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# Pathogenic Mechanisms of Marine Pathogens and Outbreak Dynamics

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**Abstract** Marine pathogenic microorganisms, including bacteria, viruses, fungi and parasites, pose a serious threat to marine ecosystems and human health. With global climate change and the increase in human activities, the marine environment has undergone significant changes, resulting in an increase in the frequency and intensity of outbreaks of pathogenic microorganisms. These pathogens not only pose a significant hazard to marine life, but also have serious implications for fisheries, aquaculture and public health. The purpose of this study is to explore the influence of environmental factors on its pathogenicity, analyze the dynamics and mechanisms of pathogenic microbial outbreaks, and provide a scientific basis for formulating effective prevention and control measures through a comprehensive review of the research progress in these aspects, so as to ultimately reduce the threat of marine pathogenic microorganisms to ecosystems and human health.
**Keywords** Marine pathogenic microorganisms; Pathogenesis; Disease outbreak dynamics; Environmental factors; Detection and monitoring

## 1 Introduction

Marine pathogens are disease-causing organisms that significantly impact marine species and ecosystems. These pathogens include bacteria, viruses, fungi, and parasites, which can infect a wide range of marine organisms such as corals, fish, shellfish, and marine mammals. The dynamics of marine infectious diseases (MIDs) are complex and influenced by various factors, including environmental changes, host-pathogen interactions, and anthropogenic activities (Bidegain et al., 2016; Thurber et al., 2020). Unlike terrestrial systems, the transmission of marine diseases often involves waterborne pathogens, which can spread through direct contact or via filter-feeding processes. The lack of physical barriers in marine environments facilitates the rapid spread of pathogens, leading to widespread outbreaks (McCallum et al., 2003).

Understanding the pathogenic mechanisms of marine pathogens is crucial for several reasons. Disease outbreaks can lead to mass mortalities and significant declines in marine populations, disrupting ecosystem balance and biodiversity (Ward and Lafferty, 2014). For instance, coral diseases have been linked to ecosystem regime shifts, resulting in the loss of coral species and degradation of reef habitats. The emergence and spread of marine diseases are often exacerbated by climate change and human activities, such as pollution and aquaculture, which can compromise host immunity and introduce new pathogens (Suffridge et al., 2014). Studying these mechanisms helps in predicting and managing disease outbreaks, thereby protecting marine ecosystems and the services they provide to human societies (Ward and Lafferty, 2014). Additionally, understanding the interactions between hosts, pathogens, and the environment can inform conservation and restoration efforts, particularly in vulnerable ecosystems like coral reefs (Thurber et al., 2020).

This study mainly synthesizes the current knowledge on the pathogenic mechanisms and disease outbreak dynamics of marine pathogens. study the various transmission pathways and factors that influence the spread of marine diseases; explore the impact of human activities on the emergence and spread of marine pathogens; Identify gaps in current research and propose future directions for studying the ecology and management of marine diseases. By achieving these objectives, this study enables a comprehensive understanding of the dynamics of marine pathogens and contributes to the development of effective strategies to mitigate the impacts of marine diseases on ecosystems and human well-being.

## 2 Types of Marine Pathogens

### 2.1 Bacteria

Bacterial pathogens are significant contributors to marine diseases, affecting a wide range of hosts including macroalgae, corals, fish, and other marine organisms. Bacteria within the phylum Bacteroidota, particularly the genera *Tenacibaculum* and *Aquimarina*, are known to cause widespread disease outbreaks in marine eukaryotic hosts. These bacteria often exhibit opportunistic lifestyles, acting as secondary pathogens or participating in polymicrobial diseases, with key virulence traits such as the production of adhesins and tissue-degrading enzymes. Additionally, bacterial pathogens can have a substantial impact on macroalgae, with evidence suggesting that environmental changes may increase the occurrence of bacterial diseases in these hosts (Egan et al., 2014).

### 2.2 Viruses

Viruses are the most abundant entities in marine ecosystems and play crucial roles in oceanic processes through their interactions with all types of marine organisms. They infect a wide range of hosts, from bacteria to whales, and are major drivers of mortality and global geochemical cycles (Suttle, 2015). Marine viruses can manipulate the life histories and evolution of their hosts in remarkable ways, challenging our understanding of their ecological roles (Rohwer and Thurber, 2019). They are also implicated in the termination of algal blooms and can move between marine and terrestrial reservoirs, raising concerns about emerging pathogens (Gleason et al., 2017).

### 2.3 Fungi

Fungal pathogens are increasingly recognized as important agents of disease in marine animals. A comprehensive review identified 225 fungal species causing infections in 193 marine animal species, with Chordata and Arthropoda being the most frequently reported hosts (Pang et al., 2021). *Microsporidia*, *Ascomycota*, *Mucoromycota*, *Basidiomycota*, and *Chytridiomycota* are the primary fungal groups involved, with *Microsporidia* being the most prevalent. These fungi can cause a range of diseases, from respiratory infections in marine mammals to infections in fish and crustaceans. Environmental factors such as global warming and marine pollution are likely to exacerbate fungal disease outbreaks (Pang et al., 2021). Additionally, anamorphic ascomycetes, such as *Aspergillus sydowii*, are known to cause diseases in corals and molluscs, with their prevalence increasing due to changing environmental conditions (Gleason et al., 2017).

### 2.4 Parasites

Parasites play a significant role in marine ecosystems, affecting a variety of hosts including algae, fish, and invertebrates. Parasitic infections can have profound impacts on host population dynamics and ecosystem functioning. For instance, parasitic dinoflagellates of the genus *Amoebophrya* and the newly described *Perkinsozoa*, *Parvilucifera infectans*, are widely distributed in coastal waters and can significantly impact host physiology, behavior, and bloom dynamics (Park et al., 2004). Parasites are also increasingly recognized for their role in algal diseases, contributing to sudden extinctions, regime shifts, and the spread of alien species (Gachon et al., 2010). The complex interactions between parasites, hosts, and environmental conditions underscore the need for further research to understand their full impact on marine ecosystems.

## 3 Pathogenic Mechanisms

### 3.1 Toxin production

Toxin production is a common strategy used by marine pathogens to damage host tissues and disrupt normal cellular functions. For instance, Vibrio vulnificus biotype 3 secretes a multifunctional autoprocessing repeats-in-toxin (MARTX) toxin, which is a critical virulence factor. However, this biotype secretes a less virulent form of the toxin, which allows it to persist longer in host reservoirs by reducing its virulence (Choi et al., 2021). Similarly, Bacillus thuringiensis produces crystal toxins that enable it to invade host tissues and access nutrients, although non-toxin-producing cheaters can outcompete toxin producers, leading to a less virulent population (Raymond et al., 2012).

### 3.2 Host invasion and colonization

Host invasion and colonization are essential steps for pathogens to establish infection. Marine Gram-positive pathogens, such as *Renibacterium salmoninarum* and *Mycobacterium marinum*, utilize various virulence factors to adhere to and invade host tissues. These factors include adhesins, hemagglutination activity, and the type VII secretion system, which facilitate the initial attachment and penetration of host cells (Gnanagobal and Santander, 2022). Enteric pathogens like Escherichia coli and Salmonella species also deploy type III secreted effector proteins to interfere with host defense mechanisms and promote colonization (Kitamoto et al., 2016).

### 3.3 Immune evasion strategies

Successful pathogens have evolved sophisticated strategies to evade the host immune system. *Staphylococcus epidermidis*, for example, forms biofilms on implanted materials, which protect it from immune responses. The biofilm exopolysaccharide polysaccharide intercellular adhesion (PIA) and other proteins modulate effector cell-mediated killing, allowing the pathogen to maintain a chronic infection (Le et al., 2018). Additionally, pathogens like *Citrobacter rodentium* can downregulate their virulence gene expression in response to specific antibody responses, thereby avoiding immune detection and elimination (Kamada et al., 2015).

### 3.4 Virulence factors

Virulence factors are molecules produced by pathogens that enhance their ability to cause disease. These factors can include toxins, enzymes, and other proteins that disrupt host cellular processes (Figure 1). For example, marine Gram-positive pathogens possess unique virulence factors such as hemolysins, Cytolysins, and immune-suppressive proteins that facilitate their survival and proliferation within the host (Gnanagobal and Santander, 2022). Enteric bacterial pathogens also utilize a wide array of virulence factors to outcompete commensal microbiota and establish infection in the gastrointestinal tract (Kamada et al., 2015). Marine pathogens employ a diverse array of mechanisms to infect their hosts and evade immune responses. These mechanisms include toxin production, host invasion and colonization, immune evasion strategies, and the expression of various virulence factors. Understanding these pathogenic mechanisms is essential for developing effective strategies to combat marine pathogen infections.

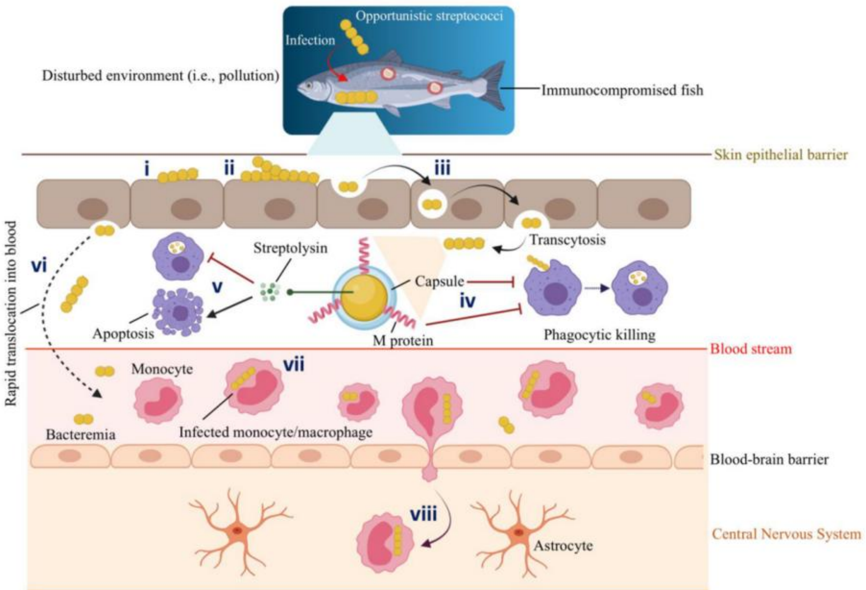


Figure 1 Schematic representation of host-pathogen interactions between marine fish and opportunistic *Streptococcus* spp. (Adopted from Gnanagobal et al., 2022)

Image caption: Gram-positive streptococci infect immunocompromised fish with a decreased immune response that lives in a conducive environment (e.g., polluted marine environment) that facilitates such an infection (Adopted from Gnanagobal et al., 2022)

Figure 1 illustrates host-pathogen interactions between marine fish and opportunistic streptococcus species. In contaminated marine environments, immunocompromised fish are more susceptible to gram-positive streptococcal infections. The infection process consists of several stages: bacteria first invade the epithelial barrier by adhesion and colonization, and then by transcellular action; Antiphagocytic factors such as capsules and M proteins of streptococci help them survive during phagocytosis. Cytolysin secreted by streptococci also inhibits phagocytosis and induces apoptosis in phagocytic cells. Infected macrophages act as "Trojan horses" that carry streptococci across the blood-brain barrier and into the central nervous system. This process illustrates how streptococcus bacteria are rapidly transferred to the circulatory system through a brief period of intracellular survival and ultimately affect the central nervous system of fish.

## 4 Environmental Factors Influencing Pathogenicity

### 4.1 Water temperature

Water temperature is a critical factor influencing the pathogenicity of marine pathogens. Elevated seawater temperatures have been shown to enhance the growth and virulence of various marine bacteria. For instance, the abundance of V*ibrio* species, including *Vibrio vulnificus*, *Vibrio parahaemolyticus*, and *Vibrio cholerae*, increases in warm, low-salinity waters, correlating with higher ambient temperatures (Baker-Austin et al., 2017). This relationship is particularly evident during heatwaves and extreme weather events, which have been linked to outbreaks of Vibrio-related diseases in temperate regions (Baker-Austin et al., 2017). Similarly, the fish pathogen P*hotobacterium damselae* subsp. damselae exhibits enhanced growth and upregulation of virulence factors at higher temperatures, suggesting that elevated seawater temperatures contribute to disease outbreaks in aquaculture (Matanza and Osorio, 2018). Additionally, increased seawater temperatures have been shown to upregulate the expression of virulence factors in Vibrio parahaemolyticus, facilitating adhesion and biofilm formation, which are critical for infection (Billaud et al., 2022).

### 4.2 Salinity and pH

Salinity and pH are also significant environmental factors that influence the distribution and pathogenicity of marine pathogens. *Vibrio cholerae*, for example, thrives in specific salinity ranges and pH levels, which are critical for its survival and proliferation in marine environments (Thurber, 2020). Changes in these parameters can affect the ecological niche of *V. cholerae,* potentially expanding its geographical distribution under future climate scenarios (Escobar et al., 2015). The interplay between salinity, pH, and other environmental factors such as chlorophyll-a and sea surface temperature further complicates the dynamics of pathogen distribution and disease transmission (Escobar et al., 2015).

### 4.3 Nutrient availability

Nutrient availability plays a crucial role in the growth and virulence of marine pathogens. The presence of nutrients such as iron can significantly influence the proliferation of opportunistic organisms and the virulence of pathogenic microbes. For instance, increased deposition of iron-rich eolian dust to typically iron-poor marine regions has been linked to the growth of opportunistic organisms and the virulence of pathogenic microbes (Issifu et al., 2022). This phenomenon is particularly evident in macronutrient-rich coastal systems, where the increased iron supply alters the micronutrient factors limiting the growth of these organisms. Additionally, nutrient uptake mechanisms are upregulated in pathogens like Photobacterium damselae subsp. damselae at higher temperatures, further contributing to their pathogenicity (Kibria et al., 2021).

### 4.4 Pollution and contaminants

Pollution and contaminants are significant environmental stressors that can influence the pathogenicity of marine pathogens. Pollutants such as plastics can serve as vectors for harmful pathogens, facilitating their dissemination in marine environments (Billaud et al., 2022). Elevated seawater temperatures, combined with plastic pollution, have been shown to enhance the adhesion properties of *Vibrio parahaemolyticus* to plastic surfaces, emphasizing the role of pollution in the spread of this pathogenic bacterium (Billaud et al., 2022). Moreover, pollution can compromise the immunity of marine organisms, making them more susceptible to infections. For example, pollution and terrestrial pathogens have been implicated in increased disease incidence in marine mammals and other taxa (Lafferty et al., 2004). The combined effects of climate change, pollution, and other anthropogenic factors create a complex interplay that drives the emergence and spread of marine diseases (Bidegain et al., 2016). Environmental factors such as water temperature, salinity, pH, nutrient availability, and pollution significantly influence the pathogenicity of marine pathogens. Understanding these factors is crucial for predicting and managing disease outbreaks in marine ecosystems.

## 5 Outbreak Dynamics

### 5.1 Transmission pathways

Marine pathogens exhibit diverse transmission pathways, significantly influencing outbreak dynamics. Waterborne transmission is a predominant route (Figure 2), where pathogens are disseminated through the water column, affecting both direct contact and filter-feeding organisms (Tien and Earn, 2010; Bidegain et al., 2016). For instance, infected individuals can shed pathogens into the water, leading to new infections through exposure to contaminated water (Tien and Earn, 2010). Additionally, scavengers and filter feeders play crucial roles in either inhibiting or facilitating the spread of pathogens, depending on their interactions with the infected hosts and the environment (Bidegain et al., 2016). The complexity of these pathways necessitates comprehensive models to predict and manage disease spread effectively.

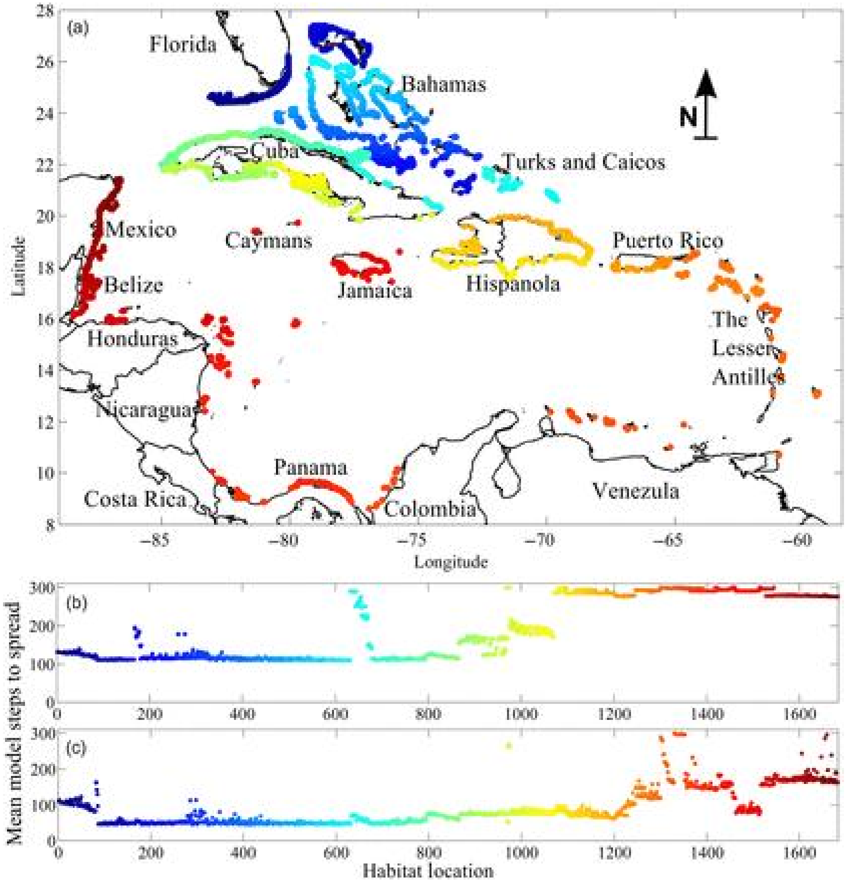


Figure 2 Habitat map and mean pathogen spread times around the Caribbean (Adopted from Kough et al., 2015)

Image caption: Colour is used to identify locations on the map and links the position of the habitat on the x-axis in the panels (b and c) of the mean pathogen spread time to a spatial location (a) (Adopted from Kough et al., 2015)

Kough et al. (2015) demonstrated the distribution and connectivity of coral reefs in islands and coastal areas through habitat mapping and pathogen transmission simulations in the Caribbean region. By comparing the two scenarios of waterborne and late larval transmission, it is clear that geographic spread and environmental interactions significantly influence pathogen transmission. This detailed approach not only contributes to understanding the dynamics of marine pathogens such as PaV1, but also highlights the critical role of spatial configuration in the management of marine diseases. These insights are essential for developing targeted conservation and intervention strategies to protect vulnerable marine ecosystems.

### 5.2 Epidemiological models

Epidemiological models are essential tools for understanding and predicting the spread of marine infectious diseases. Various models, such as the stochastic, spatiotemporal hybrid simulation model DTU-DADS-Aqua, have been developed to simulate infection transmission and control strategies in marine aquaculture (Romero et al., 2021). These models incorporate compartmental and agent-based approaches to account for infection spread within and between net-pens, considering factors like seaway distance and farm-site hydroconnectivity (Romero et al., 2021). Metapopulation models, which consider patchily distributed hosts, have also been applied to coral reefs, highlighting the prolonged nature of epizootics and the slow recovery at regional scales (Sokolow et al., 2019). These models provide valuable insights into the long-term consequences of disease introduction and the effectiveness of various control measures.

### 5.3 Factors contributing to outbreaks

Several factors contribute to the emergence and severity of marine pathogen outbreaks. Environmental conditions, such as climate change and pollution, can compromise host immunity and facilitate the introduction of new pathogens (Klinkenberg et al., 2017). For example, increased sea temperatures associated with El Niño events have been linked to higher incidences of coral bleaching and subsequent disease outbreaks. Anthropogenic activities, including aquaculture and global transport of species, also play significant roles in spreading pathogens to previously unexposed host populations (Thurber et al., 2020). Additionally, the presence of environmental reservoirs and the pathogen's ability to persist in these reservoirs can influence the likelihood and magnitude of outbreaks.

### 5.4 Case Studies of marine pathogen outbreaks

Several case studies illustrate the dynamics and impacts of marine pathogen outbreaks. The spread of infectious salmon anaemia virus (ISAv) in farmed Atlantic salmon populations in New Brunswick, Canada, and Maine, USA, demonstrated the importance of disease detection, surveillance, and depopulation measures in controlling outbreaks (Romero et al., 2021). Another notable example is the white plague type II (WPII) outbreak among corals in the upper Florida Keys, where metapopulation models successfully predicted the spatial and temporal patterns of the disease over a decade (Sokolow et al., 2019). These case studies underscore the need for robust epidemiological models and effective management strategies to mitigate the impacts of marine pathogen outbreaks.

## 6 Detection and Monitoring

### 6.1 Molecular and microbiological techniques

Molecular and microbiological techniques are fundamental in the detection and monitoring of marine pathogens. These methods include traditional culturing, polymerase chain reaction (PCR), and advanced next-generation sequencing (NGS) technologies. For instance, droplet digital PCR and Illumina MiSeq sequencing have been effectively used to detect fish pathogens such as *Flavobacterium columnare* and *Flavobacterium psychrophilu*m in aquaculture settings, demonstrating high sensitivity and accuracy (Testerman et al., 2021). Additionally, environmental DNA (eDNA) and RNA (eRNA) approaches have emerged as powerful tools for monitoring pathogens in aquatic environments. These methods offer advantages such as lower cost, reduced labor, and the ability to detect non-culturable organisms, making them suitable for large-scale surveillance (Amarasiri et al., 2021; Farrell et al., 2021). Furthermore, electrochemical sensors and nanotechnology-based smart sensors are being developed to provide rapid, sensitive, and specific detection of pathogens, which are crucial for early warning systems and outbreak prevention (Amiri et al., 2018; Alafeef et al., 2020).

### 6.2 Remote sensing and in situ observations

Remote sensing and in situ observations are increasingly being utilized to monitor marine pathogens and their environmental drivers. Satellite-based remote sensing has advanced significantly, allowing for the detection of marine microorganisms, including harmful algal blooms and bacteria, from space. These technologies have evolved from creating visual representations to developing predictive models that can provide early warnings for disease outbreaks (Grimes et al., 2014). Time series observations and the integration of satellite data with in situ measurements have enhanced our understanding of microbial dynamics and their impact on ocean health (Buttigieg et al., 2018). These methods are particularly valuable for monitoring vast and remote ocean regions that are otherwise difficult to access.

### 6.3 Early warning systems

Early warning systems are essential for mitigating the impact of marine pathogen outbreaks. The integration of molecular techniques, remote sensing, and advanced data analytics has paved the way for more effective surveillance and early detection of pathogens. For example, the combination of eDNA/eRNA monitoring with remote sensing data can provide real-time information on pathogen presence and distribution, enabling proactive responses to potential outbreaks (Amarasiri et al., 2021; Farrell et al., 2021). Additionally, the development of portable NGS and AI-based image diagnosis systems holds promise for reducing labor costs and improving the sensitivity and specificity of pathogen detection in aquatic environments (Figure 3) (Macaulay et al., 2022). These advancements are crucial for establishing robust early warning systems that can prevent large-scale disease outbreaks and protect both human and marine health.

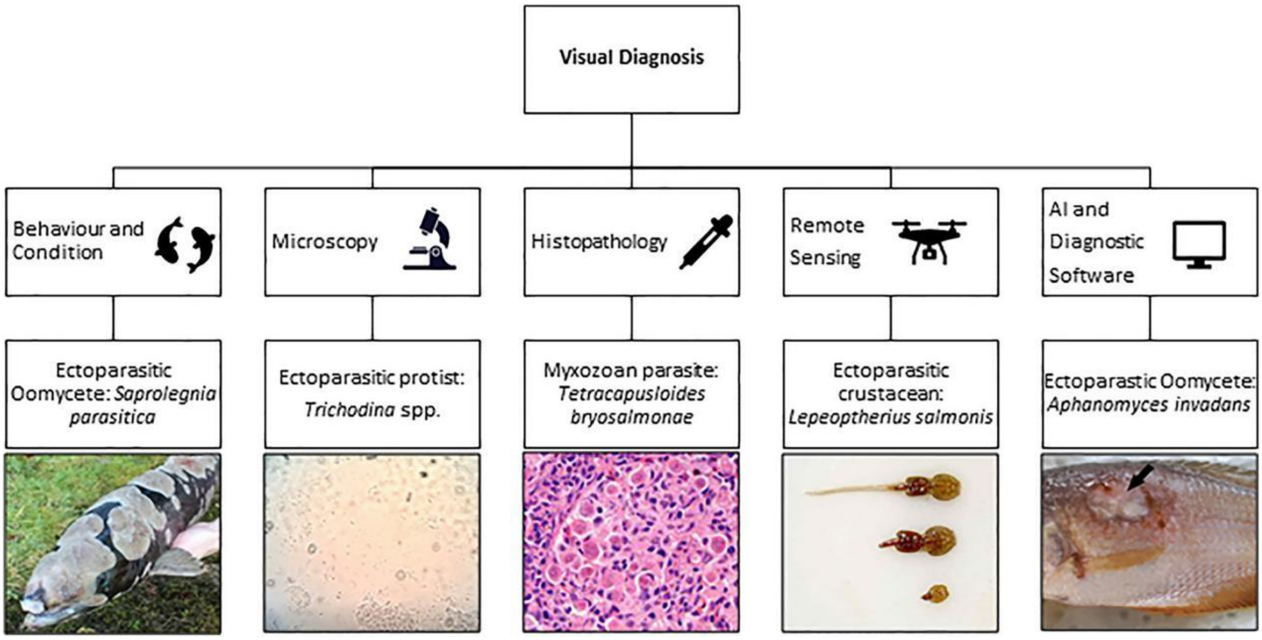


Figure 3 Visual diagnostic techniques and examples of their application in specific aquatic pathogens (Adopted from Macaulay et al., 2022)

## 7 Impact on Marine Ecosystems and Human Health

### 7.1 Effects on marine biodiversity

Marine pathogens have significant impacts on marine biodiversity, often leading to declines in various species. Disease outbreaks can alter the structure and function of marine ecosystems, affecting vertebrates such as mammals, turtles, and fish, as well as invertebrates like corals, crustaceans, and echinoderms (Zgouridou et al., 2021). For instance, recent disease-driven mass mortalities have impacted foundation species such as corals and seagrasses, herbivores like abalone, and keystone predators like sea stars, contributing to extreme population declines and endangerment (Harvell and Lamb, 2020). The increase in disease reports in several marine groups over recent decades underscores the urgency of understanding disease dynamics to formulate effective resource management policies (Zgouridou et al., 2021).

### 7.2 Economic impacts on fisheries and aquaculture

Marine diseases have profound economic impacts on fisheries and aquaculture. Infectious diseases can reduce the growth, fecundity, and survivorship of commercial species, thereby diminishing their marketability and economic value (Lafferty et al., 2015; Behringer et al., 2020). For example, diseases affecting farmed oysters, shrimp, abalone, and various fishes, particularly Atlantic salmon, result in billions of dollars in losses annually. The economic losses have driven research efforts to minimize the negative impacts of diseases on these industries. However, the relationship between fisheries, aquaculture, and disease transmission is complex and reciprocal, with different outcomes at various ecological levels (Minich et al., 2020). Additionally, parasites acquired during early marine migration can significantly impact fish recruitment, as evidenced by the substantial loss of adult salmon recruitment due to parasitic crustaceans.

### 7.3 Public health concerns

Marine diseases also pose significant public health concerns. The consumption of pathogen-infected seafood, particularly bivalve molluscs, can lead to foodborne illnesses in humans (Zgouridou et al., 2020). Climate change exacerbates this issue by accelerating the growth and spread of pathogenic microorganisms and toxic microalgae in marine habitats, increasing the risk of human exposure to these pathogens. Furthermore, the use of antibiotics and other chemicals to treat marine diseases in aquaculture can have negative implications for human health, including the potential for antibiotic resistance (Behringer et al., 2020). The interconnectedness of ocean and human health highlights the need for adaptive management approaches to mitigate the impacts of marine diseases in a changing climate (Suffridge et al., 2014).

## 8 Mitigation and Management Strategies

### 8.1 Prevention and control measures

Prevention and control measures are critical in managing marine pathogen outbreaks. Effective strategies include enhanced surveillance, early detection, and rapid response to outbreaks. Simulation models, such as the DTU-DADS-Aqua, have been developed to predict and manage the spread of infectious diseases in marine aquaculture. These models allow for the exploration of various "what-if" scenarios, helping to optimize surveillance and depopulation strategies to reduce the number of infected sites and outbreak duration (Romero et al., 2021). Additionally, adaptive management approaches are recommended to increase the resilience of ocean systems to climate change, which influences the dynamics of marine diseases (Thurber et al., 2020). Quarantining, culling, and vaccinating, although effective on land, are less successful in marine environments, necessitating the development of new tools and approaches.

### 8.2 Treatment and remediation techniques

Treatment and remediation techniques for marine diseases include both traditional and innovative methods. Traditional methods such as nutrient load reduction are used to mitigate harmful algal blooms, while experimental approaches like artificial mixing and flushing are being adapted to address the impacts of climate change on these blooms (Paerl et al., 2016). Disruption of bacterial quorum sensing is another promising strategy to combat bacterial infections in aquaculture. Techniques such as the inhibition of signal molecule biosynthesis and the application of quorum sensing antagonists have shown potential in reducing virulence and controlling infections (Glidden et al., 2021). For viral pathogens in shellfish, current water treatment practices are insufficient, and there is a need for standardized virus detection methods to manage shellfishborne diseases effectively.

### 8.3 Policy and regulatory frameworks

Effective management of marine diseases also requires robust policy and regulatory frameworks. The inclusion of virus analysis in regulatory standards for shellfish is essential to ensure public health safety. Efforts are underway to develop standardized methods for virus detection in foodstuffs, which could be incorporated into legislation (Bosch and Guyader, 2010). Additionally, policies that prioritize marine disease research, improve ecosystem health, and establish better monitoring and response networks are crucial. Developing marine veterinary medicine programs and enacting comprehensive policies that address both marine and terrestrial wildlife diseases are recommended to enhance disease management (Glidden et al., 2021). Furthermore, understanding the links between climate change and marine diseases is vital for formulating effective resource management policies.

## 9 Future Directions and Research Needs

### 9.1 Advances in pathogen research

The study of marine pathogens has made significant strides, yet several critical areas require further exploration. One of the primary research needs is the detection of origins and reservoirs for marine diseases, as well as tracing the flow of new pathogens from terrestrial to marine environments. Additionally, understanding the longevity and host range of infectious stages is crucial for managing disease outbreaks. The role of anthropogenic factors as incubators and conveyors of marine pathogens also needs to be pinpointed. Moreover, the development of more sophisticated epidemiological models tailored to marine systems is essential for analyzing disease dynamics (Bidegain et al., 2016).

### 9.2 Emerging technologies for detection and control

Emerging technologies hold promise for improving the detection and control of marine pathogens. Advances in molecular biology, such as qPCR and proteomic-based techniques, have enhanced our ability to characterize diseases and understand pathogen-host interactions (Gotesman et al., 2018). The application of RNAi and CRISPR/Cas-based therapies shows potential in combating various types of diseases caused by viral and parasitic agents. Additionally, the use of remote sensing, computer technology, and data analytics can open new avenues for studying marine diseases and improving surveillance (Thurber et al., 2020). Rapid and specific identification of microbes from complex environmental samples is another area where technological advancements are needed (Thurber et al., 2020).

### 9.3 Interdisciplinary approaches

Interdisciplinary approaches are vital for advancing our understanding of marine disease dynamics. Integrating knowledge from microbiology, molecular biology, and ecology can provide a more holistic view of disease mechanisms. For instance, expanding the pathogen component of the classic host-pathogen-environment disease triad to incorporate shifts in the microbiome leading to dysbiosis offers a better model for understanding coral disease dynamics. Furthermore, a multidisciplinary approach that addresses microbial symbiosis in both healthy and diseased states at the level of the holobiont will be key to progress in this area (Egan et al., 2016). Collaborative efforts across disciplines can also help in developing predictive models and management strategies for seagrass diseases under future global change scenarios (Sullivan et al., 2017).

## 10 Concluding Remarks

The systematic review of marine pathogens and outbreak dynamics reveals several critical insights into the mechanisms driving disease emergence and spread in marine ecosystems. The dynamics of marine infectious diseases (MIDs) are influenced by complex interactions between hosts, pathogens, and environmental factors. For instance, the transmission of diseases in marine environments can occur through direct contact with waterborne pathogens or via filter-feeding processes, with scavengers playing a role in inhibiting disease spread by removing infected animals. Coral diseases, in particular, are significantly driven by environmental changes, with shifts in the microbiome contributing to disease dynamics. Climate change has been identified as a major factor exacerbating disease outbreaks by compromising host resistance and facilitating the spread of opportunistic pathogens.

Additionally, the rapid spread of marine pathogens, such as herpes virus in pilchards and morbillivirus in marine mammals, underscores the need for robust epidemic models to predict and manage these outbreaks. The review also highlights the role of innate immunity in marine invertebrates and how environmental stressors can compromise immune responses, leading to increased disease susceptibility.

Continued research in marine pathogen dynamics is crucial for several reasons. Understanding the specific mechanisms of disease transmission and the factors that influence outbreak dynamics can inform the development of effective management strategies. For example, the role of filter feeders in modulating disease spread suggests potential interventions to mitigate outbreaks. The impact of climate change on marine diseases necessitates ongoing monitoring and adaptive management approaches to enhance the resilience of marine ecosystems. The increasing frequency and severity of disease outbreaks in marine species, such as corals and marine mammals, highlight the urgent need for comprehensive studies to identify the underlying causes and develop targeted conservation efforts. The integration of modern paradigms, such as the host-microbiome-environment triad, can provide a more holistic understanding of disease dynamics and inform future research directions.

Future studies should focus on several key areas to advance our understanding of marine pathogen dynamics and improve outbreak management.There is a need for more detailed modeling of disease transmission pathways, including the role of non-focal hosts and environmental factors, to predict and mitigate the spread of infectious diseases. Research should prioritize the identification of specific environmental stressors that compromise host immunity and facilitate pathogen proliferation, with a particular focus on the impacts of climate change and pollution. Interdisciplinary approaches that integrate microbiome studies with traditional disease ecology can provide deeper insights into the mechanisms driving disease outbreaks and inform more effective conservation strategies. Additionally, the development of adaptive management frameworks that incorporate real-time monitoring and forecasting of disease conditions can enhance the resilience of marine ecosystems to disease outbreaks. Collaborative efforts between researchers, policymakers, and stakeholders are essential to address the multifaceted challenges posed by marine diseases and ensure the sustainable management of marine resources.

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## Conflict of Interest Disclosure

The author affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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