalence, intensity and mortality, with disease responses significantly negatively correlated with flow, likely due to poorer physiological condition under chronic stress. At the cellular level, hypoxia experiments revealed that granulocytes under moderate low oxygen could transiently enhance phagocytosis and deploy antioxidant and mitophagy responses, but severe hypoxia led to ROS accumulation, mitochondrial dysfunction and impaired lysosomal degradation, suggesting that prolonged or intense hypoxia can overwhelm hemocyte resilience and thereby heighten disease susceptibility (Chen and Wang, 2025).

3 Major Pathogens and Disease Spectrum in Oyster Aquaculture

3.1 Bacterial diseases and the pathogenicity of *Vibrio* species

Bacterial diseases in oyster aquaculture are dominated by *Vibrio* spp., which occur as part of the normal microbiota but include lineages that cause severe mortality. Many *Vibrio* species from the *Splendidus* and *Harveyi* clades are frequently associated with bivalves, and several have been linked to mortality outbreaks as primary or opportunistic pathogens in cultured oysters (Destoumieux-Garzón et al., 2020). Even in non-intensive farming areas without recorded mass mortalities, Pacific oysters can naturally harbor potentially pathogenic *Vibrio* strains, indicating that virulence is present in the microbial community before overt disease is observed (Oyanedel et al., 2022). Specific pathogenic *Vibrio* species and lineages have been identified in large-scale mortality events. In China, mass summer mortality of *Crassostrea gigas* with over 60% losses was associated with *Vibrio alginolyticus*, whose virulence was confirmed experimentally and enhanced at higher temperatures, highlighting temperature-dependent pathogenicity (Wang et al., 2021; Yang et al., 2021). In Europe, *Vibrio aestuarianus* subsp. *francensis* emerged as a specialist oyster pathogen causing recurrent adult mortalities with ~25% mortality rates and shows genomic adaptations such as a copper-resistance island that may favor persistence in oyster hosts (Mesnil et al., 2023).

3.2 Viral diseases and their epidemiological characteristics

Viral infections, especially those caused by Ostreid herpesvirus 1 (OsHV-1) and its microvariants, are a major cause of disease in oyster aquaculture. OsHV-1 has been detected in at least 15 countries and is associated with massive mortalities in *Crassostrea gigas*, with microvariants such as OsHV-1 μ Var driving Pacific oyster mortality syndrome (POMS) that has become panzootic (Alfaro et al., 2019). Descriptive epidemiology from the Hawkesbury River estuary in Australia showed that OsHV-1-associated mass mortalities affected all age classes but were most severe in spat and juveniles, with incubation periods of less than 4 days and evidence of subclinical infection months before overt mortality. Epidemiological studies highlight strong influences of temperature, host age and viral genotype on disease expression. Long-term sentinel monitoring in Australian estuaries found that OsHV-1 mortality typically began when mean water temperature exceeded ~20 °C, with consistent seasonal windows of high risk and spatial clustering at the scale of farms and even baskets. Experimental infections comparing OsHV-1 microvariants isolated between 2011 and 2015 in Australia showed significant reductions in virulence over time, with earlier isolates causing higher hazard of death and cumulative mortality, suggesting that phenotypic variation among genotypes may alter outbreak severity and offering prospects for management using low-virulence strains (Cain et al., 2021).

3.3 Types and impacts of parasitic and fungal diseases

Protozoan parasites of the genera *Perkinsus* and *Haplosporidium* constitute some of the most significant non-viral, non-bacterial threats in oyster aquaculture. In eastern oysters along the U.S. Atlantic and Gulf coasts, *Perkinsus marinus* (dermo) and *Haplosporidium nelsoni* (MSX) are prevalent and have been identified as causative agents of fatal diseases that have triggered mass mortalities and constrained population recovery. (Batchelor et al., 2023). Recent qPCR-based surveys in Georgia and Maine show very high prevalence of *P. marinus* and *H. nelsoni* (often >80 %–90%), with complex relationships to oyster condition that may include emerging resistance or tolerance in some populations despite historical die-offs (Marquis et al., 2020; Batchelor et al., 2023). Other parasitic diseases, notably bonamiasis, have caused severe localized impacts in flat oyster industries and may co-occur with