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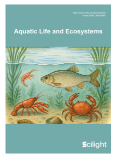

Review

Pathogen-Associated Diseases in Tuna Aquaculture: Current Challenges and Future Research Directions

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How To Cite: Liu, X.; Huang, J.; Fu, Z.; et al. Pathogen-Associated Diseases in Tuna Aquaculture: Current Challenges and Future Research Directions. *Aquatic Life and Ecosystems* **2025**. https://doi.org/10.53941/ale.2025.100006

Received: 11 September 2025
Revised: 15 October 2025
Accepted: 22 October 2025
Published: 27 October 2025

Abstract: Tuna aquaculture faces significant challenges from various pathogen-associated diseases, including bacterial, fungal, viral, and parasitic infections, which threaten both the health of farmed tuna and the economic viability of the industry. This review provides an overview of the current status of these diseases in tuna farming, with a focus on the pathogenic mechanisms, environmental stressors, and management strategies. Bacterial infections, particularly those caused by *Vibrio* species and *Photobacterium damselae*, remain major threats, often exacerbated by environmental stressors such as high water temperatures and poor water quality. Fungal diseases, which impact the gills of yellowfin tuna, and viral diseases, notably Nervous Necrosis Virus (NNV), present additional risks that result in high mortality rates, especially among juvenile fish. Parasitic diseases, including infestations by flatworms like *Cardicola forsteri* and ectoparasites such as *Caligus* species, also contribute to significant losses in tuna farming. Despite progress in understanding these pathogens, critical research gaps remain, particularly in the areas of immune system responses, pathogen-host interactions, and the development of sustainable disease control measures. The overuse of antibiotics and chemicals in disease management has led to growing concerns over antimicrobial resistance and environmental pollution. Future research should prioritize integrated disease management systems, including the development of eco-friendly control strategies such as probiotics, immunostimulants, and vaccines. Furthermore, the impact of environmental factors on disease dynamics requires more in-depth investigation, alongside the development of predictive models and real-time monitoring systems for better disease management. Addressing these challenges with a multidisciplinary approach will be crucial to improving the health and productivity of farmed tuna, thereby ensuring the sustainability of the tuna aquaculture industry.

Keywords: tuna; bacterial diseases; fungal diseases; viral diseases; parasitic infections; aquaculture management

1. Introduction

Tuna, a member of the family Scombridae and genus *Thunnus*, is a typical epipelagic migratory species found in warm waters [1]. It is predominantly distributed in tropical and subtropical seas worldwide and represents one of the most economically valuable marine fish resources in international fisheries trade [2]. The global production of farmed tuna reached approximately 154,281 tons in 2022, exhibiting a sustained annual growth rate exceeding

10% since 2020 [3]. Tuna meat is characterized by its high protein, low-fat content, and rich levels of unsaturated fatty acids (such as docosahexaenoic acid, DHA) and trace elements beneficial to human health [4,5]. With the continuous growth of the tuna market, the s pecies faces increasing challenges due to overfishing and resource depletion, which have severely threatened population numbers and sustainability [6,7].

To address this resource crisis, artificial aquaculture has gradually become an essential direction for the development of the tuna industry [8]. Tuna aquaculture primarily involves two methods: capture-based fattening and closed-cycle farming. The former relies on capturing juvenile fish for fattening, while the latter aims to reduce dependence on wild resources through fully controlled, artificial breeding [9]. Countries such as Japan [10], Spain [11], and Australia [12] have made significant breakthroughs in cage farming and artificial breeding of species, including the Atlantic bluefin tuna (*Thunnus thynnus*), southern bluefin tuna (*Thunnus maccoyii*), and yellowfin tuna (*Thunnus albacares*). In recent years, China has also made progress in exploring the artificial aquaculture of yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in the South and East China Seas [13]. Furthermore, this study summarizes the distribution of major tuna farming regions worldwide (Figure 1).

Tuna farming systems, particularly those focused on species such as yellowfin and bigeye tuna, have been instrumental in sustaining global supply [14]. These species are selected for their adaptability and economic value, with yellowfin tuna being particularly prized in international markets for sashimi and other seafood products. However, tuna's fast growth, high metabolic rate, early sexual maturity, and rapid juvenile growth [15] make it particularly susceptible to stressors such as high stocking density, monotonous diets, water quality fluctuations, and changes in temperature and salinity in artificial farming systems. These factors lead to immune dysfunction and frequent disease outbreaks [16]. The primary diseases affecting tuna aquaculture include bacterial infections (e.g., septicemia caused by *Vibrio* species), Fungal diseases, viral diseases, and parasitic infections, which often result in large-scale mortality and significant economic losses, posing a critical constraint to the sustainable development of the tuna farming industry [17–21]. Furthermore, immune suppression caused by environmental stress makes tuna more vulnerable to viral infections [16,22]. Additionally, although new aquaculture systems such as recirculating aquaculture systems (RAS) have mitigated environmental fluctuations to some extent, the closed high-density conditions in these systems facilitate the spread of pathogens, thus complicating disease management [23].

Figure 1. Global distribution of tuna aquaculture. The map highlights key tuna farming regions across Asia, Europe, Oceania, and South America. Red indicates large-scale producers (approximately 21,500 tons), such as Japan [24]; Orange represents medium-scale producers (approximately 9744 tons), including Spain [25]; Green represents the combined total of small-scale producers (approximately 8000 tons) in Australia and New Zealand [3,26]; Yellow marks smaller-scale producers (approximately 6000 tons), such as Mexico.

https://doi.org/10.53941/ale.2025.100006

Therefore, this review primarily investigates the diseases affecting tuna during the aquaculture process, focusing on the types of pathogens involved and the underlying mechanisms of disease progression. We will explore the four categories of pathogen-related diseases—bacterial, fungal, viral, and parasitic—providing a deeper understanding of their characteristics and impacts on farmed tuna. Additionally, we will discuss the interaction between environmental stressors and pathogen infections, as these factors are crucial for optimizing farming management practices, improving fish immunity, and promoting the sustainable development of the tuna industry.

2. Current Status in Bacterial Pathogen-Associated Diseases of Tuna

Bacterial diseases are one of the most common and devastating health issues in tuna (*Thunnus*) aquaculture systems, particularly under high-density cage farming and fluctuating environmental conditions, where outbreaks are more likely to occur [27]. The survival rate of tuna larvae in hatcheries is often low, with severe hyperplasia, epithelial desquamation, necrosis, and capillary dilation observed in their gills. These symptoms are accompanied by the presence of large numbers of bacteria and skin lesions, which significantly constrain the development and production efficiency of tuna farming [28]. This review also compiles the pathogenic and spoilage-related bacteria isolated from tuna species, highlighting their sites of infection and relevant references (Table 1).

Vibrio species are the primary pathogens responsible for septicemia, commonly found in seawater and brackish environments, especially in cold-water and warm-water-adapted fish species [29]. Kapetanovic et al. [30] studied bacterial diversity in cultured bluefin tuna (*Thunnus thynnus*) from the Adriatic Sea, isolating *Vibrio* species such as *Vibrio harveyi* and *Vibrio alginolyticus* from the gut and muscle tissues. The study linked high stocking densities and water quality issues to increased bacterial presence, highlighting the need for improved pathogen management strategies in tuna aquaculture. *Photobacterium damselae* subsp. *piscicida*, a Gram-negative, halophilic rod-shaped bacterium, is known to cause pseudomonad disease in fish [31]. Research indicates that *Photobacterium damselae* subsp. *piscicida* caused severe juvenile fish mortality in Mediterranean bluefin tuna (*Thunnus thynnus*) farms, making it one of the most threatening bacterial pathogens [32]. These two major bacteria pose a significant threat to the growth and survival of tuna species.

The occurrence of bacterial diseases is closely related to environmental stressors such as high water temperature, low dissolved oxygen, ammonia nitrogen accumulation, and the use of monotonous diets, all of which can reduce the fish's immunity and increase the risk of infection [33]. For instance, high water temperatures can significantly affect the immune system of fish, leading to decreased immunity and making them more susceptible to pathogenic bacteria [34]. Elevated temperatures may also promote the growth and spread of pathogenic bacteria such as *Vibrio* and *Photobacterium*, thereby increasing the infection risk [35,36].

Currently, bacterial disease control primarily relies on antibiotics and chemical agents; however, the overuse of these treatments has led to antimicrobial resistance and environmental pollution, posing a global challenge for the aquaculture industry [37]. In recent years, green control measures such as probiotics, immunostimulants, and oral vaccines have received increasing attention, though application research on tuna remains limited. These emerging methods show potential in reducing pathogen infections and improving farming environments, but more empirical research is needed to assess their effectiveness. Overall, bacterial diseases remain a major constraint on the health and productivity of farmed tuna, reflecting the complex interplay between pathogens, host immunity, and environmental stressors in intensive aquaculture systems.

Table 1. Bacterial pathogens in tuna species: reported hosts and infection sites.

Bacterial Names	Host	Site of Infection	Reference
Vibrio harveyi	*Thunnus thynnus*	Gut	Kapetanovic et al. (2006) [30]
Photobacterium damselae	*Thunnus thynnus*	Spleen and kidney	Mladineo et al. (2002) [31]
Acinetobacter johnsonii and Shewanella putrefaciens	*Thunnus obesus*	Muscle tissue	Wang, Xie (2021) [38]
Shewanella putrefaciens	*Thunnus obesus*	Muscle tissue	Yi, Xie (2022) [39]
Pseudomonas	*Thunnus orientalis*	Gut	Taniguchi et al. (2022) [27]

3. Current Status in Fungal Pathogen-Associated Diseases of Tuna

Fungal diseases represent a potential threat to the health of both farmed and wild tuna, with increasing concern over the pathogenicity of fungal infections [40]. Recent studies on fungal diseases in tuna have expanded to include the identification of fungal species, elucidation of pathogenic mechanisms, and their impact on tuna growth and immune systems, providing new strategies for disease prevention in aquaculture.

In the farming of yellowfin tuna (*Thunnus albacares*), researchers have identified various pathogenic fungi parasitizing the gills, causing lesions, necrosis, and decay. Based on morphological characteristics and molecular comparison, eight fungal genera have been identified (Table 2): *Aspergillus*, *Penicillium*, *Rhizopus*, *Mucor*, *Trichoderma*, *Curvularia*, *Verticillium*, and *Cladosporium* [40]. These fungi not only disrupt the fish's immune barriers but may also impair gas exchange in the gills, further exacerbating growth stagnation and decline in the physical condition of the tuna. Additionally, fungal infections are often linked to deteriorating water quality and elevated temperatures, especially with the increasing frequency of extreme weather events globally, which significantly raises the incidence of fungal infections and poses a serious economic threat to tuna farming [41].

However, many fish diseases commonly classified as "fungal" are in fact caused by organisms that are not true fungi. In the aquaculture of Atlantic bluefin tuna (*Thunnus thynnus*), López-Verdejo et al. [42] identified a novel microsporidian (a group belonging to the fungal lineage), which was subsequently confirmed as a new species, *Glugea thunni*. This pathogen primarily infects juvenile fish, inducing severe visceral pathologies and forming whitish xenomas within the caecal mass.

Currently, research on fungal diseases in tuna mainly focuses on pathogen identification and morphological analysis. While the pathogenic roles of some common fungal pathogens have been preliminarily revealed, key areas such as the complete lifecycle of the fungi, infection mechanisms, host specificity, and immune evasion strategies remain underexplored. Given the severe impact of fungal infections on the survival rates of tuna juveniles, aquaculture profitability, and overall health, there is an urgent need for more in-depth studies. The limited understanding of these fungi hinders effective prevention and treatment. Additionally, environmental factors like water quality and temperature complicate disease management. Fungal diseases thus pose a significant challenge in tuna aquaculture, requiring further investigation into their mechanisms and impacts.

Table 2. Fungal pathogens in tuna species: reported hosts and infection sites.

Fungal Names	Host	Site of Infection	Reference
Aspergillus	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Penicillium	*Thunnus albacares*	Gill	Suryanti et al. (2018) [40]
Rhizopus	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Mucor	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Trichoderma	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Curvularia	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Verticillium	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Cladosporium	*Thunnus. albacares*	Gill	Suryanti et al. (2018) [40]
Glugea thunni	*Thunnus thynnus*	Intestinal mesentery (associated with caecal mass), liver, peritoneum, cloaca	López-Verdejo et al. (2022) [42]

4. Current Status in Viral Pathogen-Associated Diseases of Tuna

The viral genome of tuna is primarily composed of eukaryotic viruses, concentrated in the intestines and liver, while bacteriophages are predominantly found in the mucus of the fish [43]. Compared to bacterial infections, research on viral diseases in tuna aquaculture systems is relatively limited. However, when viral diseases occur, they typically result in extremely high mortality rates, posing a significant threat to juvenile production. This review summarizes the major viruses reported from various tuna species, highlighting their viral families and associated references (Table 3).

For instance, in hatcheries of Pacific bluefin tuna (*Thunnus orientalis*) in Japan, Nervous Necrosis Virus (NNV) causes significant neurological symptoms, such as abnormal swimming, imbalance, and high mortality rates, with mortality in juvenile stages reaching over 90% [44]. Additionally, β-nodavirus also impacts the occurrence of neuronecrosis in Pacific bluefin tuna (*Thunnus orientalis*) and has been vertically transmitted in hatcheries [45]. Although no nodavirus infection was detected in the dead fish of Atlantic bluefin tuna (*Thunnus thynnus*), the risk of infection by other viruses cannot be excluded [46].

Water temperature plays a critical role in the pathogenicity of viral diseases. Matsuura et al. [47] found that when tuna were exposed to high concentrations of Red Sea bream iridovirus (RSIV) at 25 °C, a 100% mortality rate was observed, accompanied by significant pathological changes in key immune organs such as the spleen and kidneys. In contrast, when the water temperature was lowered to 15 °C, the mortality rate significantly decreased, and the degree of tissue lesions was also reduced. These results suggest that water temperature is an important factor influencing the pathogenicity of RSIV infection, with higher temperatures potentially exacerbating viral replication and spread, leading to more severe clinical manifestations. A similar phenomenon was observed in rainbow trout (*Oncorhynchus mykiss*), where higher temperatures accelerated the replication of hematopoietic necrosis virus (IHNV) [48]. This study offers new perspectives for disease management in tuna aquaculture, emphasizing the critical role of temperature regulation in controlling viral spread and enhancing fish immunity.

Although attention to viral diseases in tuna has increased in recent years, current research primarily focuses on molecular diagnostics and gene detection. For example, real-time quantitative PCR (qPCR) technology has been used for the early detection of NNV infection [49]. However, due to the long lifespan and large size of tuna, experimental infections and vaccine development face significant limitations, resulting in the lack of commercialized vaccines or specific drugs for tuna [50]. Consequently, control measures for viral diseases in tuna remain highly limited.

Current research gaps primarily focus on in-depth investigations of host susceptibility mechanisms, immune evasion strategies, and the interactions between viruses, the environment, and the host. Compared to bacterial diseases, research on viral diseases in tuna aquaculture is relatively limited. However, when viral diseases occur, they typically result in extremely high mortality rates, posing a significant threat to juvenile tuna production. Although attention to viral diseases in tuna has increased in recent years, experimental infections and vaccine development face significant challenges due to the long lifespan and large size of tuna. As a result, there are currently no commercially available vaccines or specific drugs for viral diseases in tuna, and control measures remain highly limited.

Table 3. Viral pathogens in tuna species: reported hosts.

Viral Names	Host	Site of Infection	Reference
Nervous Necrosis Virus	*Thunnus orientalis*	Brain	Nishioka et al. (2010) [44]
Betanodavirus	*Thunnus orientalis*	Brain	Sugaya et al. (2009) [45]
Red seabream iridovirus	*Thunnus orientalis*	Liver and spleen	Matsuura et al. (2021) [47]
Iridoviridae, Parvoviridae, Alloherpesviridae, Papillomaviridae	*Thunnus albacares*	Gut	Gadoin et al. (2021) [43]
Iridoviridae, Parvoviridae, Alloherpesviridae, Papillomaviridae	*Katsuwonus pelamis*	Gut	Gadoin et al. (2021) [43]

5. Current Status in Parasitic Pathogen-Associated Diseases of Tuna

Parasitic diseases are one of the major threats to the health of both farmed and wild tuna populations, particularly in high-density farming systems and early developmental stages, where they exhibit high lethality [51]. In recent years, research in this field has expanded to include parasite species identification, molecular characterization, and pathogenic mechanism exploration, providing new theoretical insights for disease control. This review summarizes the major parasites reported from different tuna species, along with their infection sites and corresponding references (Table 4).

In yellowfin tuna (*Thunnus albacares*), researchers first isolated a large ectoparasite from the subcutaneous tissue of the dorsal region [52]. The parasite was deep red in color, with a prominent head and thorax, measuring approximately 8.42 cm in length. Mitochondrial genome sequencing revealed that its total genome length was 14,620 bp, containing 36 functional genes (including 12 protein-coding genes, 22 transfer RNA genes, and 2 ribosomal RNA genes), and had a virtual control region but lacked the ATP8 gene. Morphological observation and molecular phylogenetic analysis indicated that the parasite was closely related to the genus *Pennella* [52]. The *Pennella* genus is a common ectoparasite in marine fish, and its presence often leads to local skin damage, secondary infections, and immune dysfunction, negatively impacting the growth and market value of yellowfin tuna [53]. In Japanese waters, Nagasawa et al. [54] reported the occurrence of parasitic copepods in the subcutaneous tissue of the dorsal region of two tuna species. Specifically, *Caligus chiastos* was identified from yellowfin tuna (*Thunnus albacares*), whereas *Caligus productus* was detected from bigeye tuna (*Thunnus obesus*).

Parasitic threats are even more pronounced during the embryo and larval stages of tuna. Yuasa et al. (2007) [55] first reported a protozoan parasite infecting the fertilized eggs and yolk sac larvae of yellowfin tuna. The parasite was oval-shaped, with two flagella, and moved freely around the embryo, causing it to gradually become opaque and resulting in 100% mortality within 24 h. Based on 18S rRNA sequencing, the parasite was found to be 98.1% similar to *Ichthyodinium chabelardi*, a species parasitizing Atlantic sardines (*Sardina pilchardus*), suggesting that they could be homologous or closely related species. Similar protozoan parasites pose a significant threat to the survival rates of early-stage tuna larvae, highlighting the need for parasite monitoring and control during the hatchery phase.

In the cage farming system of southern bluefin tuna (*Thunnus maccoyii*), parasitic flatworms *Cardicola forsteri* have been widely reported as one of the major pathogens responsible for mortality. Studies indicate that during the 2021 southern bluefin tuna (SBT) farming season in South Australia, infection rates of *Cardicola forsteri* and *C. orientalis* reached as high as 83% [56]. These parasites primarily inhabit the heart and gill vasculature, causing circulatory disturbances and tissue damage, and can lead to large-scale mortality in severe cases [57]. The related species *Cardicola orientalis* has also been found in Pacific bluefin tuna (*Thunnus orientalis*) and is a key parasitic disease requiring control in the Japanese tuna farming industry [58]. Additionally, the number of sea lice (*Caligus chiastos*) is closely related to the health of southern bluefin tuna (*Thunnus maccoyii*), with peak infections occurring during the summer, particularly in the first six weeks of the farming season and during the high-temperature period in March. These infections cause significant losses in farming yield and economic profit [59]. Other protozoa and myxosporeans such as *Uronema nigricans* and *Kudoa* sp. have also been found in southern bluefin tuna, leading to tissue lesions, physical deterioration, and economic losses [51,60]. Control measures for parasitic diseases include early detection (e.g., qPCR), using anthelmintics like praziquantel, cage cleaning to reduce biofouling, and managing stocking density. Cleaner fish, site rotation, and fallowing periods help control sea lice and disrupt parasite life cycles, reducing reinfection risks and supporting sustainable tuna farming [61].

Overall, current research on parasitic diseases in tuna mainly focuses on morphological identification and molecular phylogenetic analysis, revealing the pathogenic roles of several important parasites. Tuna, particularly during high-density farming and early developmental stages, faces significant parasitic threats that not only compromise their health but also lead to markedly increased mortality rates. These studies provide theoretical support for the control of parasitic diseases in tuna and contribute to the development of more effective management and treatment strategies. Moreover, understanding the interactions between parasites, host immunity, and environmental stressors is crucial for developing more effective management and treatment strategies in tuna aquaculture.

Table 4. Parasitic pathogens in tuna species: reported hosts and infection sites.

Parasite Names	Host	Site of Infection	Reference
Pennella sp.	*Thunnus albacares*	Back subcutaneous tissue	Liu et al. (2022) [52]
Caligus chiastos and *Caligus lalandei*	*Thunnus albacares*	Opercular inner surface	Nagasawa et al. (2018) [54]
Caligus chiastos	*Thunnus maccoyii*	Skin and fins	Hayward et al. (2009) [59]
Caligus productus	*Thunnus obesus*	Opercular inner surface	Nagasawa et al. (2018) [54]
Ichthyodinium chabelardi	*Thunnus albacares*	Fertilized egg and Yolk-sac larva	Yuasa et al. (2007) [55]
Cardicola forsteri	*Thunnus maccoyii*	Heart and Gill blood vessels	Carabott et al. (2023) [56]
Cardicola orientalis	*Thunnus orientalis*	Heart and Gill blood vessels	Shirakashi et al. (2016) [58]
Didymozoidae sp.	*Thunnus albacares*	Gill, Pharynx and Caecum	Huang et al. (2025) [62]

6. Future Research Directions

Future research on tuna diseases should focus on a multidisciplinary approach that integrates pathogen management, immune system understanding, and environmental control. A key area of exploration lies in developing integrated disease management systems that address bacterial, fungal, viral, and parasitic threats simultaneously. This includes the exploration of alternative treatments, such as probiotics, immunostimulants, and vaccines, alongside more traditional methods. Understanding the immune responses of tuna, particularly in relation to pathogen-specific evasion mechanisms, will be crucial in designing effective interventions. Additionally, the use of advanced technologies, such as genomic and metagenomic approaches, can enhance our understanding of pathogen behavior, resistance mechanisms, and host-pathogen interactions, paving the way for more targeted and efficient treatments.

Additionally, the use of advanced technologies, such as genomic and metagenomic approaches, can enhance our understanding of pathogen behavior, resistance mechanisms, and host-pathogen interactions, paving the way for more targeted and efficient treatments, while also enabling the estimation of potential risks to human health [63]. Studies in other marine aquaculture species have demonstrated the potential of these technologies to identify key resistance genes and track pathogen evolution, which could be applied to tuna.

The development of vaccines remains a pressing need, especially as commercial vaccines for viral and bacterial diseases in tuna are not yet available. Recent progress in nanoparticle-mediated and oral vaccine delivery systems within aquaculture has provided promising directions for the development of effective vaccination strategies in tuna. To ensure robust and long-lasting protection, future research should focus on identifying critical antigenic determinants and refining delivery routes that accommodate the distinctive physiology and extended lifespan of tuna [64]. To this end, researchers should focus on identifying key antigens and developing novel delivery systems that are effective in large, long-lived fish like tuna. Alongside vaccine development, eco-friendly disease management strategies are vital to reduce the environmental impact of aquaculture. Over-reliance on antibiotics and chemicals has led to resistance issues, so alternatives such as natural antimicrobial agents and biological control methods should be further explored. Researchers have identified plant-derived compounds as potential natural alternatives to antibiotics for mitigating antimicrobial resistance [65]. This will help mitigate the adverse environmental effects associated with traditional treatments while improving disease control.

Environmental stressors, such as fluctuating water temperatures and deteriorating water quality, exacerbate disease outbreaks in tuna aquaculture. Studies have shown that temperature fluctuations, hypoxia, and pollution can disrupt immune function and promote pathogen virulence [66].Future research should aim to better understand how these factors influence both pathogen dynamics and tuna health. Predictive models that link environmental changes with disease risk can help improve disease management strategies and minimize losses [67]. Additionally, real-time monitoring tools and disease forecasting systems, such as biosensors and environmental DNA (eDNA) detection, could enhance the ability to detect and prevent disease outbreaks at an early stage, enabling rapid and effective responses before they escalate [68,69].Integrating these environmental and health monitoring systems with advanced diagnostic platforms would allow for early detection and more efficient management of disease in tuna farming operations.

Overall, future research must aim to bridge the gaps in our knowledge of tuna diseases, focusing on the interactions between pathogens, the immune system, and the environment. By advancing our understanding of these complex factors and developing sustainable, integrated management practices, we can enhance the health and productivity of farmed tuna, ensuring the long-term sustainability of the aquaculture industry.

7. Conclusions

In summary, bacterial, fungal, viral, and parasitic diseases have all been confirmed to cause severe losses in tuna aquaculture, with outbreaks closely associated with high-density farming and environmental stressors such as fluctuating water temperature and deteriorating water quality. Current research has identified the threats posed by pathogens such as *Vibrio* spp., *Photobacterium damselae*, and *Vibrio parahaemolyticus*, parasites including *Cardicola* spp. and *Pennella* spp., as well as viruses such as NNV and RSIV. However, critical gaps remain in understanding immune mechanisms, pathogen–host interactions, and long-term disease regulation strategies.

Future research must focus on three core scientific priorities: first, elucidating the molecular and immunological mechanisms underlying pathogen invasion and host defense in tuna; second, establishing multi-omics–based pathogen surveillance and early warning systems; and third, developing cross-protective vaccines and immune enhancers suitable for large pelagic species. These directions can bridge the current mechanistic and applied gaps in disease research.

At the industry level, the long-term development of tuna aquaculture requires a transition from single-disease management to ecosystem-based health management. This includes the integration of sustainable technologies such as recirculating aquaculture systems (RAS), biosecurity zoning, and digital health monitoring platforms supported by artificial intelligence for disease prediction. Enhancing genetic resistance through selective breeding and genomic tools should also be prioritized to build more resilient farmed stocks.

Collaborative frameworks combining academia, industry, and policy will be essential to translate scientific discoveries into practical health management strategies. By advancing these interdisciplinary and technology-driven approaches, the tuna aquaculture industry can achieve both higher productivity and greater ecological sustainability, ensuring its long-term viability under global environmental and economic challenges. Looking ahead, the sustainable advancement of tuna aquaculture must also consider the broader ecological and socioeconomic dimensions of disease management. Integrating environmental DNA (eDNA) surveillance, microbiome engineering, and precision aquaculture technologies could revolutionize how health risks are monitored and mitigated in real time. Moreover, climate change—through rising sea surface temperatures, ocean acidification, and altered salinity regimes—will likely intensify pathogen virulence and host susceptibility, emphasizing the need for adaptive management frameworks that link disease control with environmental resilience. Policy interventions encouraging responsible antibiotic stewardship, traceability systems, and international collaboration for data sharing will further strengthen global capacity to combat emerging transboundary diseases. Ultimately, aligning scientific innovation with sustainable governance and industry best practices will ensure that tuna aquaculture evolves toward a circular, low-impact, and health-secure production paradigm, capable of meeting future food security demands under changing ocean conditions

Author Contributions

X.L.: Conceptualization, Investigation, Data curation, Writing—original draft. J.H.: Resources, Validation, Writing—original draft. Z.F.: Visualization, Writing—review & editing. Z.M.: Supervision, Project administration, Funding acquisition, Writing—review & editing. J.C.: Conceptualization, Supervision, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the National Natural Science Foundation of China (32460927); the Science and Technology special fund of Hainan Province (grant number ZDYF2024XDNY247), the Fund of Key Laboratory of Efficient Utilization and Processing of Marine Fishery Resources of Hainan Province (grant number KLEU-2025-3), the Project of the Department of Science, Technology and Education, Ministry of Agriculture and Rural Affairs of the People's Republic of China (grant number pending) and the Central Public-interest Scientific Institution Basal Research Fund, CAFS (2025XT03, 2023TD58).

Institutional Review Board Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no competing interests.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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