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REVIEW Open Access

Strategies for managing major diseases in Asian seabass aquaculture

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Abstract

Asian seabass (*Lates calcarifer*) is becoming an important species for aquaculture. However, the Asian seabass aquaculture industry faces a significant challenge of disease outbreaks that can jeopardize fish health and production. This review delves into the major diseases affecting Asian seabass aquaculture and explores their causes, symptoms, and management approaches. We focused on the key pathogens responsible for these outbreaks, the environmental factors contributing to disease susceptibility, and the latest advancements in disease prevention and management. By addressing these critical aspects, this review addresses the needs of aquaculturists, researchers, and policymakers with the knowledge required to promote resilient and sustainable Asian seabass farming. We aim to shed light on the challenges posed by disease while highlighting innovative strategies that offer promise for the future of this thriving industry. This comprehensive examination serves as a valuable resource for those invested in ensuring the health and vitality of Asian seabass, securing a consistent supply to meet the demands of global seafood markets.

Keywords Asian seabass, Aquaculture, Disease, Pathogen, Sustainability

Introduction

The Asian seabass (*Lates calcarifer*), also known as barramundi, is becoming a popular species in aquaculture (Yue et al. 2023). It is a warm-water marine and freshwater fish native to the Indo-Pacific region (Loughnan et al. 2019; Shaklee and Salini 1985; Yue et al. 2009; Zhu et al. 2006). Asian seabass is highly regarded for its fast growth rate, adaptability to various environmental conditions, and delicious white flesh (Hassan et al. 2021; Ye et al. 2017; Yue et al. 2024). Its importance in aquaculture lies in its economic value and potential to meet the increasing global demand for seafood. Asian seabass is a commercially significant aquaculture species in the Asia–Pacific region, with annual production exceeding 120,000 tons (Yue et al. 2024). Major producers include Thailand, Malysia, Indonesia, and Australia, with ongoing efforts to increase sustainability and productivity (Yue et al. 2024). It also has high market demand and versatility as both a foodfish and a candidate for stock enhancement programs (Khang et al. 2018; Yue et al. 2024). Furthermore, it is known for its sustainability, as it can be farmed in closed systems, which reduces the environmental impact associated with traditional open-sea fishing (Hassan et al. 2021). This makes Asian seabass a valuable resource for the aquaculture sector.

In aquaculture, Asian seabass has gained tremendous popularity among both fish farmers and consumers (Chou and Lee 1997; Yue et al. 2023). Owing to its delectable flavor and robust growth potential, this species has carved out a significant niche in the global seafood market (FAO 2009). However, like any aquaculture species, Asian seabass is not immune to the challenges faced by

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aquaculture operations. Asian seabass aquaculture faces challenges from diseases, such as vibriosis (*Vibrio* spp.), streptococcosis (*Streptococcus iniae*, *S. agalactiae*), viral nervous necrosis (VNN) and other viral diseases, as well as parasitic infections (e.g., *Cryptocaryon irritans*) (Gibson-Kueh et al. 2012; Islam et al. 2024; Yang et al. 2022c; Yazid et al. 2021). These diseases cause symptoms such as skin lesions, organ damage, neurological issues, and mass mortalities, leading to significant economic losses. Outbreaks hinder growth, increase production costs, and threaten food security.

The pursuit of sustainable aquaculture and the increasing demand for high-quality seafood have placed immense pressure on fish farmers to safeguard their stocks against diseases that threaten the welfare of Asian seabass and other aquaculture species (Houston 2017; Yue et al. 2023). This review comprehensively examines the major diseases affecting Asian seabass aquaculture, including their causes, symptoms, and strategies for managing major diseases. By addressing pathogens, environmental factors, and advancements in disease prevention, we aim to support the health of this species and ensure a stable seafood supply. Our exploration provides stakeholders with knowledge for resilient and sustainable aquaculture. We delve into the challenges posed by diseases and innovative strategies, offering hope for the industry's future.

Pathogens, etiology, and symptoms

In Asian seabass aquaculture, numerous known pathogens, including viruses, bacteria, parasites, and fungi (Table 1 and Figs. 1 and 2), significantly impact the well-being and health of Asian seabass. In the following paragraphs, we present a concise overview of major pathogens, their etiology, and associated symptoms.

Viral diseases

Asian seabass faces significant viral threats, such as iridoviruses, including scale drop disease virus (SDDV) (Domingos et al. 2021; Gibson-Kueh et al. 2012) and infectious spleen and kidney necrosis virus (ISKNV) (Dong et al. 2017; Fu et al. 2023), as well as nervous necrosis virus (NNV) (Chi et al. 2005; Liu et al. 2016a; Yang et al. 2022c), birnavirus (Chen et al. 2019), herpesvirus (Dang et al. 2023), and other emerging viruses. The potential harm posed by these viruses to fish farms, along with a brief explanation of their symptoms and causes, is outlined here.

Table 1 Major diseases in Asian seabass (*Lates calcarifer*) aquaculture

Category	Pathogen	Disease	Symptoms	References
Bacteria	*Vibrio parahaemolyticus*	Vibriosis	Fin erosion, skin ulcers, hemorrhages, lethargy, appetite loss	(Das et al. 2009)
	Vibrio anguillarum	Vibriosis	Similar to *V. parahaemolyticus* but also internal bleeding	(Kumar et al. 2007)
	Vibrio alginolyticus	Vibriosis	Skin erosions, lethargy, darkening of body	(Krupesha Sharma et al. 2012)
	Tenacibaculum maritimum	Tenacibaculosis	Skin ulcers, fin erosion, tail rot, eye clouding	(Miyake et al. 2020)
	Streptococcus spp.	Streptococcus	Skin ulcers, internal bleeding, septicemia	(Piamsomboon et al. 2020)
Virus	Singapore grouper iridovirus (SGIV)	SGIV	Internal organ hemorrhage, eye clouding, abnormal swimming, lethargy	(Huang et al. 2009)
	Betanodavirus	VNN	Erratic swimming, whirling, loss of balance, skin darkening	(Hick et al. 2011)
	Red spotted grouper nervous necrosis virus (RGNNV)	RGNNV	Similar to VNN caused by NNV	(Nallala et al. 2021)
	Infectious spleen and kidney necrosis virus genotype I-III (ISKNV-1, -II & -III))	ISKNV-I, -II, & -III	Hemorrhages, organ necrosis, and immune suppression	(Fu et al. 2023; Jitrakorn et al. 2020; Zeng et al. 2023)
Protozoa	Eimeria barramundi	Coccidiosis	Intestinal inflammation, weight loss, diarrhea	(Gibson-Kueh et al. 2011a)
	Cryptosporidium spp.	Cryptosporidiosis	Diarrhea, weight loss, dehydration	(Gibson-Kueh et al. 2011b)
Monogenean	Monogenean	Inflammation, respiratory distress	Irritation, tissue damage, and excessive mucus production, skin ulcerations and fin erosion	(Rückert et al. 2008)
Fungi	*Saprolegnia* spp.	Saprolegniosis	Cotton-like fungal growth on skin, fins, gills	(Karunasagar et al. 2003)
	Achyla spp.	Achyliosis	Fungal dermatitis, gill damage, and erratic swimming	(Ming and Hatai 2017)

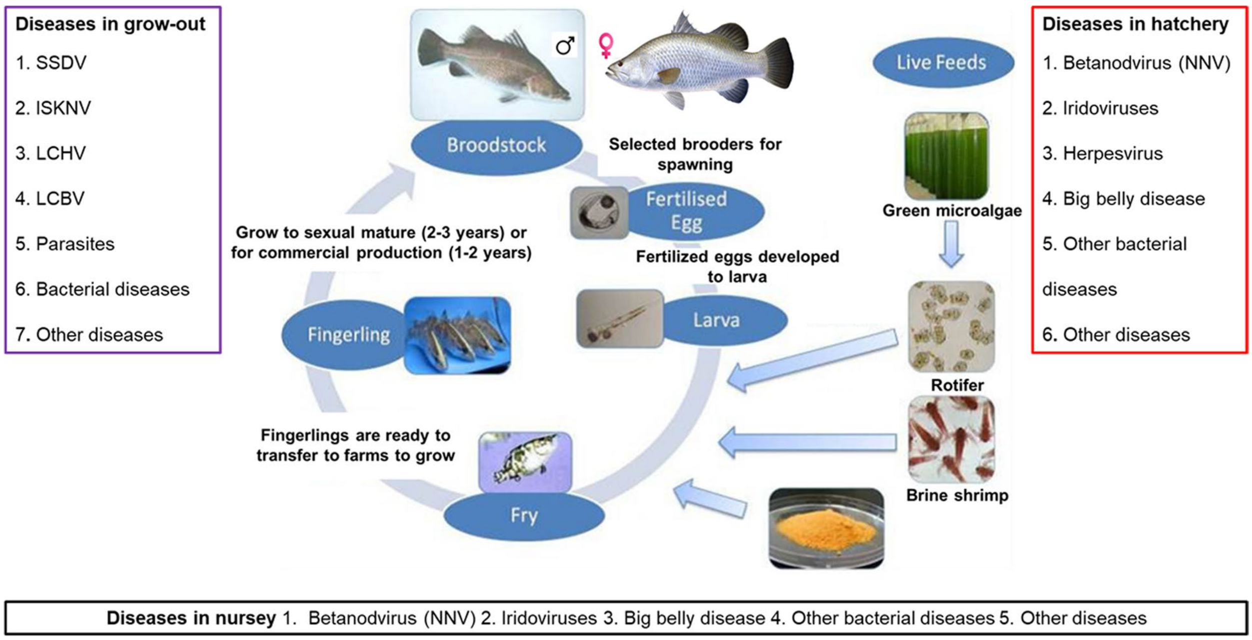

Fig. 1 Major disease occurrence attributed to various pathogens in different stages of the life cycle of Asian seabass (*Lates calcarifer*). NNV: Nervous necrosis virus; SDDV: Scale drop disease virus; LCHV: *Lates calcarifer* herpesvirus; Infectious spleen and kidney necrosis virus; ISKNV: Infectious spleen and kidney necrosis virus; LCBV: *Lates calcarifer* birnavirus; BBD: Large belly disease-causing bacterial pathogens

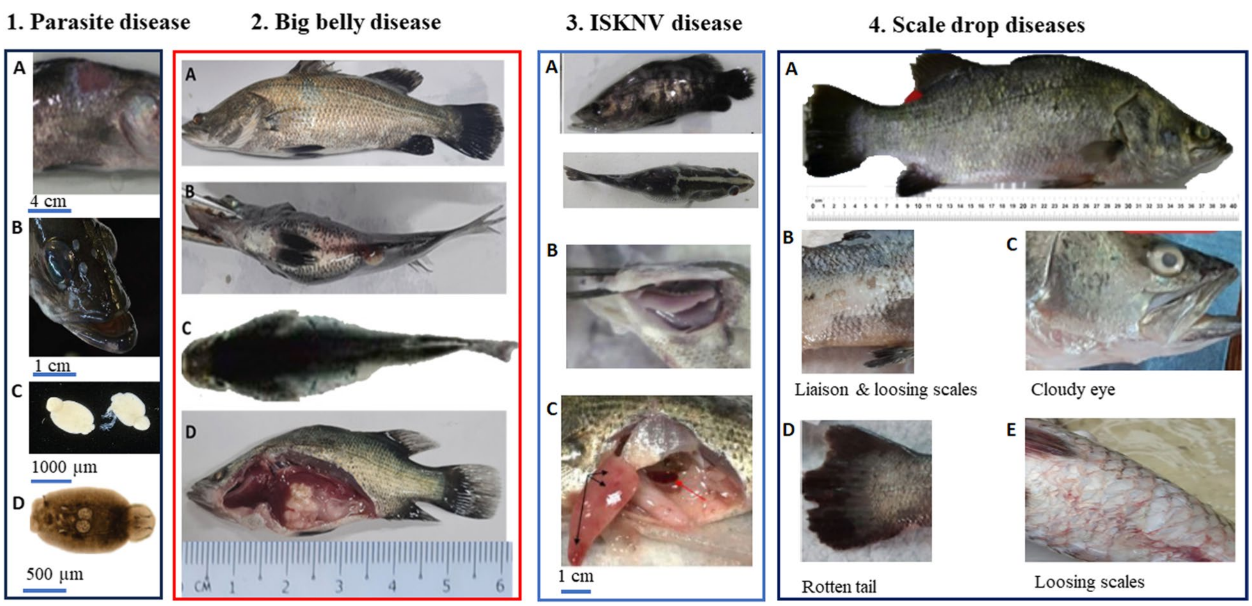

Fig. 2 Overview of symptomatology in Asian seabass (*Lates calcarifer*) arising from four major diseases caused by diverse pathogens in aquaculture settings. 1. Monogenean parasitism by Neobenedenia: **A**: An Asian seabass specimen exhibiting infection by Neobenedenia. **B**: Visible parasites on the fish's head. **C**: Neobenedenia parasites. **D**: Neobenia monogeneans observed via microscopy. 2. Big belly disease (BBD) triggered by bacterial infection: **A**: Healthy Asian seabass fingerling for comparison. **B**: Fingerling manifesting as BBD, characterized by an enlarged abdomen. **C**: Fingerling affected by BBD, displaying a darkened dorsal surface. **D**: Fingerling with BBD, showing symptoms not specified. 3. Infectious spleen and kidney necrosis virus (ISKNV) infection: **A**: Juvenile Asian seabass showing a darkened body due to ISKNV infection. B: Affected juveniles displaying symptoms of gill lamellar fusion, with the gills becoming pale and swollen. **C**: Signs of hepatic necrosis, liver inflammation, potential bleeding, kidney tissue necrosis, inflammation, and degradation. 4. Scale drop disease (SDD) induced by SDD virus: **A**: A maturing seabass infected with SDDV. **B** and **C**: Exhibiting lesions, scale loss, and cloudiness of the eyes. **D**: Presence of tail rot. **E**: Notable for scale loss on the abdomen

Iridoviruses

Iridoviruses are large, double-stranded DNA viruses in the family *Iridoviridae* that affect various aquaculture species, including Asian seabass (*Lates calcarifer*). They are characterized by an icosahedral capsid and a large, linear genome (Hick et al. 2016). In Asian seabass, iridoviruses from the genus *Megalocytivirus* and *Ranavirus* cause significant diseases. The key pathogens are SDDV (Gibson-Kueh et al. 2012), ISKNV (Dong et al. 2017), and Singapore grouper iridovirus (SGIV) (Song et al. 2004).

SDDV, also known as *Lates calcarifer* iridovirus (LCIV), is a significant viral pathogen that affects Asian seabass and, occasionally, other aquaculture species (de Groof et al. 2015; Gibson-Kueh et al. 2012). SDDV was first described in farmed fish in Singapore (de Groof et al. 2015; Gibson-Kueh 2012). Since SDDV was identified in 2015 as the pathogen causing the disease, there have been reports of Asian seabass showing scale-dropping symptoms in neighboring countries since 1992. SDDV belongs to the family Iridoviridae, which is known for its large, double-stranded DNA viruses. This virus is a member of the genus *Megalocytivirus* and is closely related to other megalocytiviruses (de Groof et al. 2015). SDDV is specifically associated with Asian seabass and causes a disease commonly referred to as scale drop disease (SDD) in the grow-out stage (Domingos et al. 2021; Senapin et al. 2019). The transmission of SDDV occurs primarily through horizontal routes, where the virus is directly spread from infected fish to susceptible fish. This can occur through contact with contaminated water, equipment, or other fish carrying the virus. Waterborne transmission is a significant mode of spread within aquaculture facilities (de Groof et al. 2015; Gibson-Kueh et al. 2012; Senapin et al. 2019). Clinical signs of SDDV infection in Asian seabass include the dropping of scales, lethargy, skin discoloration, rotting tails (Fig. 2), and a reduced appetite (de Groof et al. 2015; Gibson-Kueh et al. 2012). In severe cases, the disease can lead to high mortality rates for Asian seabass aged between 4 and 24 months and weighing 0.2 to 4 kg, causing substantial economic losses in aquaculture operations. For example, in 2023, the SSDV clouded the future of Asian seabass farming in Singapore, causing the Republic's sole fish farm operator in southern waters to cease commercial production (Ang and Begum 2023).

ISKNV can be categorized into three distinct genotypes: genotype I (ISKNV-I) (Fu et al. 2023), genotype II (ISKNV-II), and genotype III (Fusianto et al. 2023; Kurita and Nakajima 2012). ISKNV-I belongs to the *Megalocytivirus* genus, which is a group of large double-stranded DNA viruses that infect a wide range of fish species in aquaculture and wild populations but is most prominently associated with Asian seabass. ISKNV-I has high mortality rates, especially in juvenile fish, with outbreaks often leading to significant economic losses in aquaculture (Fu et al. 2023). ISKNV-II, a megalocytivirus in the *Iridoviridae* family, causes fatal systemic infections in freshwater and marine fish (Dong et al. 2017), notably Asian seabass in Zhuhai, Guangdong Province, China (Zhu et al. 2021). The mortality rates reached 85.89% for naturally infected fish and 83.30% for artificially infected fish (Zhu et al. 2021). Genetic analysis revealed that the virus presented 21 nucleotide differences between ISKNV-II and ISKNV-I. Histopathology and immunological assays confirmed the presence of ISKNV-II in the spleen, kidney, and liver. ISKNV-III is a distinct genotype within the *Megalocytivirus* genus that is associated primarily with disease outbreaks in marine fish species, including Asian seabass, and is also referred to as turbot red body iridovirus (TRBIV) (Go et al. 2016). ISKNV-III primarily infects marine species, including turbot (*Scophthalmus maximus*), groupers (*Epinephelus spp.*) and other marine fish species. Outbreaks of ISKNV-III can lead to mortality rates exceeding 50%, particularly in juvenile fish (Go et al. 2016). In addition, red sea bream iridovirus (RSIV) affects Asian seabass aquaculture (Girisha et al. 2020; Puneeth et al. 2021). RSIV is another member of the *Megalocytivirus* genus that was initially identified in red sea bream and other marine fish species. Genetic analyses (e.g., phylogenetics) have revealed differences in the nucleotide sequences of key genes (Girisha et al. 2020), allowing for differentiation between ISKNV-I and RSIV.

SGIV is a highly pathogenic member of the *Megalocytivirus* genus within the Iridoviridae family (Wang et al. 2017a; Yu et al. 2021, 2023). SGIV was first identified and characterized by Qin Qiwei and colleagues in Singapore in 2001 (Lai et al. 2008). The transmission of iridoviruses typically occurs through horizontal and environmental routes (Li et al. 2020). The virus can also persist in the environment, where it can infect water and sediment (Wang et al. 2017a). Thus, contaminated water sources can serve as a source of infection, making effective biosecurity measures crucial to prevent its spread. Clinical signs of iridovirus infection in young Asian seabass and other species may include skin discoloration, lethargy, abnormal swimming behavior, and, in severe cases, high mortality rates (Gibson-Kueh 2012). Iridovirus outbreaks occurring mainly in the hatchery and nursery stages can lead to a shortage of fingerling supplies for production and significant economic losses in aquaculture (Yu et al. 2021; Yu, Y. et al., 2022; Yu et al. 2023).

Nervous necrosis virus (NNV)

NNV, which causes viral nervous necrosis (VNN), is a significant viral pathogen that affects various aquaculture species, including Asian seabass and several other marine and freshwater species (Yang et al. 2022c). NNV is a member of the *Betanodavirus* genus and belongs to the *Nodaviridae* family. It is a small, nonenveloped, single-stranded RNA virus (Liu et al. 2016a, 2016b). NNV primarily targets the central nervous system of infected young fish, leading to severe neurological symptoms, such as erratic swimming, spiral swimming, and ultimately mortality (Kim and Kim 2015; Yang et al. 2022c). The virus is highly contagious and can cause up to 90% mortality and substantial economic losses in juveniles in aquaculture. NNV is highly prevalent in Asian seabass aquaculture across Southeast Asia, including countries such as Thailand, Vietnam, Indonesia, and Malaysia, where outbreaks are frequently reported, particularly in larvae and juveniles (Yang et al. 2022c). The virus also poses challenges in regions such as Australia (Jaramillo et al. 2017) and India (Satyanarayana et al. 2021), impacting production and necessitating significant biosecurity and management efforts. The transmission of NNVs in aquaculture systems occurs through multiple routes, including horizontal and vertical transmission (Zrnčić et al. 2022). Horizontal transmission is facilitated by direct contact between infected and susceptible fish (Ben-Asher et al. 2019). Waterborne transmission, through the shedding of viral particles into the water, can also lead to the spread of the virus among fish in the same facility (Yang et al. 2022c; Zrnčić et al. 2022). Additionally, NNVs can persist in the environment for extended periods, further increasing their potential for transmission. Vertical transmission, from infected broodstock to offspring, is another significant route of NNV transmission (Kang et al. 2023). This poses a significant challenge for the aquaculture industry, as it can result in the introduction of the virus into new generations of fish.

Lates calcarifer birnavirus (LCBV)

LCBV is a viral pathogen that affects Asian seabass (Chen et al. 2019). In the family *Birnaviridae*, it primarily targets the immune and nervous systems, leading to high mortality rates in infected fish populations. Typically, symptoms caused by LCBV in Asian seabass include lethargy, where infected fish may appear less active or lethargic than healthy individuals; reduced feeding, characterized by a noticeable decrease in appetite or feeding behavior; abnormal swimming, as fish may display erratic swimming patterns or struggle to maintain buoyancy; swollen abdomen, indicating potential internal issues such as inflammation or fluid accumulation; pale gills, signaling possible respiratory distress or compromised oxygen absorption; eye anomalies, with infected fish sometimes showing signs of eye abnormalities, such as cloudiness; and skin lesions and discoloration, including visible changes such as sores, ulcers, or unusual color changes. Additionally, severe outbreaks may result in mortality spikes, with an increased mortality rate (up to 85%) among the affected population (Chen et al. 2019). LCBV poses a significant threat to aquaculture industries, causing economic losses and impacting food security.

Lates calcarifer herpesvirus (LCHV)

LCHV is a recently discovered virus that infects fish, particularly Asian seabass. LCHV was first identified in 2015 in farmed Asian seabass within Southeast Asia (Dang et al. 2023). This has caused significant problems for Asian seabass aquaculture (Gibson-Kueh et al. 2023). LCHV can cause sudden spikes in mortality, with death rates reaching 50% in infected fish farms. Infected fish often exhibit a decreased appetite, lethargy, and abnormal swimming behavior (Dang et al. 2023; Gibson-Kueh et al. 2023). LCHV can lead to internal bleeding and inflammation of organs, especially the liver and spleen. The exact method of LCHV transmission is still under investigation, but it is likely through contact with contaminated water or infected fish. Researchers are actively working to understand and control LCHVs (Dang et al. 2023; Domingos et al. 2021; Gibson-Kueh et al. 2023; Meemetta et al. 2020; Prasitporn et al. 2021).

The Asian seabass aquaculture industry may face novel and emerging viruses. Research into the molecular biology of these viruses and their interactions with Asian seabass will further increase our ability to devise targeted interventions.

Bacterial diseases

Bacterial infections, particularly those caused by *Vibrio* and *Streptococcus* species, play a significant role in disease outbreaks among Asian seabass (Hegde et al. 2023; Hutson 2013; Islam et al. 2024). Bacterial diseases can result in high mortality rates and economic losses in Asian seabass aquaculture, emphasizing the importance of effective disease management strategies to safeguard fish health and maintain a sustainable industry. Here, we briefly introduce the etiology and pathogenesis of several major bacterial pathogens that cause high mortality rates in Asian seabass aquaculture.

Vibrio spp

Vibrio spp. are a diverse group of gram-negative, facultatively anaerobic bacteria that inhabit aquatic environments (Frans et al. 2011; Ina-Salwany et al. 2019; Ransangan et al. 2012). They are characterized by curved or comma-shaped rods, and several species within this genus are associated with fish diseases. *Vibrio harveyi* is a prominent pathogenic species known for its role in vibriosis among marine and freshwater fish species, including

Asian seabass (Ransangan et al. 2012; Zhang et al. 2020). Vibriosis in Asian seabass typically occurs when virulent strains of *V. harveyi* establish infections in fish populations. *V. harveyi* can enter fish through various routes, including the gills, skin, and gastrointestinal tract (Ransangan et al. 2012; Zhang et al. 2020). Factors such as stress, wounds, and environmental conditions can facilitate the entry of bacteria. Once inside the fish, *V. harveyi* colonizes various tissues, particularly the intestine and blood. *V. harveyi* possesses a range of virulence factors that contribute to its pathogenicity (Zhang et al. 2020). These include toxins, adhesins, and secretion systems, which help the bacterium evade the immune defenses of the fish and cause damage to host tissues (Zhang and Austin 2000). In response to *V. harveyi* infection, Asian seabass mounts an immune response, which includes the activation of both innate and adaptive immune mechanisms (Yu, et al. 2022a, b). However, virulent strains of *V. harveyi* can often overwhelm the immune system of the fish, leading to infection (Ganesan et al. 2022; Yang, et al. 2020a, b). Vibriosis manifests with a variety of clinical symptoms in Asian seabass, including abnormal swimming behavior, skin lesions, swelling, and lethargy (Hutson 2013). Fish may exhibit a reduced appetite and increased mortality rates, particularly in severe outbreaks (Houston 2017). Environmental factors, such as temperature, salinity, and water quality, play a significant role in the etiology of vibriosis (Montánchez and Kaberdin 2020). *Vibrio* spp., including *V. harveyi*, thrive in warm, brackish water. Elevated water temperatures and suboptimal salinity levels can create favorable conditions for bacterial growth and disease transmission (Ruwandeepika et al. 2012).

Streptococcus

Streptococcus species, including *Streptococcus agalactiae* and *Streptococcus iniae*, are important pathogens in Asian seabass aquaculture (Awate et al. 2023; Bromage et al. 1999). These bacteria can cause severe diseases in fish. *Streptococcus* spp. are gram-positive cocci that are facultative anaerobes (Bromage et al. 1999). They have a capsule that aids in their virulence, protecting them from the host immune response. This is a common disease in Asian seabass (Awate et al. 2023; Erfanmanesh et al. 2019). It is characterized by skin lesions, exophthalmia (pop-eye), abdominal distension, and hemorrhages. Affected fish may exhibit erratic swimming and reduced feeding (Bromage et al. 1999; Piamsomboon et al. 2020). *Streptococcus* spp. are transmitted primarily horizontally through water and can also infect fish through injuries and mucosal surfaces. Infected fish can shed bacteria into the environment, contributing to the spread of the disease (Bromage et al. 1999; Piamsomboon et al. 2020). Overcrowding, poor water quality, and stress due to factors such as temperature fluctuations can increase the susceptibility of Asian seabass to *Streptococcus* infections (Piamsomboon et al. 2020).

Aeromonas

Aeromonas species are gram-negative, rod-shaped bacteria commonly found in aquatic environments (Pessoa et al. 2019). They are opportunistic pathogens and possess several virulence factors, including adhesins and exotoxins (Tomás, 2012). *Aeromonas hydrophila* and other *Aeromonas* spp. can cause motile *Aeromonas* septicaemia in Asian seabass (Hamid et al. 2016). Infected fish present a range of symptoms, including hemorrhages, skin lesions, fin erosion, and eye abnormalities. Mortality rates can be high, particularly in stressed or overcrowded populations (Hamid et al. 2016). Some *Aeromonas* species can lead to ulcerative skin lesions and open sores in Asian seabass (Devadason 2023). These lesions can become infected and lead to severe tissue damage. Aeromonas infections can result in fin rot, characterized by the degradation of fish fins, which can impact swimming and balance (Devadason 2023; Hamid et al. 2016). Aeromonas can also affect the digestive system, leading to symptoms such as abdominal swelling and reduced feeding. Aeromonas infections are often associated with poor water quality and stress (Abdelsalam et al. 2021).

Other notable bacterial pathogens include *Flavobacterium*, *Tenacibaculum*, *Nocardia*, *Pseudomonas plecoglossicida*, and *Edwardsiella* spp., all of which have been implicated in severe outbreaks, causing substantial mortality and economic losses in Asian seabass (Islam et al. 2024). Detailed information about these bacterial pathogens and their adverse effects on Asian seabass aquaculture can be found in a previous review (Islam et al. 2024). Comprehensive management and understanding of these pathogens are crucial for effective disease control in Asian seabass aquaculture. Continued research into the molecular mechanisms of bacterial infections and host–pathogen interactions will contribute to more targeted and sustainable approaches for disease prevention.

Parasitic diseases

Parasitic infections in Asian seabass aquaculture are a concern. There are over 19 parasite species that affect the aquaculture of Asian seabass (Rückert et al. 2008), among which parasites such as protozoa, monogeneans, and helminths pose the greatest threats to the aquaculture of Asian seabass (Hutson 2013). Protozoan parasites such as *Trichodina* and *Amyloodinium* can lead to skin and gill issues (Rückert et al. 2008). Monogeneans attach to the fish's skin and gills, causing damage. Helminths are internal parasites that affect the digestive system. These infections can reduce fish health and growth, necessitating preventive measures to ensure the sustainability of Asian seabass farming (Hutson 2013; Rückert et al. 2008). Here, we outline the key parasites that significantly impact Asian seabass aquaculture.

Monogenean

Monogenean infections can cause several health issues in Asian seabass: Monogeneans attach themselves to the gills of the fish, leading to irritation, tissue damage, and excessive mucus production (Rückert et al. 2008). This can impede the ability of a fish to respire efficiently, resulting in respiratory distress. Monogeneans can also attach to the skin and fins, causing damage and inflammation (Fig. 2). This can lead to skin ulcerations and fin erosion, affecting a fish's appearance and swimming ability. Heavy infestations can stress fish, leading to reduced growth rates and poor feed conversion, which can have economic implications for aquaculture operations (Rückert et al. 2008). Monogeneans are transmitted primarily through waterborne infective larvae (Khrukhayan et al. 2016).

Ciliates

Ciliates are single-celled protozoan parasites commonly found in aquatic environments, and they can infest Asian seabass (Mahmoud 2021; Rückert et al. 2008). These microscopic organisms, often belonging to the order Apostomatida or Trichodinida, have hair-like structures known as cilia, which they use for locomotion and feeding. Ciliates such as *Trichodina* and *Epistylis* attach to gill filaments, causing irritation, inflammation, and increased mucus production. This can impair gill function, leading to respiratory distress (Mahmoud 2021; Rückert et al. 2008). Ciliates may also infest the fish's skin and mucous membranes, resulting in skin lesions and damage. These infections can contribute to reduced fish growth and overall vitality (Dickerson and Clark 1996). Severe ciliate infestations can induce stress in fish, increasing their susceptibility to secondary bacterial or fungal infections (Sufardin et al. 2021). Ciliates are transmitted through waterborne cysts and are often associated with poor water quality.

Future research on parasitic infections in Asian seabass aquaculture should focus on the following areas: (1) the development of effective and sustainable parasite control methods, which could include the development of new drugs and vaccines; (2) the use of probiotics and other natural products, the identification of parasite resistance mechanisms, and understanding how Asian seabass resists parasitic infections could lead to the development of new breeding strategies to improve parasite resistance in farmed fish; (3) the assessment of the economic impact of parasitic infections, which could help fish farmers make informed decisions about parasite control measures; the development of diagnostic tools and rapid and accurate diagnostic tools are essential for the early detection and treatment of parasitic infections; and (4) genetic improvement through molecular breeding using DNA markers associated with parasite resistance, which has been successfully performed in salmon breeding (Tsai et al. 2016). By addressing these research priorities, it should be possible to reduce the impact of parasitic infections on Asian seabass aquaculture and improve the sustainability of this important industry.

Fungal/fungal-like diseases

Fungal diseases are a potential threat to the aquaculture of Asian seabass. While not as common as some other diseases, fungal infections can cause significant mortality in hatcheries and aquaculture facilities, especially when fish are stressed or immunocompromised. The most common fungal pathogen affecting Asian seabass in aquaculture is Achlya (Lau et al. 2018). This oomycete, which is closely related to fungi but not technically a true fungus, can infect fish at all life stages, although it is most frequently observed in eggs and fry. Signs of Achlya infection in Asian seabass include fluffy white growth on the body, fins, or gills; skin ulcers; pale and lethargic fish; and loss of appetite. Several factors increase the risk of fungal infection in Asian seabass aquaculture. High organic matter content, low oxygen levels, and fluctuations in pH lead to poor water quality, which can create a favorable environment for fungal growth. Fish that are stressed due to overcrowding, handling, or poor water quality are also more susceptible to infection. Additionally, wounds or lesions on the body of a fish can provide entry points for fungal spores.

Diagnosis of major diseases in Asian seabass aquaculture

Diagnosing major diseases in aquaculture is crucial for maintaining the health and productivity of fish populations (Adams and Thompson 2011). Diagnosis involves a combination of clinical observations, laboratory tests, and monitoring practices (Austin 2019; Kumar et al. 2022; Zeldis and Prescott 2000), such as (1) Regular visual observations are essential to check for signs of disease, such as abnormal swimming, lethargy, changes in skin or fin coloration, loss of appetite, and unusual growth or lesions (Parameswaran et al. 2008). (2) Postmortem examinations of deceased fish can provide valuable information where internal and external abnormalities, such as organ damage, lesions, or the presence of parasites, can be identified (Ananda Raja and Jithendran 2015). (3) For suspected parasitic infections, skin scrapes or gill biopsies are examined under a microscope to identify and quantify the parasites (e.g., monogeneans, ciliates) (Paladini et al. 2017). (4) Bacterial infections require bacterial culture and identification. To determine the causative agent (e.g., *Streptococcus* or *Aeromonas* species), affected tissues or organs are swabbed and cultured on specific media (Abdelsalam et al. 2023). (5) Polymerase chain reaction (PCR) and other molecular methods, including the use of a CRISPR-based platform for rapid, sensitive and field-deployable detection of SDDV in Asian seabass (Sukonta et al. 2022), can be used to detect specific pathogens, especially in the case of viral diseases such as nervous necrosis (Yu et al. 2022a, b). For example, Yu et al. developed a colorimetric loop-mediated isothermal amplification (LAMP) protocol for onsite detection of SGIV, which targets the SGIV-VP61 gene (Yu. et al., 2022). The optimized colorimetric LAMP assay, which involved incubation at 63 °C for 1 h, exhibited a sensitivity of 5.66 copies/μL, which surpassed that of conventional PCR by 1000-fold. An examination of 60 DNA samples from SGIV-infected Asian seabass fins revealed that colorimetric LAMP agreed with seminested PCR in 94.87% of the cases. This method is sensitive, rapid, and specific and has potential for iridovirus disease diagnosis in the aquaculture industry. (6) Enzyme-linked immunosorbent assays (ELISAs) can be employed to detect the presence of specific antibodies or antigens associated with certain diseases (El-Adawy et al. 2023). For example, a study aimed to swiftly detect *Aeromonas veronii* infections in Nile tilapia via nanosilver-based ELISA (El-Adawy et al. 2023). *A. veronii* isolates from diseased Nile tilapia were identified through *gyrB* and *16S rRNA* gene sequences. Antisera prepared from tilapia and formalin-killed bacterial antigens were used in the ELISA. The traditional ELISA had a cutoff value of 0.46, and the nanobased ELISA had a cutoff value of 0.48. No cross-reactions occurred with other bacterial isolates. The nanodot-ELISA showed 100% sensitivity, specificity, and accuracy, outperforming traditional ELISAs. These findings suggest the potential of developing a rapid onsite field diagnosis test kit for *A. veronii* infection in other farmed fish, including Asian seabass. (7) Analysis of environmental DNA (eDNA) can also detect pathogens in water. For example, in a previous study (Kiat et al. 2023), quantitative PCR (qPCR) and digital droplet PCR (ddPCR) were employed on water samples collected over six months in a Singapore aquaculture facility. Both PCR methods successfully detected SDDV eDNA, with ddPCR being more sensitive. SDDV abundance was significantly correlated with periods of high rainfall and low salinity. This study highlighted the efficiency of ddPCR in detecting low virus levels in aquatic environments, demonstrating the potential of eDNA approaches for the early identification of viral diseases in aquaculture.

Next-generation sequencing (NGS) has had a significant impact on the aquaculture industry, particularly in the diagnosis of diseases (MacAulay et al. 2022). There are several key points to understand the importance of NGS in diagnosing diseases in aquaculture. NGS allows for the rapid and sensitive detection of pathogens, including viruses, bacteria, fungi, and parasites, which can cause devastating diseases in aquaculture. Early detection is crucial for implementing timely and effective disease management strategies (Avarre 2020; Chen et al. 2019). Aquaculture often faces the challenge of emerging and previously unknown diseases (Ghittino et al. 2003). NGS can help identify new pathogens and understand their genetic makeup, aiding in the development of specific diagnostics and vaccines (Avarre 2020; Chen et al. 2019). This study also provides detailed information regarding the genomic structure and genetic variations of pathogens. This information is invaluable for tracking the evolution of pathogens and their virulence, thereby informing disease control strategies (Avarre 2020). NGS technology enables the simultaneous analysis of many samples, making it a cost-effective option for large-scale disease monitoring and diagnosis. This is particularly beneficial for the aquaculture industry, which often deals with a high volume of samples (Yue and Wang 2017). NGS facilitates metagenomic analysis, which means sequencing all the genetic material in a sample, not just the targeted pathogen. This can be essential for identifying coinfections and understanding the overall microbial community, which might affect disease dynamics (Fang et al. 2019). Some diseases in aquaculture are associated with reservoir hosts, such as wild fish. NGS can be used to monitor the presence of these hosts and their potential role in disease transmission (Gonçalves et al. 2020). NGS data can inform the development of vaccines by identifying conserved regions in pathogen genomes or helping to design attenuated vaccines (Avarre 2020). Traditional diagnostic methods can sometimes yield false positives or negatives. NGS is more accurate, reducing the risk of misdiagnosis and preventing unnecessary measures or treatments (Chen et al. 2019). NGS data can be easily shared and compared across regions and countries. This facilitates international collaboration in monitoring and controlling diseases, which is crucial in the interconnected aquaculture industry. By assisting in the prevention and control of diseases, NGS contributes to the long-term sustainability of the aquaculture industry. Healthy stocks are more productive, reducing economic losses and negative environmental impacts. In summary, NGS has revolutionized disease diagnosis in the aquaculture industry by providing rapid, accurate tools for identifying and characterizing pathogens. Its application not only contributes to the economic viability of aquaculture operations but also plays a crucial role in the overall sustainability of this industry. However, NGS is still expensive.

Effective diagnosis is essential for implementing appropriate treatment and control measures, which may include the use of vaccines, antibiotics, antiparasitic treatments, improved husbandry practices, and biosecurity measures. Regular disease surveillance and early intervention are key to preventing outbreaks and ensuring the sustainability of Asian seabass aquaculture.

Disease management and prevention

Management strategies

Evaluating the current treatment options for major diseases in Asian seabass aquaculture, including antibiotics, antiviral agents, and vaccines, is essential for ensuring the health and sustainability of the industry (Gibson-Kueh 2012; Glazebrook and Campbell 1987). Antibiotics have been used, but concerns about antibiotic resistance and their environmental impact have prompted a re-evaluation of their use (Chokmangmeepisarn et al. 2021). Antiviral and antimicrobial agents, such as probiotics, herbs, and antimicrobial peptides (Falco et al. 2009; Lakshmi et al. 2013; Li et al. 2022), are valuable in managing viral and bacterial infections, but their effectiveness varies. Vaccines offer promising long-term solutions, reducing disease prevalence and the need for antibiotics (Fu et al. 2023; Kumar et al. 2007). A comprehensive assessment of these treatment modalities is crucial for developing more effective, environmentally friendly, and sustainable approaches for disease management in aquaculture.

Antibiotics are used to treat bacterial infections in Asian seabass aquaculture, including diseases caused by pathogens such as *Aeromonas* and *Streptococcus*. They can be highly effective in controlling these infections when used appropriately (Hutson 2013). Antibiotic use can lead to the development of antibiotic-resistant strains of bacteria, posing a threat to both aquaculture and public health. Additionally, residues of antibiotics in fish products can raise food safety concerns (Ferri et al. 2022). Therefore, currently, the use of antibiotics in the Asian seabass aquaculture industry is decreasing, while antiviral agents, which do not cause resistance, are increasingly being used in aquaculture (Bondad-Reantaso et al., 2023).

Vaccines offer a promising approach for combatting diseases in Asian seabass, which is crucial for sustainable aquaculture (Mondal and Thomas 2022). While still in development, promising vaccines (Table 2) offer hope for protecting Asian seabass from several common diseases. Injected vaccines against bacterial threats such as *V. anguillarum*, *V. harveyi*, and *S. agalactiae* are effective, with immersion followed by oral booster options emerging for greater convenience (Lan et al. 2023, 2021; Zhang et al. 2021). While effective against bacterial diseases, research continues to expand the vaccine toolbox to address viral threats such as SGIV (Ou-Yang et al. 2012) and NNV (Pakingking et al. 2009). A bivalent vaccine combining inactive ISKNV and SDDV has also shown promise, offering broader protection against multiple pathogens (Fu et al. 2023). These advancements in aquatic vaccines hold significant promise for healthier fish populations and more sustainable aquaculture practices. Research continues to refine these vaccines and expand their range of targeted diseases, aiming to ensure a healthier future for Asian seabass. Newer approaches, such as oral and immersion prime–oral boost strategies, show promise, potentially reducing stress in fish compared with injections. These vaccines are expected to significantly increase survival rates against bacterial infections, leading to healthier fish populations and

Table 2 Vaccines developed to prevent Asian seabass (*Lates calcarifer*) diseases

Vaccine against	Disease	Developer	Commercial availability	References
Iridoviruses, Including SGIV, ISKNV, RSIV,	Iridoviral diseases	Various	Yes	(MSD 2024)
Nodavirus	Virus nervous necrosis	Various	Not yet	(Pakingking Jr et al., 2009)
Vibrio. spp	Vibriosis	Various	Not yet	(Amir-Danial et al. 2023; Chin et al. 2020; Kumar et al. 2007)
Streptococcus agalactiae	Streptococcosis	Various	Yes	(Lan et al. 2021; Mohamad et al. 2021; MSD 2024)
SDDV	Scale drop disease	A lab in China	Not yet	(Fu et al. 2023)
ISKNV-I,	Spleen and kidney necrosis	A lab in China	Yes in China	(Fu et al. 2023)
RSIV-II	Spleen and kidney necrosis	A lab in China	Not yet	(Fu et al. 2023)

SGIV Singapore grouper iridovirus, *ISKNV* Infectious spleen and kidney necrosis virus; RSIV: red sea bream iridovirus; SDDV: scale drop disease virus improved aquaculture yields. However, ongoing research continues to refine these vaccines and expand their target range to combat other threats, such as viral diseases. Recent progress has been made in developing gene-deleted attenuated immersion vaccines for ISKNV, which significantly reduce virulence through targeted gene deletions. These vaccines maintain normal replication, immunogenicity, and immune protection in the host fish. Zeng et al. employed homologous recombination techniques to create a recombinant ISKNV strain (Δ*orf022l*) lacking the *orf022l* gene, which encodes a virulence-critical macro domain protein (Zeng et al. 2021). This strain exhibited a 98% survival rate in infected host fish and provided 100% immune protection against ISKNV. They also developed a double-gene-deleted strain, Δ*orf103r/tk*, lacking both the viral SOCS-encoding *orf103r* gene and the thymic kinase (*tk*) gene (Zeng et al. 2023). Δ*orf103r/tk* displayed attenuated virulence, resulting in minor lesions and a 3% mortality rate. A single immersion dose conferred long-term protection (> 95%) and robust immune responses. These studies highlight the potential of gene-deleted attenuated immersion vaccines for ISKNV prevention and are expected to be utilized in the future for the prevention and control of ISKNV disease in Asian seabass. While vaccines are increasingly employed to combat prevalent diseases, challenges such as antigen selection and delivery methods persist. Efforts have focused on enhancing vaccine efficacy, scalability, and cost-effectiveness to meet industry demands sustainably. Despite progress, ongoing research and collaboration are vital to address emerging pathogens and optimize immunization strategies for improved disease management in Asian seabass farming. The development of vaccines can be time-consuming and costly. They may not offer immediate protection, and their efficacy can vary depending on factors such as the fish's age and health. Storage and administration can also be challenging. Develop and administer vaccines tailored to the specific pathogens prevalent in the region. For example, vaccines for common diseases such as vibriosis or specific viral infections have been developed.

Antiviral agents, such as nucleoside analogs, have been developed to combat viral diseases such as nervous system necrosis (Falco et al. 2009; Lakshmi et al. 2013). They can reduce viral replication and help control outbreaks. For example, 15 phenylpropanoid derivatives were synthesized and evaluated for their anti-spring viremia of carp virus (SVCV) activity (Song et al. 2020). Among them, 4-phenyl-2-thioxo-1,2,3,4-tetrahydro-5H-chromeno[4,3-d]pyrimidin-5-one (S5) exhibited the greatest inhibition of SVCV replication, reaching 97% in epithelioma papulosum cyprini (EPC) cells. S5 treatment protected EPC cells from SVCV-induced cytopathic effects and mitochondrial injury by preserving mitochondrial functions. In vitro and in vivo studies revealed that S5 restored the antioxidant-oxidant balance by increasing antioxidant enzyme activities and reducing oxidative stress. Additionally, S5 upregulated interferon-related gene expression in zebrafish, enhanced innate immune responses and improved the survival rate of virus-infected fish. Overall, S5 shows promise as a potential therapeutic agent against SVCV infection in aquaculture. Therefore, this type of antiviral agent may also be effective in preventing diseases in Asian seabass. However, notably, these agents are often specific to certain viruses and may not be effective against a wide range of viral pathogens. There is also a risk of antiviral resistance emerging over time.

The use of herbs in Asian seabass aquaculture has been a topic of interest and research in various Asian countries, particularly Southeast Asia (Ahmadi et al. 2022; Talpur 2014). Herbs and herbal extracts are being explored for their potential benefits in improving the health and growth of Asian seabass, as well as enhancing the quality of the final product. Some studies have indicated that certain herbs and traditional medicinal plants could be used as dietary supplements or water additives to promote disease resistance, growth, and overall well-being in Asian seabass. For example, a study investigated the impact of *Azadirachta indica* (neem) leaf-supplemented diets on the innate immune response of Asian seabass fingerlings during *V. harveyi* infection (Talpur and Ikhwanuddin 2013). In terms of the immune response, fish fed a neem leaf-supplemented diet presented increased phagocytic activity, superoxide anion production, serum lysozyme activity, serum bactericidal activity, and serum antiprotease activity both before and after *V. harveyi* challenge. The experimental results indicated that neem leaf supplementation positively influenced immune parameters, as well as hematological and blood biochemical indices, in treated fish. Another study aimed to assess the efficacy of Ambon banana plant powder in feed to control Vibrio alginolyticus infection in Asian sea bass (Pattah et al. 2021). Five treatments were administered, including positive control, negative control, prevention, curative, and antibiotic application. A challenge test involving *V. alginolyticus* injection was conducted on the 15th day. Compared with control fish, those receiving supplemented feed presented elevated total erythrocyte, total leukocyte, hemoglobin, respiratory burst, and lysozyme activity. The expression of the *IL-1b* gene increased postchallenge, with the highest expression observed in the curative treatment group. The administration of *Ambon banana* plant powder at 3 g/100 g diet demonstrated control of *V. alginolyticus* infection in Asian seabass. Fermentation and fortification of *Sargassum linearifolium* with multistrain probiotics enhance mucosal barrier function, modulate the inflammatory response, and increase resistance to *Vibrio harveyi* infection in *Lates calcarifer* (Siddik et al. 2025). These herbs are believed to have antimicrobial and immunostimulant properties that could reduce the reliance on antibiotics and chemicals in aquaculture (Effendi et al. 2022). However, the adoption of herbs in Asian seabass aquaculture has not been widespread, and research is ongoing to better understand the optimal dosages, application methods, and long-term effects.

NPs offer a promising avenue for preventing diseases in aquaculture by providing targeted, efficient delivery systems for vaccines and drugs (Nasr-Eldahan et al. 2021). Their tiny size allows for direct interaction with pathogens and diseased cells, potentially enabling early detection and response to infections (Shaalan et al. 2016). Silver nanoparticles, for example, are known for their antimicrobial properties and can be used to treat bacterial infections without harming the aquatic environment (Márquez et al. 2018). Moreover, encapsulating vaccines in nanoparticles can improve their stability and efficacy, ensuring a stronger and more sustained immune response in aquatic organisms (Radhakrishnan et al. 2023). This technology could significantly reduce the reliance on antibiotics, addressing the pressing issue of antibiotic resistance in aquaculture environments. Positively charged mesoporous silica nanocarriers loaded with arbidol offer a novel and effective antiviral nanosystem against nervous necrosis virus (Liu et al. 2025). However, the environmental impact and long-term effects of introducing nanoparticles into aquatic ecosystems need thorough investigation to ensure sustainability and safety.

The choice of treatment strategy depends on various factors, including the specific disease, its severity, and the environmental and regulatory context. Integrated approaches that combine good husbandry practices, vaccination, and judicious antibiotic use can provide effective disease management while minimizing the risks associated with any single treatment method. Sustainable aquaculture requires a focus on disease prevention through improved management practices and biosecurity. Prevention is often more effective than treatment.

Disease prevention

In aquaculture, the implementation of robust biosecurity measures, vaccination programs, and effective water quality management plays a pivotal role in minimizing disease risk (Assefa and Abunna 2018) (Fig. 3). Biosecurity measures, such as controlled access and quarantine protocols, help prevent the introduction and spread of pathogens (Subasinghe and Shinn 2023). Vaccination programs bolster fish immunity, reducing their

Fig. 3 Precautionary steps to prevent disease outbreaks within Asian seabass (*Lates calcarifer*) aquaculture. **A**: Asian seabass brooders; **B**: Asian seabass juveniles in a hatchery; **C**: Asian seabass cultured in net cages in seas for commercial production; **D**: Asian seabass cultured in tanks on land for commercial production. RAS: Recycling aquaculture systems; IMTA: Integrated multitropic aquaculture

susceptibility to diseases and limiting the need for antibiotics (Erkinharju et al. 2021). Water quality management, including maintaining optimal temperature and oxygen levels and minimizing stress factors, ensures a healthy environment for fish, further increasing their disease resistance (Nasr-Eldahan et al. 2021). By combining these strategies, aquaculture operations can significantly increase their ability to maintain fish health, reduce disease incidence, and promote sustainable and responsible farming practices.

Strict biosecurity protocols can help prevent the introduction and spread of diseases in aquaculture facilities (Scarfe and Palić, 2020). It is essential to choose aquaculture locations carefully to minimize the risk of disease introduction, considering factors such as water source quality and proximity to other farms or wild aquatic populations. Implementing strict control over those who enter the facility, including visitors, equipment, and vehicles, is critically important. In addition, the use of foot baths, disinfection protocols, and secure entry points can prevent contamination. Biosecurity measures can be expensive to implement and require ongoing vigilance. These methods may not eliminate all disease risks, especially in open systems. Quarantine practices are also essential in preventing disease. New fish or equipment should be isolated in a quarantine area before introduction to the main facility. This allows for monitoring and disease detection without risking the health of existing stocks. Health certificates should be provided for any new stock to ensure disease-free introductions (Subasinghe 1997).

Environmental factors are closely related to disease susceptibility (Lieke et al. 2020). Maintaining optimal water quality, ensuring proper nutrition, and reducing stress through good husbandry practices are essential to bolster the immune system of aquaculture species and minimize disease susceptibility. Regular monitoring and proactive management of these environmental and nutritional factors contribute to the overall health and resilience of fish stocks, which is crucial for sustainable and disease-free aquaculture operations.

Maintaining appropriate stocking densities can reduce fish stress and prevent disease transmission through competition for space and resources (Krkošek 2010). Ensuring proper nutrition can improve the immune system of fish, increasing their resistance to disease. Water quality and nutrition are interconnected. Poor water quality can affect the availability and absorption of nutrients, exacerbating nutritional imbalances. Conversely, malnutrition can increase the sensitivity of fish to water quality fluctuations. In addition, transport stress can also cause disease. For example, a study revealed that the accumulation of ammonia during prolonged transport causes extensive damage to epithelial barriers in gastrointestinal tracts and depressed immunity due to marked hypoglycemia, predisposing fish to acute streptococcosis (Chew et al. 2024).

Vaccination programs are effective in preventing known diseases (Mondal and Thomas 2022). Vaccines have become promising and environmentally friendly approaches for disease prevention in aquaculture. They stimulate the fish immune system to build resistance to specific pathogens. Effective vaccines are available for diseases such as vibriosis and some viral infections (Kumar et al. 2007; Lan et al. 2023; Ou-Yang et al. 2012; Pakingking Jr et al., 2009; Zhang et al. 2021; Zhang et al. 2020) (Table 2). Vaccine utilization in the Asian seabass aquaculture industry has undergone significant advancements. It is essential to establish a vaccination schedule on the basis of the fish's growth stage and susceptibility to diseases.

Effective disease prevention in aquaculture relies on the integrated implementation of these biosecurity measures, which are tailored to specific farm conditions and the prevalent diseases in the region. Regular assessment and adjustments are crucial for maintaining the health and sustainability of fish populations under aquaculture conditions.

Selective and molecular breeding and genome editing for disease resistance

Selective breeding allows for the development of aquaculture stocks with enhanced resistance to specific diseases, reducing the need for disease treatment and increasing overall fish health (Yang et al. 2022c). Disease-resistant strains reduce the environmental impact of aquaculture through lower antibiotic and chemical usage, promoting more sustainable practices. Disease-resistant stocks can significantly reduce mortality rates and production losses, ultimately increasing profitability (Liu et al. 2024). Notably, the shrimp, Asian seabass, Japanese flounder, and salmon industries have achieved substantial success in breeding for disease resistance, with commercial lines exhibiting improved resilience to common pathogens (Liu et al. 2024; Norris 2017; Okutsu et al. 2007).

In Singapore, a breeding program has been established to increase the resistance of Asian seabass to three diseases, namely, big belly disease (BBD), VNN, and the disease caused by iridovirus (Yue et al. 2024). In 2012, two F_1 broodfish batches experienced BBD outbreaks in a hatchery, resulting in only 437 survivors out of 60,000 F_2 juveniles (Liu et al. 2024). Molecular parentage analysis (Liu et al. 2012; Yue and Xia 2014) identified four resilient F_1 parents. From their surviving offspring, 82 F_2 fish were selected on the basis of growth, family origin, and allelic variety. These 82 fish, from 37 families, were used to establish a third line for breeding F_3, aiming to increase resistance to various diseases, including betanodavirus and iridovirus (Liu et al. 2024). The process of selecting for NNV and iridovirus resistance began in F_3 following quantitative trait locus (QTL) mapping (Liu et al. 2016b; Wang et al. 2017a), association mapping (Yang. et al., 2020; Yang et al. 2021; Yu et al. 2021, 2023), and genome-wide association studies (GWASs) (Wang et al. 2017b) in F_2 and F_3 (Liu et al. 2024). Using 82 resilient F_2 broodfish with high BBD resistance and robust growth, six mass crosses were conducted, yielding 60,000 fertilized eggs per cross. From each cross, 192 fastest-growing F_3 fish were tagged at 90 dph and genotyped with 10 DNA markers. Molecular breeding values (MBVs) were estimated for 1,152 preselected fish, with the top 200 F_3 individuals, representing diverse families, chosen as broodfish to produce F_4. The F_4 selection followed the same strategy, resulting in 200 elite brooders from 1,152 candidates.

In ongoing efforts to increase the disease resistance of Asian seabass in Singapore via DNA markers associated with resistance to pathogens, a breeding line (line 3) was selected for resistance to BBD, NNV, and iridovirus. The F_3 generation, derived from selected broodfish with high BBD resistance, demonstrated resilience over five years without BBD outbreaks. Conversely, batches from growth-selected F_2 broodfish experienced BBD outbreaks in 4 out of 18 batches of F_3 young fish, indicating the effectiveness of molecular parentage analysis in controlling BBD epidemics. Since 2014, no NNV or iridovirus outbreaks have been reported in F_3, F_4, or F_5 offspring at the hatchery of the Marine Aquaculture Center, Singapore.

Genome editing (Yang et al. 2022a) holds promise for enhancing disease resistance in Asian seabass, a commercially important fish species. Research efforts have focused on the use of tools such as CRISPR-Cas9 (Yang et al. 2022a) to target genes associated with immunity and disease resistance pathways (Yang et al. 2020a, b). By modifying specific genes, scientists aim to bolster the ability of fish to fight pathogens, such as bacteria, viruses, and parasites, thereby reducing economic losses due to disease outbreaks in aquaculture settings. Several studies have demonstrated successful genome editing of genes for disease resistance in Asian seabass, showing the potential to create lines of fish with improved disease resistance traits (Ahmed et al. 2020; Yang et al. 2022b). For example, through QTL mapping (Liu et al. 2016b, 2016c), GWAS (Wang et al. 2017b) and positional cloning (Yang et al. 2020a, b), the *gab3* gene was found to be a negative regulator of NNV resistance in Asian seabass (Yang et al. 2022b). Knockout of this gene in zebrafish and an Asian seabass cell line improved resistance to NNV (Yang et al. 2020a, b). However, challenges in gene editing in Asian seabass remain, including the limited number of known genes for disease resistance, very long generation interval (4 years) (Yue et al. 2023), and very low success rate of microinjection for gene editing in marine fish species. Therefore, it is essential to identify the causative genes responsible for disease resistance and improve the efficiency of gene editing. Additionally, regulatory frameworks surrounding the use of gene editing in aquaculture need careful consideration to ensure that safety and ethical standards are met. While genome editing offers exciting prospects for disease resistance in Asian seabass, ongoing research and collaboration are crucial to translate these advancements into practical solutions for sustainable aquaculture practices.

Despite progress, challenges such as SDD persist, emphasizing the need for ongoing improvements for resistance to emerging diseases. The emergence of new diseases underscores the importance of enhancing overall resilience via the use of genomic tools such as genome sequencing and genome editing, along with vaccination strategies, to fortify the Asian seabass aquaculture industry against future threats. Despite these advancements, there are challenges in implementing molecular breeding for disease resistance. These include how to precisely phenotype disease resistance, the cost of genotyping, ethical concerns around genetic modification, and the need for international cooperation and standardization. Phenotyping approaches for disease resistance in farmed fish encompass various methods to assess individual- or population-level resistance to pathogens. These approaches include the following: (1) Clinical observation: monitoring fish for signs of disease such as lesions, abnormal behavior, or mortality rates (Gibson-Kueh et al. 2012); (2) challenge tests: exposing fish to specific pathogens under controlled conditions to evaluate their susceptibility and immune response (Liu et al. 2016b, 2016c); (3) immunological assays (Vaniksampanna et al. 2023): measuring immune parameters such as antibody production, phagocytic activity, or cytokine expression to gauge the immune response; (4) microbiome analysis (Miyake et al. 2020; Xia et al. 2014): assessing the composition and diversity of the fish microbiome to understand its role in disease resistance; and (5) metabolic profiling (Low et al. 2017): analyzing metabolic pathways associated with immune function to identify biomarkers of disease resistance. Combining these approaches can identify DNA markers and genes for disease resistance to enhance breeding programs and management strategies aimed at improving disease resistance in farmed fish populations. As the Asian seabass aquaculture industry continues to grow, ensuring that molecular breeding practices are sustainable and environmentally friendly is crucial.

Future directions and conclusions

Continued monitoring and research are vital to address emerging diseases in Asian seabass aquaculture. Addressing antibiotic resistance necessitates alternative disease control strategies, but environmentally friendly approaches are crucial for long-term sustainability. Enhanced biosecurity measures are essential to prevent disease introduction and outbreaks. Disease dynamics, which are influenced by environmental factors, require adaptive management strategies. To promote sustainability in Asian seabass aquaculture, genetic research should focus on disease resistance alongside selective breeding programs. The continuous improvement of vaccines and exploration of probiotics and immunostimulants are essential. Implementing technology-driven solutions such as real-time monitoring and automated disease detection systems is paramount. The development of specialized feeds to increase fish immunity should be prioritized. Integrating these measures and innovative solutions can effectively combat disease challenges, ensuring the sustainable growth of the industry. Through knowledge dissemination, collaboration, and advocacy for sustainable practices, we can secure the future of Asian seabass aquaculture. With concerted efforts, the industry holds promise for meeting global seafood demand while safeguarding species' welfare and vitality.

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Authors' contributions
GHY and CJG: Conceptualization, Methodology, Software. GHY and CJG: Data curation, Writing- Original draft preparation. GHY and CJG**:** Visualization, Investigation. GHY and CJG: Validation. GHY and CJG: Write, review and editing.

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Data availability
All the data supporting the findings of this study are available in the cited papers in the article and its supplementary information files.

Declarations

Ethical approval and consent to participate
Not applicable**.**

Consent to publication
We give our consent for the publication of identifiable details, which include figure(s) and/or statements and declarations.

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